

Modern Concepts in Crop Production

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This book give light on crop growth analysis in relation to environment; Agroclimatic zones of Himachal Pradesh and India; Inverse yield nitrogen law; Mitscherlich yield equation, its interpretation and applicability; Baule unit; Effect of lodging in cereals; physiology of grain yield in cereals; optimization of plant population and planting geometry in relation to different resources, concept of ideal plant type and crop modeling for desired crop yield; Scientific principles of crop production; seed production techniques in various crops; crop response production functions; concept of soil plant relations; yield and environmental stress; Integrated farming systems, organic farming, resource conservation technology including modern concept of tillage; dry farming; determining the nutrient needs for yield potentiality of crop plants; precision agriculture

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Objective

To teach the basic concepts of soil management and crop production

Theory

UNIT I

Crop growth analysis in relation to environment; Agroclimatic zones of Himachal Pradesh and India

UNIT II

Inverse yield nitrogen law; Mitscherlich yield equation, its interpretation and applicability; Baule unit

UNIT III

Effect of lodging in cereals; physiology of grain yield in cereals; optimization of plant population and planting geometry in relation to different resources, concept of ideal plant type and crop modeling for desired crop yield

UNIT IV

Scientific principles of crop production; seed production techniques in various crops; crop response production functions; concept of soil plant relations; yield and environmental stress

UNIT V

Integrated farming systems, organic farming, resource conservation technology including modern concept of tillage; dry farming; determining the nutrient needs for yield potentiality of crop plants; precision agriculture

Suggested Readings

- Balasubramaniyan P & Palaniappan SP. 2001. *Principles and Practices of Agronomy*. Agrobios.
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UNIT I

Crop growth analysis in relation to environment; Agroclimatic zones of Himachal Pradesh and India

Crop growth analysis in relation to environment

According to the yield equation, productivity of crop canopies is analyzed in terms of

- total incident solar radiation (Q),
- the proportion of the incident solar radiation that is intercepted by the crop canopy (I_A'),
- the efficiency of conversion of intercepted radiation into plant dry matter (i.e., C), and
- the partitioning of dry matter among various plant/crop components (i.e., ρ).

Historically, the methodologies used in the study of the productivity of crop canopies have been dependent on available technology. In the 1950s, crop canopies were analyzed in terms of weight, weight distribution, and leaf area. This is called growth analysis. In general, growth analysis is the study of crop canopies over periods of weeks across areas of 0.1 to 10 m². In the 1960s, the infrared gas analyzer (IRGA) enabled quick measurements of CO₂ exchange rates and leaf photosynthetic rates (or leaf carbon exchange rate, CER) of field-grown crop canopies were studied. Leaf photosynthesis is measured on cm² leaf area over minutes. Although leaf photosynthesis does give an instantaneous measure of "plant growth", photosynthetic rates vary with leaf age, leaf position in the canopy, recent "light history" (i.e., sunlit vs. shaded leaf area), and time of the day. In the 1970s, whole-canopy crop enclosures were developed to alleviate some of the problems associated with single-leaf photosynthetic measurements. Canopy photosynthesis is measured over periods ranging from minutes to days for crop canopies covering 0.5 to 2 m² of ground area. Canopy photosynthesis represents an instantaneous measure of the canopy response to a change in environmental variables, but the measurement system is cumbersome and inflexible. Chlorophyll-fluorescence technology became available during the 1990s and chlorophyll fluorescence enables very quick and easy measurements of photosynthetic parameters of leaves. However, the measurements are made on very small pieces of leaf and it is extremely challenging to obtain values that represent the canopy.

Usually, a thorough analysis of the productivity of crop canopies would use two or more of the methods described above in combination and, most importantly, the results should represent the canopy as a whole and should therefore account for spatial variability (e.g., plant-to-plant variability). The magnitude of plant-to-plant variability in crop canopies consisting of plants that have the same genotype is one of the most difficult concepts to get across to biologist who are not familiar with crops. In carefully conducted experiments in research plots with a maize hybrid, for instance, the range from plants with the lowest dry matter to the plants with the highest dry matter at maturity is fourfold at low plant densities and tenfold at high plant densities. Under "normal" commercial conditions that range from lowest to highest plant weight will probably be much higher. The correct sample size is the sample size that will represent the canopy as a whole (i.e., in the example describe above, a few plants would certainly not suffice; possibly, 40-50 randomly selected plants would be a representative sample). The best method to analyze a crop canopy is always a compromise between the accuracy of the measurement (i.e., how good is the measurement) and the precision of the measurement (i.e., how repeatable is the measurement when we use another plant or set of plants). The difficulty to measure plant productivity accurately and precisely is probably the greatest challenge in any effort to improve the efficiency of production in agriculture, irrespective whether it involves traditional plant breeding, biotechnology, cropping systems research, or organic agriculture.

Growth analysis

Total crop dry matter is the spatial and temporal integration of all plant processes and, therefore, it is the most relevant parameter in the study of crop canopies. Rate of dry matter accumulation varies across the life cycle of a crop and dry matter and leaf area are sampled at intervals ranging from days to weeks to quantify effects of environmental influences or to analyze genotypic differences between crop cultivars. In growth analysis two basic measurements are made, dry weight and leaf area, and a large number of parameters are derived from these measurements.

Parameter	Symbol	Unit
Crop Growth Rate	CGR	g (crop) m ⁻² d ⁻¹
Leaf Area Index	LAI	m ² (leaf) m ⁻²
Specific Leaf Area	SLA	m ² (leaf) g ⁻¹ (leaf)
Relative Growth Rate	RGR	g (crop) g ⁻¹ (crop) d ⁻¹
Net Assimilation Rate	NAR	g (crop) m ⁻² (leaf) d ⁻¹

The pattern of rate of dry matter accumulation of a crop canopy is typically characterized by a sigmoid curve. Three more or less distinct phases can be distinguished (see Fig. 1): (i) a period of exponential growth during early development, followed by (ii) a period of more or less constant rate dry matter accumulation, and (iii) a period of declining crop growth rates during the final phase of development when green leaf area declines due to leaf senescence and leaf photosynthesis declines due to leaf

aging. It is important to realize that the parameters SGR and NAR are only relevant during the first phase.

(i) *Early phases of development.* Rate of dry matter accumulation during early development is directly related to LAI and as LAI is closely associated with plant dry matter during this phase, rate of dry matter accumulation of a crop is a function of its own weight:

$$dW/dt = SGR \times W \quad [1]$$

integrating Equation [1] gives:

$$W_t = W_0 \times e^{SGR \times t} \quad [2]$$

$$W_t / W_0 = e^{SGR \times t} \quad [2a]$$

where W_0 and W_t are the crop weights at times $t = 0$ and $t = t$, and SGR is the slope of the natural log of crop dry matter vs. time, i.e.:

$$\ln(W_t / W_0) = \ln e^{SGR \times t} = SGR \times t \quad [3]$$

The increase in LAI, and, consequently, the increase in rate of dry matter accumulation, is proportional to rate of dry matter accumulation per unit leaf area (NAR). During this phase of development, an increase in leaf area leads to an increase in rate of dry matter accumulation (because light interception is directly related to leaf area during this phase of development) and an increase in dry matter accumulation leads to an increase in leaf area (because proportion of dry matter allocated to leaves remain fairly constant).

Various equations are used to estimate mean net assimilation rate NAR_{mean} . NAR is the ratio of rate of dry matter accumulation and leaf area index and a mean ratio should take into account the rate of change of each of its components. During exponential dry matter accumulation, and assuming an equal exponential rate of increase for LAI and dry matter, mean NAR can be estimated as follows:

$$NAR_{mean} = [(W_2 - W_1) / (t_2 - t_1)] \div [(LAI_2 \div LAI_1) / (LAI_2 - LAI_1)] \quad [4]$$

where NAR_{mean} is the mean net assimilation rate during a period from $t = t_1$ to $t = t_2$. The second part of Equation [4] expresses the inverse of mean LAI from $t = t_1$ to $t = t_2$. In contrast to mean NAR, instantaneous NAR can be estimated by calculating rate of dry matter accumulation at time t (i.e., by differentiating the "growth curve" at time $= t$) and measuring LAI at time $= t$.

Instantaneous NAR at time $= t$ is rate of dry matter accumulation divided by LAI.

The NAR will decline once mutual shading among leaves in the canopy will occur. Rate of dry matter accumulation will become "constant" when a change in LAI will not influence absorbance of incident irradiance: the canopy has attained the phase of "constant" growth. Similarly, a crop will have attained the phase of "constant" growth when leaf-area expansion has been completed, even if PAR absorbance is less than 100%. Dry matter accumulation during this period is relatively unimportant in the context of dry matter accumulation during the growing season. For instance, a maize crop will accumulate less than 15% of dry matter at maturity during this period.

(ii) *The period of a relatively constant rate of dry matter accumulation.* This period is the most important phase of development for dry matter accumulation and grain yield of most crops. For instance, maize may accumulate up to 75% of its dry matter at maturity during this period and, consequently, this period contributes most to final yield. Rate of dry matter accumulation during this period is fairly constant and, consequently, CGR is the appropriate parameter to use. CGR will vary with incident solar irradiance and abiotic stresses may reduce CGR. Because CGR is relatively constant, total dry matter accumulated during this period is closely related to the duration of the period.

(iii) *Final phase of development.* Rates of dry matter accumulation per day start to decline due to aging during the final phase of development. The decline in the rate of dry matter accumulation during this phase is associated with functional and visual leaf senescence. Functional leaf senescence is the decline in photosynthesis per unit leaf area due to aging. Visible leaf senescence is the loss of chlorophyll in the leaf. Whereas no photosynthesis will occur in a leaf that has lost all its chlorophyll, a leaf that has retained all its chlorophyll does not necessarily maintain its rate of photosynthesis. For instance, Echarte et al. (2008) depicted that leaf photosynthesis (CER) declines during the grain-filling period of maize, even if chlorophyll content remain constant under a high N fertilizer level. The sevenfold increase in grain yield of corn hybrid in North America during the last 70 years has been attributed, in part, to increased functional and visual "stay green".

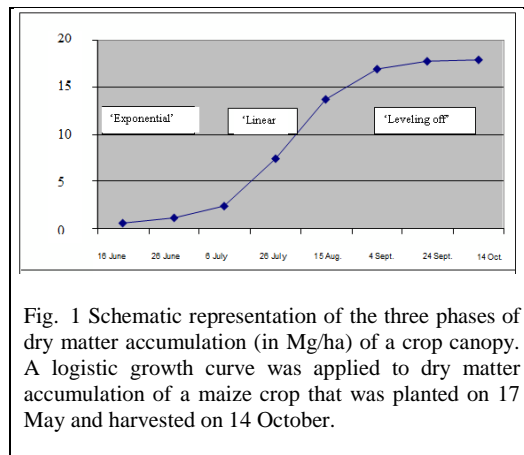


Fig. 1 Schematic representation of the three phases of dry matter accumulation (in Mg/ha) of a crop canopy. A logistic growth curve was applied to dry matter accumulation of a maize crop that was planted on 17 May and harvested on 14 October.

Environmental physiology

Light, CO₂, temperature, water and nutrients are taken as key driving variables for growth responses in a wide range of species. Growth indices, especially whole-plant and leaf RGR, serve as an indicator of plant response and of interactions between environmental factors where they occur. Variation in whole-plant RGR is then resolved into contributions from NAR and LAR. Ecological implications for managed and natural communities are considered.

Light

Light has an impact on both extent and activity of plant canopies. Taking cucumber as an archetype for herbaceous crop plants (Figure 2) leaf growth increases with daily irradiance due to increased cell number rather than increased cell size. Leaf thickness is also positively affected by daily irradiance, principally resulting in a greater depth of palisade (Table 1). Indeed, mean cell volume is more than doubled under strong irradiance ($3.11 \times 10^{-5} \text{ mm}^3$ at $3.2 \text{ MJ m}^{-2} \text{ s}^{-1}$ cf. $1.46 \times 10^{-5} \text{ mm}^3$ at $0.5 \text{ MJ m}^{-2} \text{ d}^{-1}$ in Table 1), and because cross-sectional area is virtually unchanged cell depth is responsible. This greater depth of palisade in strong light confers a greater photo-synthetic capacity on such leaves (expressed on an area basis) and translates into larger values for NAR and a potentially higher RGR. At lower irradiance (Table 1) leaves are thinner and SLA will thus increase with shading, and because $\text{LAR} = \text{SLA} \times \text{LWR}$ a smaller absolute size at lower irradiance can be offset by larger SLA resulting in LAR increase.

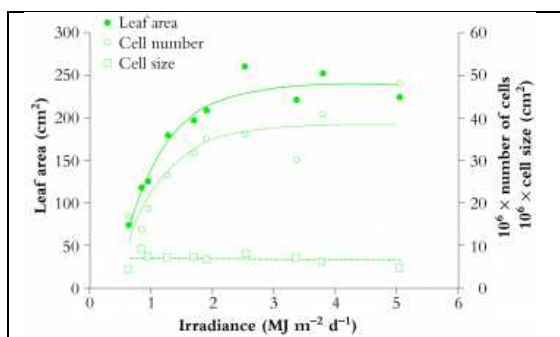


Figure 2. Area of individual leaves on cucumber (*Cucumis sativus*) responds to daily irradiance and reaches a maximum above about $2.5 \text{ MJ m}^{-2} \text{ d}^{-1}$. Area increase (node 2 in this example) is due to greater cell number under stronger irradiance. Mean size of mesophyll cells is little affected and has no influence on area of individual leaves (Based on Newton 1963)

Table 1. Leaf size and other physical attributes measured on *Cucumis sativus* foliage at node 3 show a positive response to daily irradiance in growth cabinets

Attribute	Daily irradiance (MJ m^{-2})	
	0.5	3.2
Area of leaf (cm^2)	127	356
Leaf thickness (μm)		
Sections	88	211
Vol./area	111	222
Mean cell volume ($10^4 \mu\text{m}^3$)	1.46	3.11
Cell cross-section (μm^2)	131	138

(Based on Wilson 1966)

G.E. Blackman (Agriculture Dept, Oxford University) appreciated the significance of such $\text{LAR} \times \text{NAR}$ interaction for whole-plant growth, and in a series of comprehensive papers with a number of collaborators documented shade-driven growth responses for many species. RGR response to growing conditions such as shade, and the degree to which upward adjustment in LAR could offset reduced NAR, was a recurring theme. Plants were commonly held in either full sun or under combinations of spectrally neutral screens that reduced daily irradiance to either 24% or 12% of full sun. These three treatments commenced with onset of rapid growth by established seedlings, and harvests taken as plants were judged to have doubled in size over successive intervals. Steady exponential growth ensured that treatment effects on RGR could be resolved into component responses by NAR and LAR.

In a series of 20 pot experiments, Blackman and Wilson (1951a) first established a close relationship between NAR and daily irradiance where shade-dependent reduction in NAR was similar for 10 species. More precisely, NAR was linearly related to log irradiance and extrapolation to zero NAR corresponded to a light-compensation point of 6–9% full sun for eight species, and 14–18% full sun for two others. Significantly, neither slope nor intercept of NAR versus \log_{10} daily irradiance differentiated sun-adapted plants such as barley, tomato, peas and sunflower from two shade-adapted species (*Geum urbanum* and *Solanum*

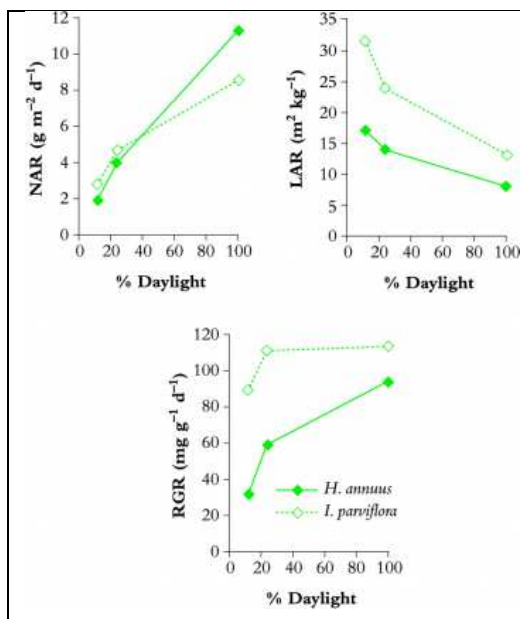


Figure 3. A sun-adapted plant such as *Helianthus annuus* adjusts LAR to some extent in response to lower daily irradiance but not enough to maintain RGR. By contrast, a shade-adapted plant such as *Impatiens parviflora* with somewhat higher LAR and RGR in full sun makes further adjustment in LAR so that RGR does not diminish to the same extent in moderate or deep shade as does that of *H. annuus* (Based on Blackman and Wilson 1951b; Evans and Hughs 1961)

dulcamara). LAR proved especially responsive to light and accounted for contrasts between sun plants and shade plants in their growth response to daily irradiance.

Concentrating on sunflower seedlings, Blackman and Wilson (1951b) confirmed that NAR increased with daily irradiance (Figure 3a) and that LAR was greatly increased by shading especially in young seedlings (uppermost line in Figure 3b). Response in RGR tracked LAR and especially in young seedlings which also showed highest RGR and were most sensitive to shading. LAR appeared sensitive to both daily maxima as well as daily total irradiance. Variation between species in adjustment to shade, and ultimately their long-term shade tolerance, would then derive from plasticity in LAR.

A subsequent comparison between sunflower and the wood-land shade plant *Impatiens parviflora* by Evans and Hughes (1961) confirmed this principle of LAR responsiveness to irradiance (Figure 3). Sunflower achieved noticeably higher NAR in full sun than did *I. parviflora*, but LAR was considerably lower and ironically translated into a somewhat slower RGR for sunflower. This species contrast was, however, much stronger in deep shade (12% full sun) where RGR for *I. parviflora* had fallen to 0.090 d^{-1} whereas sunflower was only 0.033 d^{-1} . Clearly, *I. parviflora* is more shade tolerant, and retention of a faster RGR in deep shade is due both to greater plasticity in LAR as well as a more sustained NAR. Adjustments in both photosynthesis and respiration of leaves contribute to maintenance of higher NAR in shade-adapted plants growing at low irradiance.

Daily irradiance (photosynthetically active energy) at low to mid latitude ($20\text{--}30^\circ$) can reach 15 MJ m^{-2} on clear days in midsummer. The tropics can be lower due to cloud cover, while at higher latitudes ($30\text{--}50^\circ$) lower daily maxima are offset by long days. Plant growth and reproductive development vary accordingly, and some early results, including those from northern hemisphere experiments, must be viewed in this context. Warren Wilson (1966, 1967) analysed the performance of open-grown seedling sunflowers at Deniliquin and recorded the highest known value for NAR, namely $29.9 \pm 0.4 \text{ g m}^{-2} \text{ d}^{-1}$. Pooling data from Deniliquin and Oxford (Figure 4), NAR in widely spaced and nutrient-rich sunflower plants was linearly related to daily irradiance with a mean maximum NAR of about $25 \text{ g m}^{-2} \text{ d}^{-1}$ at about $15 \text{ MJ m}^{-2} \text{ d}^{-1}$. In assimilatory terms, sunflower shows remarkable capacity and plasticity.

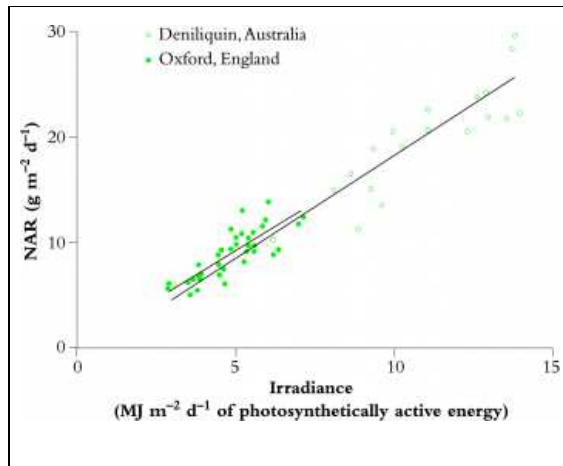


Figure 4 NAR for open-grown seedlings of sunflower (*Helianthus annuus*) responds linearly to daily irradiance across a wide range from low values recorded at Oxford to the highest recorded value for NAR of about $30 \text{ g m}^{-2} \text{ d}^{-1}$ at Deniliquin under daily irradiance of $13.5 \text{ MJ m}^{-2} \text{ d}^{-1}$ (Based on Warren Wilson 1969)

Temperature

Within a moderate temperature range readily tolerated by vascular plants ($10\text{--}35^\circ\text{C}$) processes sustaining carbon gain show broad temperature optima. By contrast, developmental changes are rather more sensitive to temperature, and provided a plant's combined responses to environmental conditions do not exceed physiologically elastic limits (i.e. adjustments remain fully reversible). Temperature effects on RGR are generally attributable to rate of canopy expansion rather than rate of carbon assimilation. In the early days of growth analysis, Blackman *et al.* (1955) inferred from a multi-factor analysis of growth response to environmental conditions that NAR was relatively insensitive to temperature, but whole-plant growth was obviously affected, so that extent (LAR) rather than performance per unit surface area (NAR) was responsible. Such inferences were subsequently validated. Using day/night temperature as a driving variable, Potter and Jones (1977) provided a detailed analysis of response in key growth

Table 2 relative rate of whole plant growth ($\text{RGR}_w \text{ d}^{-1}$) and relative rate of canopy expansion ($\text{RGR}_A \text{ d}^{-1}$) (obtained via functional growth analysis) are both sensitive to day/night temperature regime with a broad optimum around $32/21^\circ\text{C}$. RGR_w and RGR_A were higher in C_4 than in C_3 species and especially under warm conditions.

Species	Phs mode	21/10°C		32/21°C		38/27°C	
		RGR _w	RGR _A	RGR _w	RGR _A	RGR _w	RGR _A
Cotton	C ₃	0.086	0.073	0.206	0.197	0.188	0.172
Soybean	C ₃	0.108	0.124	0.202	0.199	0.165	0.168
Cocklebur	C ₃	0.165	0.151	0.269	0.263	0.204	0.176
Maize	C ₄	0.096	0.133	0.255	0.354	0.178	0.189
Johnson grass	C ₄	0.156	0.139	0.391	0.370	0.359	0.324
Pigweed	C ₄	0.262	0.239	0.482	0.436	0.393	0.328

(Based on Potter and Jones 1977)

Cotton, *Gossypium hirsutum* L.; soybean, *Glycine max* [L.] Merr.; cocklebur, *Xanthium pensylvanicum* Waltr.; maize, *Zea mays* L.; Johnson grass, *Sorghum halepense* [L.] Pers.; pigweed, *Amaranthus retroflexus* L.

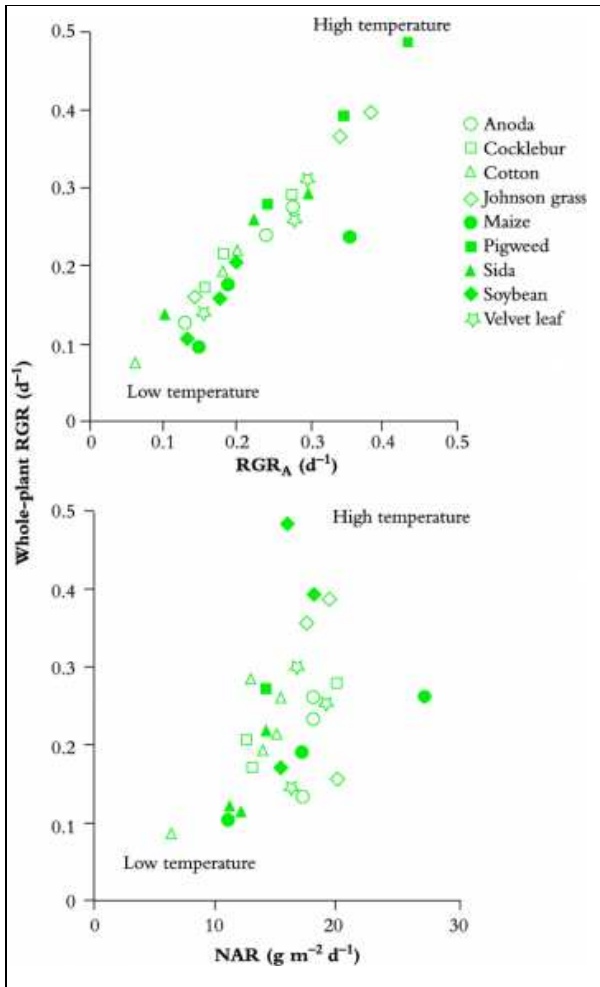


Figure 5 Variation in whole-plant RGR is linked to relative rate of canopy expansion (RGR_A). Nine species (including C_3 and C_4 plants) grown under three temperature regimen (21/10 °C, 32/21 °C and 21/27 °C day/night) expressed wide variation in RGR that showed a strong correlation with RGR_A but was poorly correlated with variation in NAR. Extent rather than activity of leaves appears to be more important for RGR response to temperature. (Based on Potter and Jones 1977)

Table 3 Temperature enhances canopy growth in wheat via faster expansion of individual leaves (r) and faster appearance of successive leaves (shorter phyllochron Δt_0). Final size of individual leaves (A_x) is little affected

Temp. (°C)	Node	Final size A_x (cm ²)	RGR leaf r (d ⁻¹)	Phyllochron Δt_0 (d)
Expt 1				
6	2	205	0.095	11
	4	—	—	—
10	2	200	0.160	7.1
	4	320	—	—
18	2	195	0.290	3.5
	4	313	—	—
Expt 2				
6	3	250	0.096	13.0
	3	250	0.171	6.50
14	3	252	0.253	4.33
	3	247	0.316	3.25

(Based on Trought and Drew 1982; Trought, unpublished data)
 In Expt 2, RGR leaf (r) represents a mean value for all leaves, and phyllochron is a mean value for intervals separating leaves at nodes 2-3 and nodes 3-4.

indices for a number of species (Table 2). Data for maize, cotton, soybean, cocklebur, Johnson grass and pigweed confirmed that 32/21°C was optimum for whole-plant relative growth rate (RGR_W) as well as relative rate of canopy area increase (RGR_A). Both indices were lowest at 21/10°C. Moreover, variation in RGR_W and RGR_A was closely correlated across species and treatments (pooled data).

All populations described in Potter and Jones (1977) maintained strict exponential growth. NAR could then be derived validly and temperature effects on NAR could then be compared with temperature effects on RGR_W and RGR_A (Figure 5). With day/night temperature as a driving variable, most values for NAR fell between 10 and 20 g m⁻² d⁻¹. Correlation between NAR and RGR_W was poor (Figure 5b). By contrast, variation in both RGR_W and RGR_A was of a similar order and these two indices were closely correlated (Figure 5a).

Focusing on canopy expansion as a factor in RGR_W response to temperature, RGR_A is a composite index and refers to relative rate of canopy area increase by an entire plant. Sources of variation in RGR_A include frequency of leaf initiation and appearance, rate of lamina expansion and final size of individual leaves. Temperature effects on whole-plant RGR_A can thus be resolved into component processes which correspond to parameters in Equation

$$A(t) = A_x \left(1 + d e^{r(t-t_0)} (1-d) \right) - 1/d$$

namely A_x , r , t_0 and frequency of leaf appearance (phyllochron, derived by subtraction of t_0 for leaves on successive nodes). An example of temperature effects on those component processes is outlined in Table 3. Wheat seedlings were raised at air temperatures of 6, 10 and 18°C and growth in area by successive leaves studied in detail. Recognizing that leaf growth dynamics and final size vary with node, comparisons between these treatments are restricted to equivalent nodes. A_x from node 4 at 6°C is not recorded because plants grew so slowly that leaf 4 had still not emerged by the time this growth experiment was terminated. Leaves at node 2 did, however, attain full size but differed little between temperature treatments, while leaves from node 4 at 10°C and 18°C were also comparable. Unlike the positive effects of daily irradiance on final leaf size, temperature effects on A_x were lacking in these wheat experiments. By contrast, relative rate of area increase (r) was strongly affected by temperature; and because A_x remained unchanged, duration of leaf growth must have been shortened. Similarly, appearance of new leaves was also accelerated under warm conditions; phyllochron decreased from 11 d at 6°C to only 3.5 d at 18°C.

Generalizing from data in Table 3, positive effects of temperature on r and Dt_0 with little contribution from A_x will account for temperature effects on relative rate of canopy expansion by whole plants (RGR_A).

Carbon dioxide

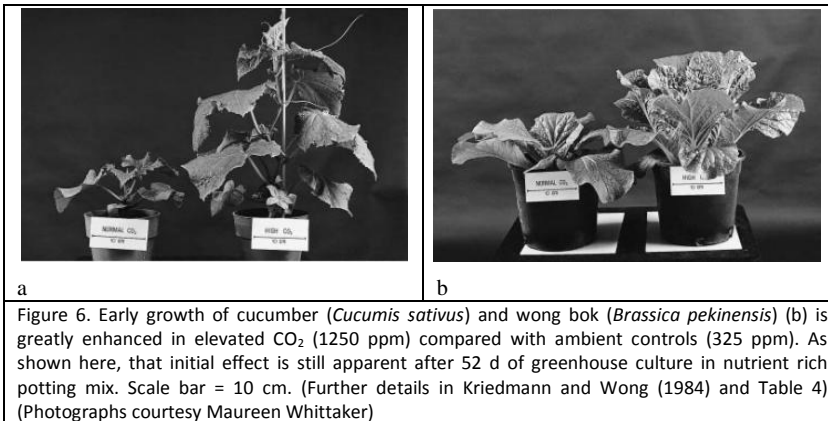


Figure 6. Early growth of cucumber (*Cucumis sativus*) and wong bok (*Brassica pekinensis*) (b) is greatly enhanced in elevated CO₂ (1250 ppm) compared with ambient controls (325 ppm). As shown here, that initial effect is still apparent after 52 d of greenhouse culture in nutrient rich potting mix. Scale bar = 10 cm. (Further details in Kriedmann and Wong (1984) and Table 4) (Photographs courtesy Maureen Whittaker)

Growth responses to elevated CO₂ can be spectacular, especially during early exponential growth (Figure 6a, b) and derive largely from direct effects of increased CO₂ partial pressure on photosynthesis. C₃ plants will be most affected, and especially at high temperature where photorespiratory loss of carbon has the greatest impact on biomass accumulation.

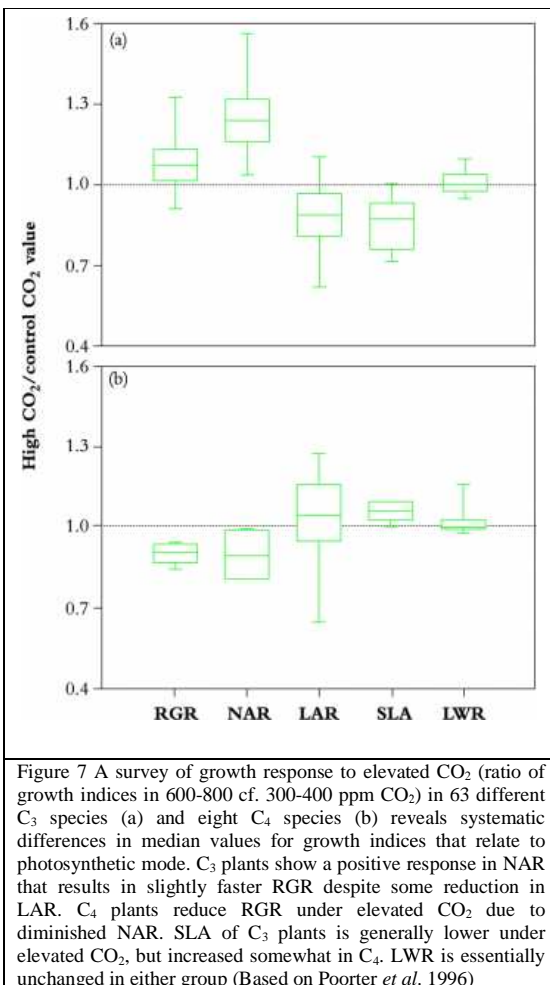


Figure 7 A survey of growth response to elevated CO₂ (ratio of growth indices in 600-800 cf. 300-400 ppm CO₂) in 63 different C₃ species (a) and eight C₄ species (b) reveals systematic differences in median values for growth indices that relate to photosynthetic mode. C₃ plants show a positive response in NAR that results in slightly faster RGR despite some reduction in LAR. C₄ plants reduce RGR under elevated CO₂ due to diminished NAR. SLA of C₃ plants is generally lower under elevated CO₂, but increased somewhat in C₄. LWR is essentially unchanged in either group (Based on Poorter *et al.* 1996)

Global atmospheric CO₂ partial pressure is expected to reach 60–70 Pa (c. 600–700 ppm) by about 2050 so that growth response to a CO₂ doubling compared with 1990s levels has received wide attention (e.g. Cure and Acock 1986; Poorter 1993). Instantaneous rates of CO₂ assimilation by C₃ leaves usually increase two- to three-fold but short-term response is rarely translated into biomass gain by whole plants where growth and reproductive development can be limited by low nutrients, low light, low temperature, physical restriction on root growth (especially pot experiments) or strength of sinks for photoassimilate. Given such constraints, photosynthetic acclimation commonly ensues. Rates of CO₂ assimilation (leaf area basis) by CO₂-enriched plants, grown and measured under high CO₂, will match rates measured on control plants at normal ambient levels.

Acclimation takes only days to set in, and because plant growth analysis commonly extends over a few weeks, CO₂-driven responses in growth indices tend to be more conservative compared with instantaneous responses during leaf gas exchange. Moreover, C₄ plants will be less affected than C₃ plants so that broad surveys need to distinguish between photosynthetic mode. For example, in Figure 7, average NAR for 63 different cases of C₃ plants increased by 25–30% under 600–800 ppm CO₂ compared with corresponding values under 300–400 ppm CO₂. However, NAR increase was not matched by a commensurate response in RGR, and decreased LAR appears responsible. CO₂-enriched plants were less leafy than controls (i.e. lower LAR), but not because less dry matter was allocated to foliage (LWR was on average unaltered). Rather, specific leaf area (SLA in Figure 7) decreased under high CO₂ so that a given mass of foliage was presenting a smaller assimilatory surface for light interception and gas exchange. Accumulation of non-structural carbohydrate (mainly starch;

Wong 1990) is commonly responsible for lower SLA in these cases, and in addition generally correlates with down-regulation of leaf photosynthesis.

By contrast, in C₄ plants LWR was little affected by elevated CO₂, but in this case SLA did show slight increase with some positive response in LAR. However, photosynthetic acclimation may have been more telling because NAR eased and RGR even diminished somewhat under elevated CO₂.

Global change, with attendant increase in atmospheric CO₂ over coming decades, thus carries implications for growth and development in present-day genotypes and especially the comparative abundance of C₃ cf. C₄ plants, but elevated CO₂ also has immediate relevance to greenhouse cropping. In production horticulture, both absolute yield and duration of cropping cycles are factors in profitability. Accordingly, CO₂ effects on rate of growth as well as onset of reproductive development and subsequent development are of interest.

Young seedlings in their early exponential growth phase are typically most responsive to elevated CO₂, so that production of leafy vegetables can be greatly enhanced. This response is widely exploited in northern hemisphere greenhouse culture (e.g. Wittwer and Robb 1964) and was put to good effect in 'Head Start' programs at Beltsville (Krizek *et al.* 1974). In commercial operations, ambient CO₂ is often raised three- to four-fold so that growth responses can be spectacular (Figure 6 a, b) but tend to be short lived (Table 4) as accelerated early growth gives way to lower RGR. During each cycle of growth and development, annual plants show a sigmoidal increase in biomass where an initial exponential phase gives way to a linear phase, eventually approaching an asymptote as reproductive structures mature. If CO₂ enrichment hastens this progression, a stage is soon reached where RGR is lower under elevated CO₂ due to accelerated ontogeny (see Gifford *et al.* 1996).

Table 4 Brassica pekinensis (wong bok) and Cucumis sativus (cucumber) are strongly affected by elevated CO₂ (ambient x 3.85) during early growth, but the response in both NAR and RGR biomass muted as plants grow. Canopy expansion (RGR_A) is especially sensitive to CO₂ enrichment but only during early growth

Species	Age (d)	Ambient CO ₂		Enriched CO ₂			
		RGR	NAR	RGR _A	RGR	NAR	RGR _A
<i>B. pekinensis</i>	0–18	0.195	7.00	0.23	0.258	30.1	0.96
	18–24	0.307	9.77	0.297	0.291	11.8	0.222
	24–40	0.155	6.64	0.130	0.147	9.30	0.120
	40–52	0.114	8.1	0.061	0.066	6.65	0.020
<i>C. sativus</i>	0–21	0.107	6.93	0.164	0.173	13.3	0.215
	21–40	0.138	8.69	0.093	0.147	12.9	0.122
	40–52	0.036	3.27	0.061	0.051	5.80	0.035

(Based on Kriedemann and Wong 1984)
RGR (whole-plant relative growth rate; d⁻¹)
NAR (net assimilation rate; g m⁻² d⁻¹)
RGR_A (relative rate of canopy expansion; d⁻¹)

For example, wong bok (*Brassica pekinensis* in Figure 6 b) is a highly productive autumn and winter vegetable that serves as 'spring greens' and is especially responsive to CO₂ during early growth. In present trials (Table 4) RGR_A at c. 330 ppm CO₂ was initially 0.230 d⁻¹ compared with 0.960 d⁻¹ at c. 1350 ppm CO₂, but by 40–52 d, RGR_A had fallen to 0.061 and 0.020 d⁻¹ for control and CO₂ enriched, respectively.

CO₂-driven response in NAR and RGR also diminished with age, and especially where these larger individuals failed to sustain higher RGR past 18 d (Table 4). Nevertheless, a response in NAR was maintained for a further two intervals so that a CO₂ effect on plant size was maintained (Figure 6 b).

Intensive greenhouse fruit crops such as tomato and cucumber are also raised under elevated CO₂, and as noted above for cucumber and leafy greens, young plants are especially responsive (and in tomato, even at low light; Hurd 1968; Hurd and Thornley 1974). Marketable yield of fruit is also increased with CO₂-enriched plants commonly flowering earlier and producing about 30% more crop over a whole season with early cycles of reproductive development typically more responsive (50% increase; Madsen 1974). Photosynthetic acclimation in CO₂-enriched plants contributes to this diminished response over time, and has led to a management practice where CO₂-enriched greenhouses gradually revert to ambient as cropping seasons progress. An alternative strategy might be to 'pulse' greenhouses with CO₂ rather than enrich continuously, thereby forestalling photosynthetic acclimation. A duty cycle of 2 d enriched followed by 1 d ambient has been suggested (Kriedemann and Wong 1984).

Table 5 Tuber yield from solanum tuberosum (pot grown) is greatly enhanced by CO₂ enrichment subsequent to tuber differentiation. NAR respond to both early and late CO₂ enrichment, but relative rate of canopy expansion (RGR_A) is little affected at either stage

	Phase 1 (0–55 d)	Phase 2 (56–110 d)
Tuber yield (g plant ⁻¹)		
Control	5.5	17.5
CO ₂ -enriched phase 1	10.9	22.0
CO ₂ -enriched phase 2	5.9	30.5
NAR (g m ⁻² d ⁻¹)		
Control	4.29	1.91
CO ₂ -enriched phase 1	5.74	1.77
CO ₂ -enriched phase 2	4.56	3.49
RGR _A (d ⁻¹ × 100)		
Control	5.79	0.77
CO ₂ -enriched phase 1	5.80	0.50
CO ₂ -enriched phase 2	5.60	0.53

(Based on Collins 1976)

Potato (*Solanum tuberosum* L.) offers an interesting variant in CO₂ effects on growth indices where differentiation of tubers provides sinks that can sustain NAR response to CO₂ (Table 5). In this experiment, over 400 potato plants were established in large containers of potting soil and held in a greenhouse (sunlight plus day length extension to 15 h) under either ambient (300–370 ppm CO₂) or enriched conditions (600–700 ppm CO₂) from emergence to bloom (early enrichment 0–55 d; phase 1) or from bloom to final harvest (late enrichment 55–110 d; phase 2). Tuber yields at 55 d were increased significantly from 5.5 g plant⁻¹ in control to 10.9 g plant⁻¹ under CO₂ enrichment. Tuber number per plant was not significantly increased. By final harvest, tuber weight had increased to 17.5 and 22.0 g plant⁻¹ for control and early enrichment respectively, but reached 30.5 g plant⁻¹ in response to late enrichment (phase 2).

Moreover, plants receiving late enrichment also sustained their NAR at 3.49 g m⁻² d⁻¹ during phase 2 compared with 1.77 in early-enriched plants and 1.91 in controls (Table 5). Presumably, photoassimilate generated by leaves during late enrichment with CO₂ was directed to tubers rather than accumulating in leaves and suppressing further assimilation. A strong ontogenetic progression was none the less evident in canopy development where relative rate of increase in leaf area per plant (RGR_A) dropped by an order of magnitude between phase 1 and phase 2, and also became insensitive to elevated CO₂.

Nutrients (nitrogen and phosphorus)

Leaf expansion is particularly sensitive to nutrient supply (especially nitrogen, phosphorus, potassium (N, P, K) and magnesium) due primarily to the needs of enlarging cells for synthesis of new materials and generation of turgor. Reiterating assumptions made earlier, an initial exponential phase in lamina expansion coincides with an especially active period of cell division, whereas the subsequent asymptotic phase is largely driven by cell enlargement. Relative rate of lamina expansion (r) at the end of that exponential phase is thus taken as indicative of cell division activity, whereas A_x reflects enlargement of that cell population. Nutrient deficiency or imbalance is first detected in leaf growth rather than leaf assimilation, and in terms of canopy development, nutrient supply impacts on phyllochron (Δt_0), relative rate of expansion (r) and final leaf size (A_x) (see Equation $A(t) = A_x \{ 1 + d e^{r(t-t_0)} (1-d) \}^{-1/d}$).

Such effects are nicely demonstrated by *Gmelina arborea* Roxb. (colloquially gmelina), a close relative of teak and favoured for tropical plantations by virtue of fast growth.

Table 6 Leaf response to N and P nutrition in *Gmelina arborea* shows that S supply had a strong effect on final size (A_x), with moderate effect on relative rate of expansion (r), whereas P supply impacted principally r and phyllochron (Δt_0)

Nutrient treatment	Leaf [nutr] ^a	Final size A_x (cm ²)	RGR (leaf) r (d ⁻¹)	Phyllochron Δt_0 (d)
High N	2.94	168	0.36	4.9
Med N	1.18	92	0.34	7.4
Low N	0.63	29	0.24	9.8
High P	0.103	113	0.23	8.5
Med P	0.052	107	0.19	11.2
Low P	0.029	12	0.12	18.9

(Based on Cromer *et al.* 1993)

^a[nutr] refers to leaf [N] or leaf [P] as mmol N or P g⁻¹ dry mass for N and P experiments respectively. A_x and r refer to node 6 in both experiments, and Δt_0 from node 6 to node 7.

Like teak, *G. arborea* carries large leaves that commonly grow to 750 cm² on high-quality sites. Leaves on greenhouse plants are smaller, but their growth dynamics are still informative. Plants grown on high, medium or low N supply (Table 6) with leaf [N] 2.94%, 1.18% and 0.63% N (dry mass) respectively show a strong decline in final size (A_x) in $A(t) = A_x \{ 1 + d e^{r(t-t_0)} (1-d) \}^{-1/d}$). By comparing high N with medium N, and noting little change in r (0.36 d⁻¹ on high N and 0.34 d⁻¹ on medium N), this reduction in A_x must be due mainly to a diminished enlargement of a given population of cells that were generated during the previous exponential phase of leaf growth. By contrast, rate of appearance of new leaves is

affected by N supply, due probably to a slower initiation, so that phyllochron (Δt_0 in Table 6) increased from 4.9 to 7.4 to 9.8 d on high, medium and low N supply respectively.

Phosphorus effects on leaf growth in *G. arborea* are amenable to a similar analysis. In this case, A_x was less sensitive to reduction from high P to medium P, whereas r was reduced from 0.23 to 0.19 d⁻¹ (and to 0.12 d⁻¹ on low P). Phyllochron was similarly sensitive, and as with N effects, Δt_0 became protracted with reduction in P supply (namely 8.5, 11.2 and 18.9 d on high, medium and low P respectively). These plants were taking twice as long to produce new leaves on low P as on low N.

In keeping with common experience on a wide range of plants, nutrient deficiency slowed canopy development in *G. arborea*, but present analysis has shown that N and P effects are qualitatively different. N deficiency is obvious as a reduction in leaf size, whereas P deficiency impacts to a relatively greater extent on leaf number due to slower appearance. Moderately N deficient plants (leaf [N] c. 1.2 mmol N g⁻¹ dry mass) produced a slower succession of smaller leaves that expanded reasonably quickly, but moderately P deficient plants (leaf [P] c. 50 μmol P g⁻¹ dry mass) produced even fewer leaves (longer phyllochron) that expanded slowly but nevertheless achieved reasonable size. Relative rate of leaf expansion (*r*) was not different on high N cf. moderate N ($r = 0.36 \pm 0.03$ and 0.34 ± 0.04 respectively) but *r* was different on high P cf. moderate P ($r = 0.228 \pm 0.005$ and 0.192 ± 0.008 respectively). In the same experiment on *G. arborea*, Cromer *et al.* (1993) show dose response curves for *r* with N saturation ≥ 1.5 mmol N g⁻¹ dry mass and P saturation ≥ 100 μmol P g⁻¹ dry mass.

N, P and K are highly mobile nutrient elements, and even on well-nourished plants individual leaves show considerable nutrient turnover as older (full size) leaves help furnish nutrient requirements of younger expanding leaves at higher nodes. For example, Hopkinson (1964) provided a detailed P budget for cucumber foliage showing a strong import (up to 0.6 mg P leaf⁻¹ d⁻¹) that coincided with rapid expansion, followed by a steady net export (up to 0.15 mg P leaf⁻¹ d⁻¹) in response to the P demands of expanding leaves at higher nodes. The time-course of post-maturation senescence will vary according to the overall balance between nutrient supply and demand which depends in turn on root-zone nutrient availability versus requirements for continuing growth and development of new organs.

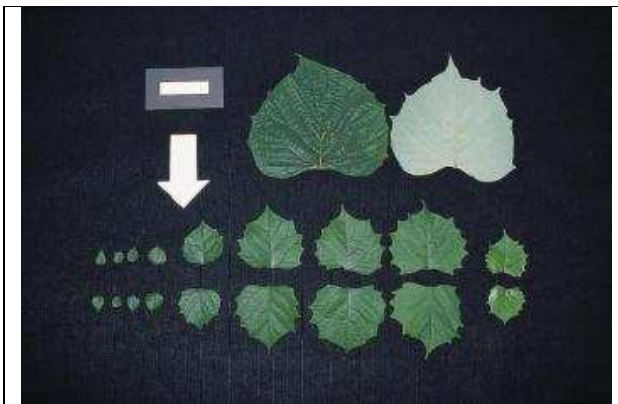


Figure 8 *Gmelina arborea* (a relative of teak) is a highly productive tropical tree with large leaves and is favoured as a plantation species. Leaf growth is especially responsive to a step-up from low to medium P supply (subsequent to leaf appearance at node 4, arrow). Relative rate of leaf expansion (*r*) increased from 0.134 to 0.228 d⁻¹, and phyllochron (Δt_0) decreased from 21.4 to 6.2 d. Upper row shows comparative size of leaves from node 6 on two high-P plants. Scale bar = 10 cm. (Further details in Cromer *et al.* 1993)(Photograph courtesy P E. Kriedemaun)

Where nutrient supply is restricted, turnover in mature leaves will accelerate (especially in fast-growing species) and senescence will hasten — a common feature under N, P or K deficiency. Conversely, when such nutrient-deficient plants are restored to full supply, leaf growth response can be dramatic (Figure 8) with sharp reduction in phyllochron (from 21.4 to 6.2 d in this example) and major increase in A_x (from 65 to 181 cm² at node 9; see Cromer *et al.* 1993).

Growth responses to nutrient supply are usually unmistakable, even spectacular (Figure 8) and commonly referenced to nutrient element concentration (e.g. [N] or [P]) on a dry mass basis. However, given the highly dynamic nature of tissue N and P, especially when growth-limiting supply enhances recycling from older organs to new growing points, how meaningful are whole-plant or even leaf values for [N] or [P] as driving variables in growth analysis? In effect, [N] and [P] will vary in both space and time according to patterns of plant growth and development, which are themselves influenced by nutrient supply.

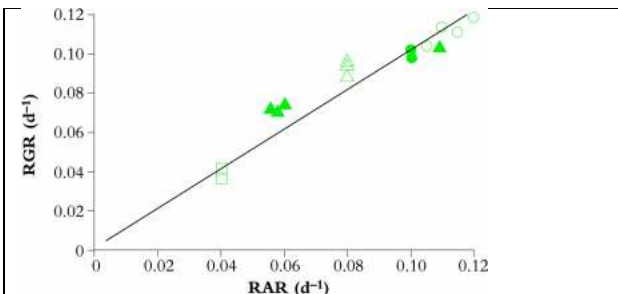


Figure 9 RGR of young seedlings (*Eucalyptus grandis*) in aeroponic culture (see Ingestad and Lund 1986 for details on technique) can be set by the relative addition rate of a single limiting nutrient (N in this experiment, with all other nutrient elements non-limiting). Clusters of symbols refer to five different RARs, namely 0.04, 0.06, 0.08, 0.10 and 0.12 d⁻¹ (with some minor variation) (Based on Cromer and Jarvis 1990)

Analysis of nutrient-dependent changes in growth indices therefore require test plants where nutrient element concentration can be 'set' in space, and also remain stable in time. These prerequisites can be met by aeroponic culture in a constant environment (see Ingestad and Lund 1986). Seedlings are held in aeroponic spray chambers where a small volume of nutrient solution is recirculated continuously, and further nutrients are introduced at a predetermined relative addition rate (RAR). In effect, a steady exponential growth is set by the RAR of a key nutrient (N or P in present

examples, but K is equally amenable) while all other essential nutrients are kept non-limiting. RAR thus represents

a driving variable for RGR which in turn shows an initially linear response to RAR (Figure 9) eventually reaching a point of saturation (not shown here).

Within a plant's dynamic range of growth response to nutrient supply, RGR and RAR are linearly related so that plants grown this way are well suited to growth analysis. Moreover, whole-plant concentrations of critical nutrients are 'set' by RAR such that higher RAR produces higher whole-plant nutrient concentration and remain reasonably stable over time. Cromer and Jarvis (1990) demonstrated this for N in *Eucalyptus grandis* and Kirschbaum (1991) for P.

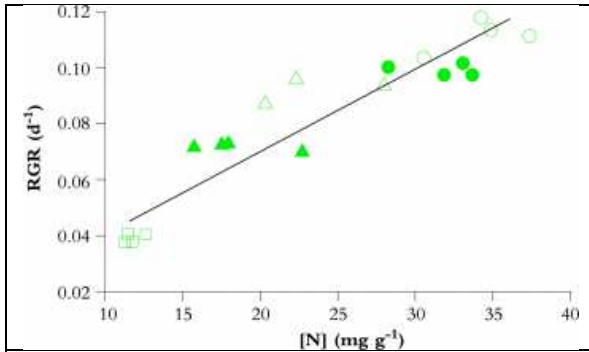


Figure 10 Under stable environmental conditions RGR of young seedlings (*Eucalyptus grandis*) growing in aeroponic culture can be set by the relative addition rate (RAR) of a single limiting nutrient (N in this experiment). If exponential growth is maintained, plant-N concentration [N] will be proportional to RAR, and RGR is then linearly related to [N]. (Based on Cromer and Jarvis 1990)

Using this Ingestad technique, growth and photosynthetic responses to plant-nutrient concentration are not complicated by interactions between ontogeny and nutrient recycling discussed earlier. For example, RGR response to plant [N] (Figure 10) can now be resolved into NAR and LAR contributions. Taking data from Cromer and Jarvis (1990) for comparisons (cf. Figure 9) their highest RAR_N, 0.12 d⁻¹, resulted in an RGR of 0.111 d⁻¹, while their lowest RAR_N, 0.04 d⁻¹, generated an RGR of only 0.039 d⁻¹. Corresponding plant [N] values were 34.1 and 11.7 g N kg⁻¹ dry mass, and resultant values for NAR were 5.55 and 4.45 g m⁻² d⁻¹ respectively. Higher [N] thus increased NAR by a factor of 1.247. Leaf weight ratio (LWR) increase was somewhat larger (factor of 1.463) and was accompanied by increased SLA (factor of 1.561).

Combining outcomes from Cromer and Jarvis (1990) with those from P experiments by Kirschbaum *et al.* (1992), some key differences between N and P in their effects on growth indices in seedlings of *E. grandis* were apparent. Cromer and Jarvis (1990) concluded, *inter alia*, that '...effects of N on allocation of dry matter to leaves and the way in which dry matter is distributed to intercept light, have a larger influence on seedling growth rate than do effects of N on net rate of carbon gain per unit leaf area'. By contrast, when considering P-dependent effects on RGR, Kirschbaum *et al.* (1992) conclude that '...Carbon fixation rate per unit of plant dry weight increased about 5-fold with increasing nutrient addition rate over the range of addition rates used. That increase was due to a doubling in specific leaf area and a doubling in assimilation rate per unit leaf area, while leaf weight as a fraction of total plant weight increased by about 20%.' Unlike N, effects of P on RGR were due more to changes in leaf physiology than to changes in dry matter distribution.

Light x nutrients

Light and nutrients are not only prerequisites for growth, but show a positive interaction in their effect on growth indices. Plant biomass formed per unit plant nutrient (plant-nutrient productivity) increases with irradiance. Birch seedlings grown in aeroponic units under 24 h illumination and constant environment at Uppsala (Figure 11a) and *Eucalyptus grandis* seedlings in Ingestad units under natural light (Figure 11b) provide examples of light effects on N and P productivity. In both cases, nutrient productivity has been calculated in terms of whole-plant biomass formed per day per unit plant N or plant P.

Recall from Equation 6.6 that $NAR = (1/A) (dw/dt) =$ productivity per unit area. In that case, carbon assimilation (biomass gain) was referenced to leaf area per plant. By analogy, nutrient productivity can be referenced to N or P content per plant, so that nitrogen productivity (designated NAR_N) would be

$$NAR_N = \frac{1}{N} \frac{dW}{dt} = \frac{1}{W} \frac{dW}{dt} \times \frac{W}{N} = \frac{RGR}{[N]}$$

Similarly, phosphorus productivity (NAR_P) would be

$$NAR_P = \frac{1}{P} \frac{dW}{dt} = \frac{1}{W} \frac{dW}{dt} \times \frac{W}{P} = \frac{RGR}{[P]}$$

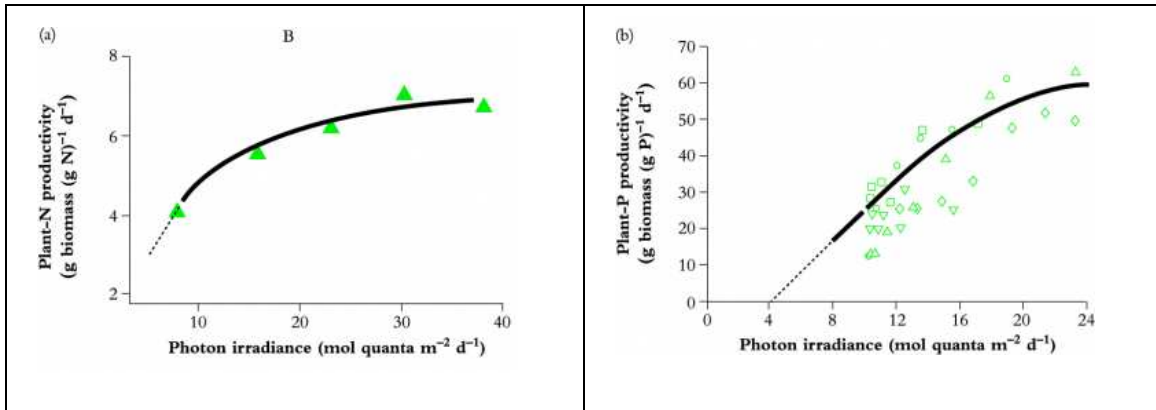


Figure 11 Plant-nutrient productivity (biomass formed per unit plant nutrient per unit time) can be inferred from analysis of plants grown in aeroponic culture, and varies with daily irradiance. In (a), plant-N productivity of birch seedlings (*Betula pendula*) grown under continuous illumination in cabinets was saturated around 30 MJ m⁻² d⁻¹. In (b), plant-P productivity of *Eucalyptus grandis* seedlings in naturally illuminated phytotron cabinets remained unsaturated up to 24 MJ m⁻² d⁻¹ (a) Based on Ingestad and McDonald 1989, (b) based on Kirschbaum 1991)

Both indices are integrated over successive harvests as with NAR_A, and the same caveats apply, namely both whole-plant biomass and nutrient element content must be increasing exponentially so that a linear relationship exists between whole-plant biomass (*W*) and plant content of N or P. Leaf-N productivity and leaf-P productivity (i.e. whole-plant biomass increase per unit leaf N or leaf P per unit time) can be derived in the same way.

Plant-N productivity from birch seedlings increases with photon irradiance and approaches an asymptote around 30 mol quanta m⁻² d⁻¹ (Figure 11a). Plant-P productivity from *E. grandis* seedlings (Figure 11b) can be described by a linear function to c. 24 mol quanta m⁻² d⁻¹ and returns numeric values an order of magnitude higher, reflecting the contrasting requirements of these two nutrient elements. Corresponding estimates of NAR_N and NAR_P on a leaf basis can be used as parameters in process-based models of plant growth where canopy assimilation (and hence biomass gain) is simulated from data on canopy light climate and nutrient concentration in leaves (see Sands 1996).

CO₂ x nutrients

CO₂ is a further prerequisite for growth, and also shows a positive interaction with nutrient supply on plant growth indices. Initially strong responses that diminished over time were attributed to a shift in allocation of photoassimilate under elevated CO₂ which resulted in reduced LAR, due in part to decreased SLA plus increased root mass relative to shoot mass in some cases. Photosynthetic acclimation to elevated CO₂ was an additional factor restricting NAR (hence lower RGR), especially on low-nutrient supply. A positive interaction between CO₂ and nutrient supply on NAR would be expected and if nutrient input drives leaf expansion to the extent demonstrated earlier, then the combined effects of LAR × NAR on RGR will be compounded.



Figure 12 Growth of *Eucalyptus camalduleensis* (cultured 90 d in unshaded greenhouses) shows a positive and interactive response to factorial combination of N supply and CO₂ (1.2 or 6.0 mM nitrate with 330 or 660 ppm CO₂). Treatments left to right are: low N + low CO₂, high N + low CO₂, low N + high CO₂ and high N + high CO₂. Scale bar = 50 mm. (Further details in Wong et al. 1992) (Photograph courtesy R E. Kriedemann)

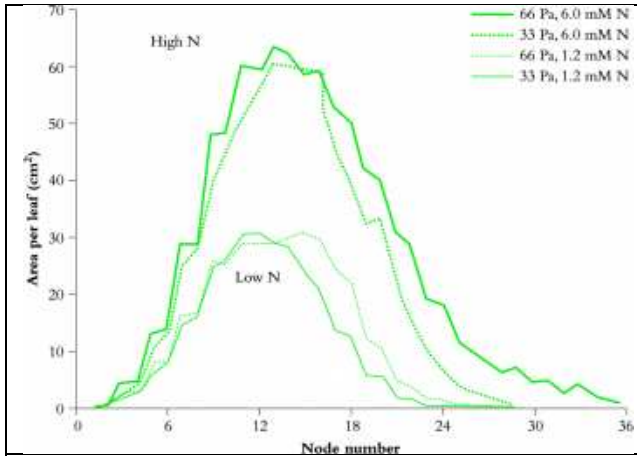


Figure 13 Overall growth of *Eucalyptus camaldulensis* showed a strong positive response to CO₂ × N (see Figure 6.16). However, mean area per leaf at each node depended mainly on N supply, showing no consistent interaction with CO₂. In contrast, the number of nodes was increased by CO₂, so that plants were taller and carried more leaves. N and CO₂ were supplied in a 2 × 2 factorial combination of 1.2 or 6.0 mM nitrate with 330 or 660 ppm CO₂ for 90 d in unshaded greenhouses (Based on Wong et al. 1992)

where CO₂-dependent increase in RGR (DRGR) was clearly influenced by N supply. All three *Symphyomyrtus* species returned a greater DRGR on high N. By contrast, the *Monocalyptus* species *E. pauciflora* showed no such CO₂ × N interaction.

Given the scale of CO₂ × N effects on canopy growth (Figure 12, and Wong et al. 1992), *E. camaldulensis* was taken for more detailed analysis at final harvest (Figure 13). CO₂-enriched plants on high N were clearly tallest and carried the largest canopies (Figure 12) but maximum area per leaf (around node 12 in Figure 13) was driven by N rather than CO₂. Nutrient impact on leaf expansion is well known, and present effects are consistent with those general responses. Accordingly, CO₂ × N interaction on canopy area of *E. camaldulensis* can be attributed to stem extension and generation of leaf number (CO₂ effect at high N), as well as greater size per leaf (nutrient effect and independent of CO₂).

Leaf function is also reflected in leaf-N productivity (whole-plant dry mass formed per unit leaf N per day; Table 7). Species differences are again evident where *E. camaldulensis* and *E. cypellocarpa* were decidedly higher while *E. pulverulenta* and *E. pauciflora* were somewhat lower. In addition, elevated CO₂ increased leaf-N productivity for both *E. camaldulensis* and *E. cypellocarpa* on either high N or low N, whereas the other two species, *E. pulverulenta* and *E. pauciflora*, varied in scale and direction. Indeed, high N may have proved supraoptimal for those two species, and especially in combination with high CO₂.

Table 7 Leaf N productivity (leaf N use efficiency for whole plant growth) in eucalypt seedling varies as a function of CO₂ and N supply, but with contrasts between species that relate to source habitat

CO ₂ (ppm)	N supply (mM)	Leaf-N productivity (g dm (mol N) ⁻¹ d ⁻¹)			
		Sp. 1	Sp. 2	Sp. 3	Sp. 4
330	1.2	102.9	100.7	63.3	52.9
330	6.0	85.8	94.2	52.6	88.1
660	1.2	162.1	127.7	85.4	83.8
660	6.0	112.5	136.6	38.8	78.3

(Based on Wong et al. 1992)
 Species 1, *Eucalyptus camaldulensis*; species 2, *E. cypellocarpa*; species 3, *E. pulverulenta*; species 4, *E. pauciflora*.

Leaf N is ultimately responsible for carbon gain, so that NAR and leaf-N productivity are functionally related. In those species adapted to fast capture of nutrient-rich sites such as *E. camaldulensis* and *E. cypellocarpa* a capacity for high NAR based upon efficient use of leaf N (i.e. high leaf-N productivity) would confer a selective advantage. By contrast, *E. pulverulenta* and *E. pauciflora* were collected from resource-poor sites where fast growth would have been selectively neutral.

Using CO₂ and N supply as driving variables, Wong et al. (1992) tested these ideas on seedlings of four species of eucalyptus which represented ecologically distinctive groups, namely *Eucalyptus camaldulensis* and *E. cypellocarpa* (both fast growing, widely distributed and reaching immense size) versus *E. pulverulenta* and *E. pauciflora* (more limited distribution, smaller final size and restricted to poor sites). In addition, two subgenera were represented: *E. camaldulensis*, *E. cypellocarpa* and *E. pulverulenta* belong to the subgenus *Symphyomyrtus*, whereas *E. pauciflora* belongs to *Monocalyptus*. Systematic differences between subgenera in physiological attributes have been noted (Noble 1989). According to that scheme, *E. pauciflora* would show more muted response to CO₂ × nutrient inputs compared with the other three species.

In Wong et al. (1992) early exponential growth showed a strong response to CO₂ × N treatments

Water

Growth is a turgor-dependent process, and later phases of leaf expansion that depend principally upon cell enlargement are especially sensitive to water stress. When plants encounter water stress, leaf area increase is either diminished or even ceases well ahead of any clear reduction in leaf gas exchange. NAR is thus less sensitive to water stress than RGR_A, a distinction reported as early as 1943 for greenhouse tobacco plants at the Waite Institute. In a posthumous paper compiled by J.G. Wood, Petrie and Arthur (1943) subjected tobacco to four watering treatments, namely high-water range, low-water range, early temporary drought and late temporary drought. Growth indices were derived from nine sequential harvests and plant biomass analyzed for total N, protein N, soluble sugars and crude fibre. NAR was expressed in terms of area, mass and protein content of leaves.

Total plant biomass at final harvest was greatly reduced by the low-water treatment due largely to early reductions in leaf expansion. NAR (area basis) was not affected to the same extent as final biomass but NAR ('protein' basis) was substantially reduced because leaf 'protein' was increased by water stress.

Especially significant, and perhaps paradoxically, J.G. Wood reported that 'Both early and temporary drought cause an initial depression in growth rate due to a depression in net assimilation rate; this is followed by an increase in growth rate greater than that of the high-water plants. This increase is due to the greater protein content of the plants subjected to temporary drought.' A single cycle of early drought and subsequent recovery resulted in whole-plant RGR that was still comparable to non-stressed controls. Since NAR (area basis) was relatively insensitive, significant reduction in final biomass must have been due to an initial reduction in leaf growth.

Early temporary drought (applied from day 64 to day 81 in a growing season of 175 d) enhanced growth of both shoots and roots subsequent to stress relief (rewatering). Total leaf area at 118 days was 7000 cm² following early drought, compared with 5300 cm² in unstressed controls, so that final size per leaf on upper nodes must have been considerably greater. A build up of 'protein' during drought was thought to have boosted expansion of later-formed leaves subsequent to rewatering, but in retrospect, accumulation of osmotically active materials during drought stress was almost certainly an added factor in this compensatory growth. For example, some sunflower cultivars respond to drought stress and recovery cycles by generating individual leaves that are as much as 60% larger than leaves on corresponding nodes of unstressed controls (Rawson and Turner 1982). Leaf-growth dynamics that underlie such a remarkable response are discussed below and are based on some earlier studies of Takami *et al.* (1981).

Table 8 moisture stress in pot grown *Helianthus annuus* slowed emergence of new leaves and reduced their final size but with little effect on RGR of individual leaves (*r*). This outcome implies that later stages of leaf expansion (where cell enlargement rather than cell division predominates) are especially sensitive to water supply. Similarly, rewatering has little effect on *r*, but took effect by node 23 where Δt_0 is reduced and final size (A_x) is increased substantially compared with well-watered controls

Treatment	Node	Final size A_x (cm ²)	RGR (leaf) <i>r</i> (d ⁻¹)	Phyllochron Δt_0 (d)
Watered	5	186	0.26	—
Stressed	5	154	0.28	—
Watered	13	392	0.26	1.4
Stressed	13	84	0.24	1.2
Watered	17	314	0.22	1.4
Post-stress	17	253	0.20	3.2
Watered	23	198	0.18	1.1
Post-stress	23	228	0.19	0.8

(Based on Takami *et al.* 1981)

Takami *et al.* (1981) grew sunflowers in a greenhouse under natural light in Canberra (March–May 1980). Seedlings were initially well watered to ensure good establishment (first 15 d). After thinning to two plants per pot, irrigation was then withheld from some pots, and unstressed controls were maintained near field capacity. Drought stress developed slowly (as intended) and drought-stressed plants recovered fully within 4–6 d of irrigation. Just prior to rewatering, pre-dawn leaf turgor was actually higher in stressed plants (0.63 MPa) compared with controls (0.39) notwithstanding a rather lower bulk leaf water potential ($\Psi_{\text{leaf}} = -0.47$ and -0.16 MPa in stressed and control respectively).

Leaf growth dynamics (Table 6.8) are based on comparisons between mean data for control and stress-recovered plants, and apply to corresponding nodes, namely 5, 13,

17 and 23. Final leaf size varies with node number in sunflower, hence the need for strict correspondence. Leaves at node 5 (Table 8) encountered an intensifying stress soon after appearance. Stressed plants maintained similar *r*,

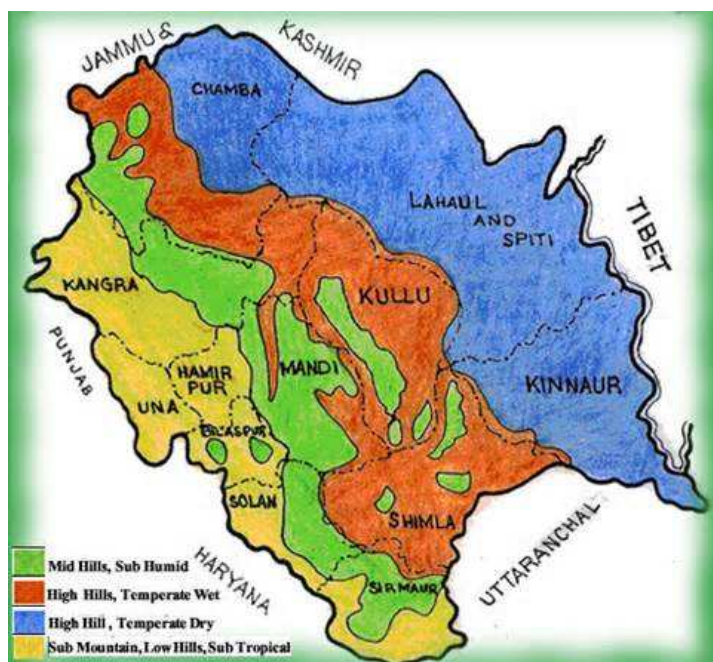
and failed to reach the same final size (A_x) as well-watered controls. Taking r as indicative of cell division during the exponential phase of lamina expansion with subsequent growth driven mainly by enlargement, drought stress has restricted cell enlargement rather than cell division.

Leaves at node 13 on droughted plants (prior to stress relief on day 36) were similar in RGR ($r = 0.24 \text{ d}^{-1}$ cf. 0.26 d^{-1} in well-watered controls) but greatly restricted in final size (84 cm^2 cf. 392 cm^2 in controls), again emphasising the sensitivity of cell enlargement to moisture stress.

Phyllochron (Δt_o in Equation 6.14) was little affected up to node 13 (Table 8) but after-effects of previous stress became apparent on rate of leaf appearance from node 14 to node 17, resulting in Δt_o increasing from 1.4 to 3.2 d. Subsequent leaf appearance (node 17 to node 23) was even accelerated in stress-recovered plants, resulting in a $\Delta t_o = 0.8 \text{ d}$ cf. 1.1 d in non-stressed controls. r at node 23 was unchanged by stress-recovery treatments but final size was substantially greater (228 cm^2) in stress-recovered compared with non-stressed controls (198 cm^2). Such compensatory growth by individual leaves following stress relief would draw on N-based resources that accumulate during drought, while turgor-driven expansion to a greater final size could partly arise from drought-induced osmotic adjustment.

Agroclimatic zones of Himachal Pradesh and India

The important rational planning for effective land use to promote efficient land use is well recognized. The ever increasing need for food to support growing population @ 2.1% in the country demand a systematic appraisal of our soil and climatic resources to recast effective land use plan. Since the soils and climatic conditions of a region largely determine the cropping pattern and crop yields. Reliable information on agro ecological regions homogeneity in soil site conditions is the basic to maximize agricultural production on sustainable basis. This kind of systematic approach may help the country in planning and optimizing land use and preserving soils, environment. India exhibits a variety of land scopes and climatic conditions those are reflected in the evolution of different soils and vegetation. These also exists a significant relationship among the soils, land form climate and vegetation. The object of present study is to delineate such regions as uniform as possible introspect of physiographic, climate, length of growing period (LPG) and soils for macro level and land use planning and effective transfer of agro - technology.



Agro Climatic Zones: - Agro climatic zone is a land unit in terms of major climate and growing period which is climatically suitable for a certain image of crops and cultivars (FAO 1983). An ecological region is characterized by district ecological responses to macro - climatic as expressed in vegetation and reflected fauna and aquatic systems. Therefore an agro-ecological region is the land unit on the earth surface covered out of agro - climatic region, which it is super imposed on land form and the kinds of soils and soil conditions those act as modifiers of climate and LPG (Length of growing period). With in a broad agro climatic region local conditions may result in several agro - ecosystems, each with it's own environmental conditions. However, similar agro ecosystems may develop on comparable soil, and landscape positions. Thus a small variation in climate may not result in different ecosystems, but a pronounced difference is seen when expressed in

vegetation and reflected in soils.

India has been divided into 24 agro - climatic zone by Krishnan and Mukhtar Singh, in 1972 by using "Thornthwait indices". The planning commission, as a result of mid. term appraisal of planning targets of VII plan (1985 - 90) divided the country into 15 broad agro - climatic zones based on physiographic and climate. The emphasis was given on the development of resources and their optimum utilization in a suitable manner with in the frame work of resource constraints and potentials of each region. (Khanna 1989).

Agro Climatic Region of Himachal Pradesh: Western Himalayas Region

NARP Zone	Districts	Suitable Crops
HP-1 Sub-Montane and Low Hills Sub-Tropical Zone	Una, Bilaspur, Hamirpur districts and parts of Sirmour, Kangra, Solan and Chamba districts.	Rice, Wheat, Sugarcane, Citrus, Mango, Litchi, Guava, deciduous forest, dry deciduous shrubs, Vegetables, oilseeds, Barley.
HP-2 Mid Hills Sub-Humid Zone	Palampur and Kangra Tehils of Kangra district, Rampur Tehsil of Shimla district and parts of Mandi, Solan, Kulu, Chamba, Bilaspur and Sirmur district.	Rice, Wheat, Arhar, Sesamum, Temperate fruits, Citrus, Vegetables, lower west Himalayan temperate forest and Himalayan chirpine forest.
HP-3 High Hills Temperate Wet Zone	North - western Himalayan region lying in the state	Maize, Rice, Oilseeds, Pulses, Rajmash, Soybean, Barley, Bee keeping, Apple, Pear, Plum, Peach, Apricot, chestnut, Vegetables.
HP-4 High Hills Temperate Dry Zone	Kinnaur, Lahaul and Spiti and part of Chamba district.	Barley, Maize, Pulses, Potatoes, Minor millets, Kutheris, Hopes, Kumin, saffron, Apples, Nuts, Dry fruits, Chilgoza, Neoza pine, Yak, Jersey cow, Cabbage seed, Sugerbeet, Chicory, Agro-forestry Alnus, Ulnas, Cettis, Salix.

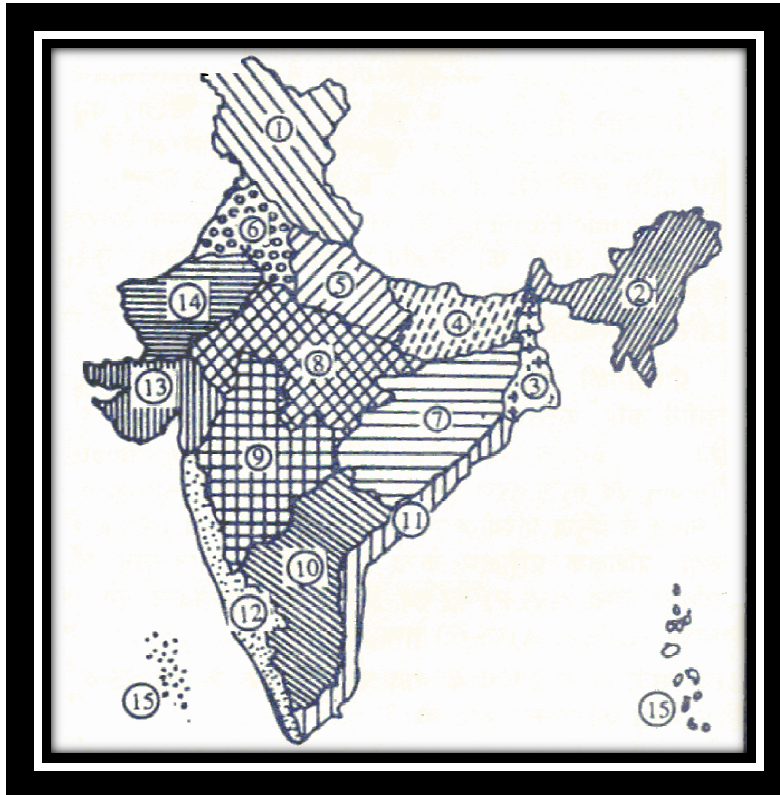
Agro Climatic Features of the Sub Regions				
Sub Region	Rainfall (in mm)	Climate	Soil	Crop
High altitude temperate	165	Humid to cold arid	Hill soils, mountain, meadow skeletal, tarai	Wheat, maize, rice, Jowar.
Hill temperate	2000	Humid	Brown Hill	Rice, maize, wheat, rapeseed
Valley temperate	400	Sub-humid	Sub-mountain, mountain skeletal, meadow	Wheat, maize, rice, sugarcane.
Sub-tropical	1030	Semi-arid to humid	Alluvial (Recent), brown hills.	Wheat, barley

AGRO-CLIMATIC ZONES OF INDIA

Based on the criteria of homogeneity in agro-characteristics such as rainfall, temperature, soil, topography, cropping and farming systems and water resources, the country has been divided into 15 agro-climatic regions.

Agro climatic zones of India :- (Planning commission 1989)

1	Western Himalayan Region	Ladakh, Kashmir, Punjab, Jammu etc. brown soils & silty loam, steep slopes.
2	Eastern Himalayan Region	Arunachal Pradesh, Sikkim and Darjeeling. Manipur etc. High rainfall and high forest covers heavy soil erosion, Floods.
3	Lower Gangatic plains Regions	West Bengal Soils mostly alluvial & are prone to floods.
4	Middle Gangatic plains Region	Bihar, Uttar Pradesh, High rainfall 39% irrigation, cropping intensity 142%
5	Upper Gangatic Plains Region	North region of U.P. (32 dists) irrigated by canal & tube wells good ground water
6	Trans Gangatic plains Region	Punjab Haryana Union territory of Delhi, Highest sown area irrigated high
7	Eastern Plateaus & Hills Region	Chota Nagpur, Garhjat hills, M.P, W. Banghelkhand plateau, Orissa, soils Shallow to medium sloppy, undulating Irrigation tank & tube wells.
8	Central Plateau & hills Region	M. Pradesh
9	Western Plateau & hills Region	Sahyadry, M.S. M.P. Rainfall 904 mm Sown area 65% forest 11% irrigation 12.4%
10	Southern Plateau & Hills Region	T. Nadu, Andhra Pradesh, Karnataka, Typically semi and zone, Dry land Farming 81% Cropping Intensity 11%
11	East coast plains & hills Region	Tamil Nadu, Andhra Pradesh Orissa, Soils, alluvial, coastal sand, Irrigation
12	West coast plains & Hills Region	Sourashtra, Maharashtra, Goa, Karnataka, T. Nadu, Variety of cropping Pattern, rainfall & soil types.
13	Gujarat plains & Hills Region	Gujarat (19 dists) Low rainfall arid zone. Irrigation 32% well and tube wells.
14	Western Dry Region	Rajasthan (9 dists) Hot. Sandy desert rainfall erratic, high evaporation. Scanty vegetation, femine draughts.
15	The Island Region	Eastern Andaman, Nikobar, Western Laksh dweep. Typical equatorial, rainfall 3000 mm (9 months) forest zone undulating.



1. WESTERN HIMALAYAN REGION:

This consists of three distinct sub-zones of Jammu and Kashmir, Himachal Pradesh and Uttar Pradesh hills. The region consists of skeletal soils of cold region, podsollic soils, mountain meadow soils and hilly brown soils. Lands of the region have steep slopes in undulating terrain. Soils are generally silty loam with altitudinal variations. They are and prone to erosion hazards and slides and slips are quite common. Rice, maize, millets, wheat and barley are the main crops. The productivity level of all crops is lower than the all India average. Ginger, saffron, many temperature flowers and vegetables are grown in this region. This zone is having highest area (45.3%) under forests. Land use planting based on the concept that land up to 30% slope is suitable for agriculture on terraces, 30-50% slopes for horticulture and silvi-pastoral programmes, and above 50% slopes for forestry is a suggested strategy for development of the region. With the full backing of storage and cold storage facilities for transport, marketing and processing, this region will be able to supply fruits and vegetables to rest of the country.

2. EASTERN HIMALAYAN REGION

Sikkim and Darjeeling hills, Arunachal Pradesh, Meghalaya, Nagaland, Manipur, Tripura, Mizoram, Assam and Jalpaiguri and coochbehar districts of West Bengal fall under this region, having high rainfall and high forest cover. Shifting cultivation (Jhum), practiced in nearly one third of the cultivated area, has caused denudation and degradation of soils, with the resultant heavy runoff, massive soil erosion and floods in the lower reaches and basins. Since this area has a high potential for agriculture including forestry and horticulture, a complete package of supply of inputs (quality seeds, saplings, fertilizers and pesticides) coupled with marketing and processing, has to be organized for each sub-zone.

3. LOWER GANGETIC PLAINS

The West Bengal – Lower Gangetic Plains region consists of four sub-regions. This one accounts for about 12% of the country's rice production. Floods and inundation of fields in Barind and Central plains often destroy standing crops. Sesamum, Jute, mustard, *rabi* maize and potato are emerging as new crops of this zone. The per capita land availability here is very low (0.095 hectares) as this zone has highest density of population (692 per km²). Marine fisheries programme are well developed but need to be more organized. Scope for forage production and livestock rearing is very high.

4. MIDDLE GANGETIC PLAINS:

This zone consists of 12 districts of eastern Uttar Pradesh and 27 districts of Bihar plains. Eastern U.P. has been further sub-divided into nine regions based on the heterogeneity in soil, land use, topography and climatic factors. This region has a geographical area of 16 m ha and a high population of 85 millions. The rainfall is high and 30% of the gross cropped area is irrigated and the cropping intensity is 142%. There is large area under salt affected (usar) lands. Rice is the principal crop but its productivity is low. Zinc deficiency in rice is wide spread. There is urgent need to improve the yield, through a technological backup along with supply of seeds of high yielding varieties and adoption of improved package of practices by the farmers. It is suggested to put unculturable wasteland under silvi-pasture and culturable land under agro-forestry. Poultry, dairying and inland riverine fishery also should receive priority.

5. UPPER GANGETIC PLAINS:

This zone consists of 32 districts of Uttar Pradesh divided into three sub-zones of Central, North- West and South – West UP. The zone has 144% cropping intensity. Irrigation is largely through canals and tube wells. A good potential for exploitation of ground water exists. Growth in agriculture has to come through increasing productivity as net sown area is already exploited. In all the Diara lands (flood prone areas) development of fruit trees is important. Milk production from cows is very low. Genetic improvement through cross breeding and increasing the area under fodder crops is important.

6. TRANS-GANGETIC PLAINS

This zone consists of Punjab and Haryana, Union Territories of Delhi and Chandigarh and Sriganganagar district of Rajasthan. It is delineated into three sub-zones, namely, foothills of Shiwalik and the Himalayas, plains (Semi arid) and arid zone bordering the Thar desert. The major characteristics of the area are: highest net sown area, highest irrigated area, least poverty level, high cropping intensity (170%) and high ground water utilization. Rice-wheat system is prevalent. There is need to evolve short duration genotypes and also to diversify of the cropping. Food processing industries should be established in areas where farmers have started taking up cultivation of vegetables and fruit crops.

7. EASTERN PLATEAU AND HILLS

The eastern Plateau and Hills region consists of the following sub-regions:

- I. Sub-region of Wainganga, Madhya Pradesh Eastern Hills and Orissa inland,
- II. Orissa Northern and M.P. Eastern Hills and plateau
- III. Chotanagpur North and Eastern Hills and plateau
- IV. Chotanagpur South and West Bengal Hills and Plateau, and
- V. Chattisgarh and South-Western Orissa Hills.

The soils of the region are shallow and medium in depth and the topography is undulating with a slope of 1 to 10%. Rainfall is nearly 1300 mm. Integrated water shed development approach to conserve soil and rainwater should be strengthened. Tank irrigation is significant for sub-zone 2 and sub-zone 5. Irrigation by tube wells is significant in sub-zone 1. In *kharif*, 82% of the area is under rice. Most soils are acidic and in some areas application of lime is necessary. Cultivation of crops like redgram, groundnut, and soybean in uplands is to be encouraged. Mustard and vegetables are to be grown in irrigated areas. The rehabilitation of degraded peripheral forests is to be taken up on a large scale. Nearly 30% of the forestland is estimated as degraded. Inland fisheries programme needs to be encouraged.

8. CENTRAL PLATEAU AND HILLS

This zone comprises of 46 districts of Madhya Pradesh, Uttar Pradesh and Rajasthan. Irrigation and intensity of cropping are low. The literacy percentage is low and the poverty ratio is high. Per capita availability of land is very high (0.446 ha). Since 75% of the area is rainfed, a watershed management programme is to be implemented. Food crops should be replaced by oil seeds.

9. WESTERN PLATEAU AND HILLS

This zone comprises of major parts of Maharashtra, parts of Madhya Pradesh and one district of Rajasthan and is divided into four sub-zones. This region forms a major part of peninsular India, with an annual average rainfall of 904 mm. Net sown area is 65% and only 12.4% area is irrigated. Sorghum and Cotton are the major crops in nearly half of the cultivated area. This zone is known for the best quality oranges, grapes and bananas. The area under fruit crops is about one lakh hectares. Farmers are adopting sprinklers and the drip methods of irrigation, particularly, for fruit and vegetable crops.

10. SOUTHERN PLATEAU AND HILLS:

This zone comprises of 35 districts of Andhra Pradesh, Karnataka and Tamil Nadu, which are typically semi-arid zones. Rainfed farming is adopted in 81% of the area and the cropping intensity is 111%. Low value cereals and minor millets

predominate in the cropping systems. The adoption of proven dryland technology in the watershed areas should aid agriculture in this area. Crop diversification has to be intensified and crops that require less moisture should be preferred. Poultry has developed quickly in many areas of the zone.

11. EAST COAST PLAINS AND HILLS:

This zone consists of six sub-zones i) Orissa coastal ii) North Coastal Andhra and Ganjam, iii) South Coastal Andhra, iv) North Coastal Tamil Nadu, v) Thanjavur and vi) South Coastal Tamil Nadu. Rice and groundnut are the important crops. Nearly 70% of the cultivated area does not have irrigation facility and, therefore, a watershed management programme can be taken up to 6.45 m ha. Tanks account for nearly 20% of the irrigated area in the zone and programmes such as desilting tanks, strengthening of bunds and structures and improvement of field channels need to be taken up through a community approach. Drainage programmes, particularly in the south coastal Andhra Pradesh (Krishna – Godavari delta) and Cauvery delta areas are a vital need, because water logging is a critical constraint affecting crop yields. Alkaline-saline soils in the region total up to 4.9 lakh hectares. Area under waste lands estimate to 25.33 lakh ha. Waste land development programmes should be given priority. The zone with over 2,000 km of coastline and many inland waterways is suitable for fisheries. Brackish water fisheries and aquaculture hold great promise in this area. Roughly 40% of the marine potential is taken advantage of in Andhra Pradesh and 46% in the Tamil Nadu Coast.

12. WEST COAST PLAINS AND GHATS:

This zone runs along the west coast, covering parts of Tamil Nadu, Kerala, Karnataka, Maharashtra and Goa with a variety of crop patterns, rainfall and soil types. This is an important zone for plantation crops and spices and fisheries. Literacy is the highest in Kerala and so is unemployment. Cropping intensity is 124%. Productivity of rice and millets is low and there is need for diversification to horticulture crops such as Mango, Banana and Coconut. Fruit marketing and processing should be systematized by developing appropriate infrastructure. The approach of homestead (group farming) system (one of the agro-forestry systems) of reclaiming and using khar lands (saline soils) or pokhali lands (acidic soils) needs to be planned and implemented. This zone is important for multi-storeyed cropping.

13. GUJARAT PLAINS AND HILLS:

This zone consists of 19 districts of Gujarat classified into seven sub-zones. The zone is arid with low rainfall in most parts and only 22.5% of the area is irrigated, largely through wells and tube wells. Only 50% of the cultivated area is under food crops resulting in food deficit. However, it is an important oilseed zone. The cropping intensity is 114% and nearly 60% of the zone is considered drought prone. The major thrust should be on rainwater harvesting, dry farming and canal and ground water management. The long coastline and river deltas should be used fully for developing marine fishing and brackish/backwater aquaculture.

14. WESTERN DRY REGION

This region comprises of nine districts of Rajasthan and is characterized by hot sandy desert, erratic rainfall, high evaporation, no perennial rivers and scanty vegetation. The ground water is deep and often brackish. Famine and drought are common features forcing people and animals to migrate to other places in search of water, food and fodder. The land-man ratio is high (1.73 ha/person). The average annual rainfall is only 395 mm with wide fluctuations from year to year. The forest area is only 1.2%. The land under pastures is also low (4.3%). The cultural waste and fallow lands are substantial, accounting for nearly 42% of the geographical area. The net irrigated area is only 6.3% of the net sown area. Cropping intensity is 105%. Pearl millet, cluster bean (guar) and moth are the lead crops in kharif and wheat and gram in rabi, but the yield levels per hectare are low. Any change in the cropping pattern is not advocated because of the fodder value of the crops. The acute shortage of fuel, fodder and forage warrants stringent efforts for development of silvipastoral systems and energy plantations to meet the scarcity and to stabilize partially the sand dunes. The Indira Gandhi Nahar Project and DDP are the two main water sources of great potential in this zone. The small area of 0.31 m ha under forests is also in a degraded condition. Increasing tree cover is important to (a) check desertification, (b) provide fodder to livestock, (c) meet the fuel needs of the population, and (d) provide timber implements.

15. ISLANDS REGION:

This zone covers the island territories of the Andaman and Nicobar and Lakshadweep, which are typically equatorial. Rainfall of 3,000 mm is spread over eight to nine months. It is largely a forest zone having large undulating areas leading to heavy loss of soil due to runoff. Nearly half of the cropped area is under coconut. This is the smallest zone with a high literacy rate and low poverty levels.

Inverse yield nitrogen law

In 1940, the protein content of wheat varied across the state of Kansas. It went from 10% in eastern Kansas to 18% in western Kansas. The less developed soil in the west with the lower rainfall produced fewer bushels per acre while the more developed soil in the east with the higher rainfall produced big yields per acre. The bison, prior to our arrival, ate the short grasses that grew in western Kansas rather than the high yield grasses growing in the eastern portion of that state.

In an experiment soybeans were grown with increasing amounts of potassium (the K in NPK on the bag of fertilizer) while holding the calcium constant. The crop was grown with three different levels of potassium. The result was that the crop with the largest amount of potassium added increased the yield by 25%. The chemical analysis, however, revealed that the nitrogen content of the smallest crop, of the intermediate crop and of the largest crop were 2.8%, 2.5% and 2.19% respectively. The nitrogen content of the smallest crop was almost 28% more than the largest crop. The phosphorus concentration for the same three crops was .25%, .18% and .14% respectively. That is about a 78% increase in the concentration of phosphorus in the smallest crop compared to the largest crop. For calcium the concentration was .75% of the dry weight in the smallest crop and .27% in the largest crop. That is a 278% increase in the concentration of calcium from the largest crop to the smallest crop. Even with the 25% increase in yield of the largest crop, the amounts of these three nutrients in the total crop was lower than the amounts of the same three nutrients in the smallest crop.

How Cattle Choose Their Food When Given a Choice

On the Poriot Farms near Golden City, Missouri a herd of over 100 beef cattle demonstrated how they choose their nutrition when given a choice. The cattle were sent out to graze on a virgin prairie field that had received no soil treatment. Growing in this field were bluegrass, white clover and some soybeans. The cattle, however, did not eat the bluegrass, white clover and soybeans. Instead they crossed this field going through an open gate into a field that had grown corn in the previous year but that had been left unused because of a shortage of labour. This field had received a soil treatment. Growing in this field were weeds, including cockleburrs, nettles, plantain, cheat, wild carrots, butterprint, wild lettuce, berry vines and many others. To obtain access to water, the cattle had to cross the field growing the bluegrass, white clover and soybeans daily but they refused to eat those crops, instead they returned to the unused cornfield to eat the weeds which they kept down to a short growth during the season.

The Change In Nutrient Content Between Hybrid Corn and Open Pollinated Corn

In 1956, O.W. Wilcox published a paper called, “Inverse Yield—Nitrogen Law of Nature”. This paper showed how increasing yields per acre of different crops resulted in a higher carbohydrate content but a smaller protein content. Thus a crop like sugar cane produces a high yield per acre with a high carbohydrate content with a small protein content. By comparison, the legumes produce a low yield per acre but with a high concentration of protein. Corn lies on the graph between the legumes and sugar cane, relatively closer to the legumes than the sugar cane. When corn was hybridized, however, corn’s position on the graph moved closer to the sugar cane and away from the legumes. The hybridization of the corn resulted in the crop increasing in yield and starch content while the protein content was decreasing. Hybrid corn is genetically altered food using only genes within the species so it not considered a Genetically Modified Organism. Yet its genetics have been altered such that you can’t save the seeds from one year’s crop to grow the same crop the next year. The seeds of a hybrid crop will not produce the same crop as the parent crop. As a result, the grower must buy seeds every year (good for the seed company) and the grower is able to increase his yield (good for the grower). Since the grower is paid on yield, this looks like a good deal for both the seed company and the grower. It may not be, however, such a good deal for the person or animal that eats hybrid corn rather than open pollinated corn.

Wilcox (1929) proposed inverse yield-nitrogen law which states that **power of growth or yielding ability of any crop plant is inversely proportional to the mean nitrogen content in the dry matter**. A crop plant with high mean percentage of nitrogen in dry matter has less dry matter production potential than a crop plant with low percentage of nitrogen.

Relation between nutrient supply and crop growth

Growth is defined as the progressive development of an organism, and there are several ways in which this development can be expressed. There have been various mathematical models to describe or define plant growth. These models can be useful in predicting the crop response to plant nutrients and other growth factors. The rate of plant growth changes with time and the maximum growth rate occurs at a point on the curve where the slope is maximum. Although the general shape of the curve is determined by the genetic constitution of each plant species and by the environment, numerous growth factors can alter the shape of the growth curve. Although the growth curves are helpful in understanding the general pattern of plant development, they indicate nothing about the factors affecting growth.

Plant growth is a function of various growth factors, which may be expressed as

$$G = f(x_1, x_2, x_3, \dots, x_n) \tag{1}$$

Where, G is some measure of plant growth and $x_1, x_2, x_3, \dots, x_n$ the various growth factors.

If all but one of the growth factors are present in adequate amounts, an increase in the quantity of this limiting factor will generally increase plant growth. This relationship was renamed the law of minimum by Liebig. This however, is not a simple linear relationship. Although linear responses occur over small portions of the yield response curve, the addition of each successive increment of a growth factor results in a progressively smaller increase in growth.

In 1909, E A Mitscherlich of Germany was among the first to quantify the relationship between plant growth response and the addition of a growth factor. He state that “ **yield can be increased by each single growth factor even when it is not present in the minimum as long as it is not present in the optimum**” and that an “**increase in yield of crop as a result of increasing a single growth factor is proportional to the decrement from the maximum yield obtainable by increasing the particular growth factor**”.

Mitscherlich's Equation

The growth equation defined in the preceding section is a generalized expression relating growth to all the factors involved. Mitscherlich developed an equation that related growth to the supply of plant nutrients. He observed that when plant were supplied with adequate amounts of all but one nutrient, their growth was proportional to the amount of this one limiting element that was supplied to the soil. Plant growth increased as more of this element was added, but the increase in growth was progressively smaller with each successful addition of the element (Fig 1).

Mitscherlich expressed this mathematically as

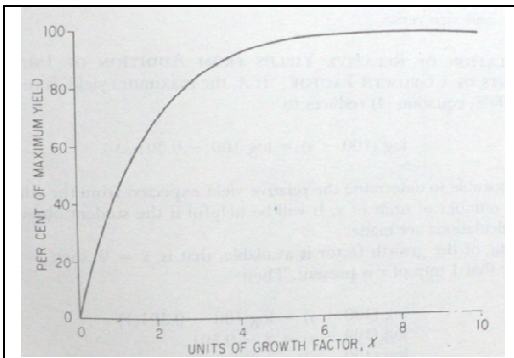


Fig 1 Percentage of maximum yield as function of increasing additions of a growth factor, x

$$dy/dx = (A-y)c, \quad (2)$$

where dy is the increase in yield resulting from an increment dx of the growth factor x, A is the maximum possible yield obtained by supplying all growth factor in optimum amounts, y is the yield obtained after any given quantity of the factor x has been applied, and c is a proportionality constant that might be considered as an efficient factor.

The Mitscherlich equation could be reduced to

$$Y = A(1 - 10^{-cx}) \quad (3)$$

None of these expressions is conveniently handle as written, but they may also be stated as the integral of Eq 2 using common logarithms:

$$\text{Log}(A-y) = \text{log } A - c(x) \quad (4)$$

The symbols used are the same as those in Eq 2.

Calculation of the value of the proportionality factor c

The constant c in Eq 4 becomes 0.301 when yields are expressed on relative basis of A=100 and x is a quantity of a growth factor. This is shown by first rewriting Eq 4 as follows:

$$\text{Log } A - \text{Log } (A-y) = cx \text{ or } \text{log } (A/(A-y)) = cx$$

When nutrient supply (x) is increased to produce 50% of the maximum yield,

$$A/(A-y) = 100/50 = 2$$

$$\text{Thus } \text{log } 2 = c(1) \text{ and } c = 0.301$$

The value of c varies with the particular growth factor. Mitscherlich found that the value of c was 0.122 for N, 0.60 for P and 0.4 for K. He claimed that it was constant for each fertilizer nutrient, independent of the crop, the soil, or other conditions. The average value for c in British experiments conducted before 1940 was 1.1 for N, 0.80 for P, and 0.80 for K. in numerous other investigations, it has been observed that c is not a constant term and that it varies rather widely for different crops grown under different conditions.

The significance of the c term is that it gives an indication of whether the maximum yield level can be achieved by a relatively low or high quantity of the specific growth factor. When the value of c is small, a large quantity is needed and vice versa.

Calculation of relative yields from addition of increasing amounts of a growth factor

If A, the maximum yield, is considered to be 100%, Eq 4 reduces to

$$\text{Log}(100-y) = \text{log } 100 - 0.301(x) \quad (5)$$

It is possible to determine the relative yield expected from the addition of a given number of units of x. if none of the growth factor is available, that is, x = 0, then y = 0; but suppose that 1 unit of x is present. Then

Table 1 Example of diminishing returns to increasing addition of factor x described by the Mitscherlich Equation		
Units of growth factor, x	Yield (%)	Increase in yield (%)
0	0	
1	50	50
2	75	25
3	87.5	12.5
4	93.75	6.25
5	96.88	3.125
6	98.44	1.562
7	99.22	0.781
8	99.61	0.390
9	99.80	0.195
10	99.90	0.098

$$\log(100 - y) = \log 100 - 0.301 (1)$$

$$\log(100 - y) = 2 - 0.301$$

$$\log(100 - y) = 1.699$$

$$100 - y = 50$$

$$y = 50$$

and the addition of 1 unit of the growth factor x results in a yield that is 50% of the maximum.

Assume, however, that 2 units of the growth factor were present.

In this instance

$$\log(100 - y) = \log 100 - 0.301 (2)$$

$$\log(100 - y) = 2 - 0.602$$

$$\log(100 - y) = 1.398$$

$$100 - y = 25$$

$$y = 75$$

The same operation may be repeated until 10 units of the growth factor have been added. The result of such a series of calculation is given in Table 1.

It is obvious that the successive increases of a growth factor result in a yield increase that 50% of that resulting from addition of the preceding unit until a point is reached at which further increases are of no consequence. Again this relationship is shown in Fig 1.

Plant growth as a function of nutrient input is logarithmic and generally follows a pattern of diminishing increase, as expressed in the Mitscherlich equation (Fig 1). The growth of annual plants does tend to reach a maximum with increasing input of nutrients under a particular set of environmental conditions and often the plants that produce the highest yield of dry matter have the lowest percentage of N in their tissues. However, it remains for posterity to determine whether a single expression can be developed that will universally predict the amount of growth that can be produced from the input of a given quantity of plant nutrients when environmental and genetic growth factors adequately described.

Bray's Nutrient Mobility Concept

A modification of the Mitscherlich concept was proposed by R Bray and co-workers at the University of Illinois. In brief, crop yields obey the percentage sufficiency law of Mitscherlich for such elements as P and K, which are relatively immobile in the soil. This concept, in turn, is based on Bray's nutrient mobility concept, which states that as **the mobility of a nutrient in the soil decreases, the amount of that nutrient needed in the soil to produce a maximum yield (the soil nutrient requirement) increases from a value determined by the magnitude of the yield and the optimum percentage composition of the crop, to a constant value.**

The magnitude of this constant is independent of the amount of crop yield, provided that the kind of plant, planting pattern and rate, and fertility pattern remain constant and that similar soil and seasonal conditions prevail. Bray further states that for a mobile element such as NO₃-N, Liebig's law of the minimum best expresses the growth of a crop. Bray has modified the Mitscherlich equation to

$$\log(A-y) = \log A - C_1b - Cx$$

where A, Y and x have the connotations already given; C₁ is a constant representing the efficiency of b for yields in which b represents the amount of an immobile but available form of nutrient, such as P or K, measurable by some suitable soil test; an C represents the efficiency factor for x, which is the added fertilizer form of the nutrient b.

Bray showed that the values for C₁ and C are specific and fairly constant over a wide area, regardless of yield and season, for each of the following crops: corn, wheat and soybeans. The factors that will alter the values, however, are wide differences in soil series, plant population and planting patterns, and distribution in the soil of the immobile nutrient under study. Hence, as management practices and fertilizer placement methods are changed to obtain higher yields, the value change and must be reexamined.

Limited Applications of Growth Expressions

Numerous equations or functions have been used to describe the relation between plant growth and nutrient input. Steenbjerg and Jakobsen of Denmark, in commenting the variability among growth response curves, point out that "the constants in formulas are not constants because the variables in the formulas are not independent variables." Factors other than nutrient interactions obviously affect the shape of yield curves. They include other environmental factors, which were discussed in the preceding sections. The change in the shape and position of yield-plant nutrient input curves with changes in environmental condition is of the greatest importance to the practical agriculturalist. Understanding the interactions between these crop growth factors is essential to identifying and crop management practices needed for profitable crop production.

The term *limiting growth factor* has been clearly illustrated by the variable nature of the response curves and surfaces previously discussed. If, for example, a crop has inadequate moisture, the application of a given amount of fertilizer will provide a lower yield than if moisture were adequate. Another example and an important one, is the application of fertilizer to a crop growing on a soil that is too acid for maximum growth, regardless of the amount of fertilizer added. If lime is not applied, acidity becomes the limiting factor that reduces the yield response to fertilizer and the farmer's return on the investment. The importance to practical farm operations of the concept of growth patterns and how it may be altered by various limiting factors cannot be overstated.

Effect of lodging in cereals; physiology of grain yield in cereals; optimization of plant population and planting geometry in relation to different resources, concept of ideal plant type and crop modeling for desired crop yield

Effect of lodging in cereals

In cereals, lodging is considered to be a serious malady for long time. Development of semidwarf varieties of crops reduced the problem to some extent, but not completely. Use of higher level of fertilizers, irrigation and sometimes reverting to older cultivars for specific needs and increase in the mechanized harvesting may lead to further losses due to lodging. Presently, development of new varieties for higher yields has reached a plateau and no further increase is achieved unless biotechnological interventions are made.

Definition and types of lodging:

Lodging is the state of permanent displacement of the stems from their upright position. It is induced by external forces like wind, rain or hail. Lodging is often not distributed uniformly throughout an affected field but may be scattered over certain sections or spots. Berry *et. al.* (2004) described the types of lodging as stem lodging and root lodging.

Lodging is the permanent displacement of the stems from their upright position. In cereals, considerable loss in yield and quality occurs due to lodging. Crop is more susceptible to lodging at the later stages of crop maturity. Losses in yields due to lodging vary from crop to crop and the loss is greatest in crops like wheat, rice, barley and millets. Losses will be greatest under high input and mechanised agriculture. All high yielding factors like variety, fertilizers, population and irrigation affect the lodging. Careful management of the factors like selection of resistant genotypes, following raised bed cultivation, proper N and K fertilizer application, irrigation at right time and quantity, pest management and disease management and growth regulator application will reduce the lodging and improve the yield and quality.

Lodging in relation to time and space:

Occurrence of lodging is dependent on season. Time of rainfall occurrence is more related to lodging than the amount of rainfall. Root lodging in winter wheat is associated with as little as 4 mm of rain. Wind speed played secondary role in lodging. Higher than the normal wind speed resulted in lodging. Sterling *et. al.* (2003) demonstrated through tunnel experiments that root lodging could occur within 5 minutes when the soil was saturated and the crop was subjected to a mean wind speed of 8 m/s.

In cereals, lodging tends to be more when crop is near harvest. Lodging may begin as early as the emergence of the ear or panicle. Winter wheat has been observed to lodge at any time from the emergence of its ear until its grains have matured (Easson *et. al.*, 1993).

Differences in occurrence of lodging between fields were due to different management practices. This may also be due to topographical variations which affect local wind speeds. Within a field, the margins frequently show lodging. Plants next to the path ways caused by tractor movement (tram lines tend to remain upright. Under moderate lodging (10-50%), most of the margin was lodged with the lodged area extending into the center of the field. In severely lodged conditions, the entire margin of the field lodged.

Lodging effects on cereal yield:

Usually yields of cereals decreased due to lodging. In rice loss was reported up to 50% in Japan. In India wheat losses were reported to be in the range of 12-66%. Similarly in barley losses were 40% (Dyson, 1984) and oats 35-40% (Pendelton, 1954). Losses due to lodging were also reported in maize, sorghum and sugar cane. Yield was reduced by reduction in the grain size and number or by reducing the amount of crop that can be recovered by the combine harvester. Greatest yield reduction occurs when lodged at anthesis or early grain filling.

Lodging effects on cereal quality

Lodging also reduced the cereal quality considerably. Bread making quality in wheat is measured in terms of Hagberg Falling Number (HFN). For good quality wheat HFN of 250 is desirable. Lodging at early grain filling or late grain filling significantly reduced the HFN, 1000 grain weight and specific weight. However the protein content increased significantly. The small grains and low specific weight indicate that lodging reduced the supply of assimilates to the grains and this increased the concentration of protein.

Shriveling of the grain and reduction in test weight is the most common feature due to lodging. Malting quality of barley was adversely affected (Pinthus, 1973). Sprouting in the heads has also been found to occur more frequently in lodged than standing crops.

Lodging in relation to stage of occurrence

Pinthus (1973) summarized the loss in yield of different cereals at different stages. Greater yield reductions (27-40%) were observed at heading than at 15-20 days after heading (17-39%). The reductions were greatest at heading stage irrespective of crops and locations. Jedel and Helm (1991) reported reductions in yield of barely cultivars when lodged at

milk stage. Extent of lodging also dependent on cultivars, where barley variety Samson recorded 19-28% while Johnston 22-40%.

Extent of lodging and yield

The degree of lodging also affected the yields. At IRRI, Setter *et. al.* (1997) subjected three different rice cultivars to artificial lodging stress. 75% lodging significantly reduced the plant height and similarly affected the yield. Plant height and yield of any of the cultivars did not differ significantly between natural growing and 35% lodging. This indicated that slight lodging at flowering did not affect the yield.

Management options to reduce lodging

Various factors affect lodging significantly. Environmental factors like temperature, rainfall (water/irrigation), wind velocity and light affect the lodging. Nitrogen application has higher significance, while potassium, seeding rate and seeding time had moderate effect on the lodging.

Genotypes

Lodging in semi dwarf wheat is normally associated with short and stiffer straw when grown at moderate nitrogen levels (Stapper and Fischer, 1990). In the Indian sub continent, varieties bred at moderate nitrogen level (120 kg/ha) tend to lodge when exposed to 180 kg N/ ha or more (Narang *et. al.*, 1994). Tripathi *et. al.* (2003) reported some of the genotypes are lodging resistant and some as susceptible despite they were semi dwarf wheat. PBW 343, UP 2338 and Seri 82 were rated as tolerant while WH 542 and HD 2329 as susceptible to lodging.

Increase in the plant height is usually attributed to lodging most of the times. However, this is not always applicable. Wheat variety Baviacora a tolerant variety despite having 103 cm plant height recorded low lodging (6%) due to low number of tillers/m² (413) with greater diameter of first (3.915 mm), second (4.216 mm) and third basal internodes. On the contrary Pastor with similar height (101 cm) is prone to lodging (55%) due to higher number of tillers / m² (482) and lesser diameter of internodes.

In a rotation, cultivar and nitrogen rates experiment Wallace *et. al.* (1999) observed some significant difference in the ability of corn hybrids when exposed to 160 km/hr of wind speed. Pioneer hybrid 3162 found to be tolerant and recorded 4% lodging or broken plants.

Depth of anchorage of the roots is important to have erect plants. Sugarcane plants having a depth of 260 mm anchorage had a very low lodging. However anchorage depth of 120 mm was prone to lodging. Sugarcane cultivar Q 152 was more resistant to lodging than Q 187 and Q 174 (Nils and Allan, 2005).

Any addition of genes for specific traits sometimes makes the genotypes susceptible to lodging (Tripathi *et. al.*, 2005). Seri 82, a lodging resistant wheat cultivar became susceptible to lodging once the Lr 19 gene (for leaf rust resistance) was incorporated.

Method of planting and tillage

Information on tillage effects on lodging behaviors of crops is scarce. More lodging of spring wheat was found on ploughed land than after slit seeding into an unplowed grass sward (Hull, 1967). Subsoiling increased lodging of barley over that obtained on a regularly prepared seed bed, whereas rolling after sowing decreased it. Lodging of corn was not affected by tillage. However yield was significantly improved under conventional tillage (Pedersen and Lauer, 2002). Tillage affected the lodging when combined with higher rates of nitrogen application in wheat.

Planting on raised beds is one of the better options to control lodging (Tripathi *et. al.*, 2005). Lodging prone wheat cultivars which are high yielding can be cultivated on raised beds to improve yields. Pastor a lodging susceptible wheat cultivar (37.1%) lodges only 0.8% under bed planting. But bed planting is not suitable to all cultivars. Bed planting also reduced the wheat plant height (Sayre and Hobbs, 1998) and improved the grain yields by significantly affecting the lodging score.

Use of improved seed planters in rice in Japan also improves the lodging index. Hill seeder is the new implement where it throws the rice seeds in a group which looks like hill transplanted rice. This gives more strength to the plants and increases the pushing resistance. Lodging index and lodging degree decreased with the hill seeding (Satoshi, 2005).

Lodging in rotations

Continuous cultivation of corn in 1993 and 1994 resulted in lesser broken plants percentage but corn-soybean rotation had higher broken plants (Wallace *et.al.*, 1999). Pioneer hybrid 3162 did not lodge under Corn—Corn or Corn –Soybean, while other hybrids Pioneer 3379, 3394 and 3417 lodged severely under corn- soybean rotation. Similar observations were made by Pedersen and Lauer, 2002.

Nitrogen

High rates of nitrogen increases lodging by making plants taller. The increase is ranged from 2.3% to 10%. Increasing nitrogen increased length of lower internodes and decreased the upper internode length. Heavy nitrogen reduced the strength of stem base and the anchorage system, stem diameter and stem wall width (Hobbs *et.al.*, 1998).

Elongation of lower internodes is entirely due to self shading. Entire application of nitrogen at planting resulted in lodging, irrespective of nitrogen status of the soil. Application at early booting or at first irrigation is ideal to have lower percentage of lodging.

Higher nitrogen may also bring about restrictions in the development of coronal roots. Root anchorage of a semi dwarf wheat variety was found to be weakened due to application of high N rates. In general, its effect on root growth is less than on shoot growth and therefore increased N supply will always result in an increased shoot: root ratio, which is conducive to lodging (Pinthus, 1973).

Irrespective of the crop rotation followed increase in the nitrogen rate from 50 kg/ha increased the broken plants. However, the breakage is more under corn-soybean rotation (Wallace *et. al.*, 1999). However, nitrogen application did not result in significant lodging between higher N rates from 240 kg N/ha to 300 kg N/ha (Tripathi, *et. al.*, 2003)

Plant population

Increased stand densities of most cereal crops of the gramineae family will result in taller plants with stem smaller in diameter and subjected more to breakage. Increased lodging in corn can result in lower grain yields by placing mature ears too close to the ground to be machine harvested (Bruns and Abbas, 2005).

Berry *et. al.*, (2004) reported gradual increase in the percentage of lodging in wheat increased linearly from 100 to 400 plants/sq.m. Reducing the number of plants within a row or using wider row spaces both reduced lodging. Reducing the number of plants from 400 plants/ sq m to 100 plants/sq m reduced the lodging from 100% to negligible amounts. Establishing fewer plants result in more number of crown roots and better anchorage.

Freeze and Bacon (1990) reported significant lodging when wheat row spacing was 4 inches in comparison to 6 or 8 inches.

Higher plant populations in corn significantly increased the yield but simultaneous increase in lodging was noticed (Pedersen and Lauer, 2002 and William and Thelen, 2002). Stalk breakage is easier due to smaller diameter at higher populations. Maintaining plant population of 70,000 to 1, 00,000 plants/ha of corn found to be ideal for high yields and lower lodging percentage (Bruns and Abbas, 2005). However lodging was not consistent with varied row width in corn (William and Thelen, 2002).

Sowing date and depth of sowing

Lodging risk of wheat is almost always reduced by delaying sowing. A delay of only 2 weeks can reduce the amount of lodging by as much as 30%. Berry *et. al.* (2004) showed that sowing winter wheat 6 weeks earlier increased both root and stem lodging risk by increasing the base bending moment of the shoot by about 30%. Earlier sowing results in greater number of extended internodes (Stapper and Fischer, 1990). Earlier sowing may also increase the prevalence of stem base diseases, which may increase lodging by weakening the stem. Sowing 4 weeks earlier increased the amount of *Fusarium* foot rot in wheat.

Deeper drilling helps in adjusting the depth of crown roots of plants to a depth of 40 cm. Hence, it is better to sow between 4-7 cm. Drilling more shallowly than 4 cm may be expected to raise the crown and its structural roots, thus weakening anchorage.

Irrigation

Restriction of excessive vegetative growth by delaying or withholding first irrigation reduces the lodging. This indicates possibilities of reducing lodging by delaying or withholding first irrigation. Delaying the first irrigation from 20 DAS to 40 DAS reduced the lodging in wheat from 60% to 10.1%. However, giving irrigation at 30 DAS is found to be optimum with reduced lodging and better yields in wheat under *Tarai* conditions of Uttar Pradesh, India (Pandey *et. al.*, 1997).

Surplus moisture in the upper soil layer weakens the anchorage of the root system. On the other hand, dryness of the upper layer may, restrict the development of the coronal root system and thus promote lodging. Lodging on clay soils under dry conditions may be due to cracking of the soil which damages the roots (Hurd, 1964).

Poor soil aeration may increase susceptibility to lodging due to the effects on respiration inhibition and changes in metabolism which promote cell elongation and thus increase lodging. The promotion of lodging due to poor aeration and high moisture content of the soil is especially evident in water logged fields. Soil aeration and soil structure also affect nitrogen availability, which in turn affects lodging.

Reduction in early vegetative growth and plant height greatly reduce susceptibility to lodging during and following later irrigations. This suggests withholding spring irrigation as long as possible preferably until the early boot stage. Irrigation is conducive to lodging, which is particularly detrimental during the period of grain development. Trials with winter wheat in the northern Caucasus showed that lodging was promoted less by sprinkler irrigation than by furrow irrigation (Pinthus, 1973).

Clipping and Grazing

Excessive foliage during the period of elongation of the lower culm internodes may be prevented by clipping or grazing.

This should be done before culm elongation has proceeded sufficiently. This method is successful in controlling lodging and in certain cases caused subsequent increase in grain yield. However, in most cases grain yield was reduced following grazing or chipping. This method is effective in reducing lodging but it reduced the yields.

Application of chemicals/Growth regulators

Plant growth regulators (PGR's) are synthetic compounds, which are used to reduce the shoot length of plants. This is mainly achieved by reducing cell elongation, but also by decreasing the rate of cell division. In cereals, PGR's are used to reduce lodging. They are most commonly used for this purpose in north and western European countries and in Canada and the USA. In the UK, 84% of the winter wheat is treated with PGR's. The most commonly used are chlormequat chloride and mepiquat chloride. Ethephon is the most commonly used ethylene-releasing compound used on cereals. PGR's applied before the emergence of the ear reduced lodging in almost all the experiments. Herbert (1982) showed that applying chlormequat and choline chloride to winter wheat at the beginning of stem extension could reduce the percentage area lodged from about 73% to less than 8%. Most growth regulators are only active for a few days after application and can therefore shorten internodes most effectively when applied during their extension.

Application of ethephon (480 g/ha) controlled lodging by reducing plant height but also decreased average grain yield by 8.3% (Tripathi, *et. al.* 2003). Wheat yields were also improved by 500-1000 kg/ha by application of ethephon in wheat varieties (Hobbs *et.al.* 1998).

Potassium Trace Elements Application:

Effects of P, K, and trace elements are less pronounced than that of nitrogen. Most of the reports cite reduction in lodging due to potassium application. On potassium deficient soils, applying 100 kg/ha mostly reduced lodging in wheat and rye. No further effects were observed when an extra 200 kg/ha was applied. Corn lodging reduced from 60% to 27% due to continuous application of 120 lbs/acre of K₂O (Anonymous, 1998). However in control, without the application of K₂O stalk lodging percentage remained high. Potassium imparts resistance to lodging by increasing the rind thickness (mm) and crushing strength (kg). Potassium sulphate and potassium chloride were ideal for the reduced effect on lodging. Potassium fertilization reduced the disease incidence.

Addition of silicon significantly increased the rigidity of rice stalk and this increase was remarkably higher at lower dose of nitrogen. The larger quantities of nitrogen greatly reduced the efficiency of silicon in imparting rigidity of plants (Idris *et.al.*, 1975). Root weight was significantly increased by application of silicon (Srivastava and Kumar, 2003).

Diseases

Important diseases like stalk rot in sorghum caused lodging. Under experimental condition 100% lodging occurred and grain yield losses were 23 to 64% in CSH-6 hybrid, at three locations in India and Sudan. This is because natural charcoal rot infection of plants was induced by subjecting them to drought by withdrawing irrigation at different growth stages (Mughogho and Pande, 1983). At Dharwad nearly 100% lodging was noticed when irrigation was given upto boot swollen stage or ligule visible stage and not throughout the crop period.

Physiology of grain yield in cereals

Cereals are at the top of the list of human nutritional needs, with wheat and maize especially important in the food of Western cultures while rice dominates Asian meals. The primary use of wheat and maize grains after harvest, however, is very different: the former has a more direct inclusion in our diets through diverse products, among which bread is by far the dominant, whereas the main use of maize is for animal feeding. Another distinctive trait of these two cereals is their position in current cropping systems which is linked to the growing requirements of each species but also to the profitability determined by grain price, production cost and its value in the rotation. Thus, in rainfed regions where both crops can be widely grown and no economic pressure (e.g. subsidies) helps buffer market trends, land area cropped to each cereal can shift substantially.

Grain yield of most cereals, but particularly of wheat and maize, exhibited a sustained increase during the second half of the last century. Evidence from the last decade, however, suggests a softening in this trend for most of these crops (Calderini and Slafer 1998; Slafer and Otegui 2000). This change in trend turns gloomier in view of the expected global demand of these staples. While world demand for wheat has been increasing at a rate of 3% per year, the rate of increase in yield potential of this cereal has been of 0.8% per year (McWilliam 1989). In this context, future cereal breeding needs to be even more efficient than in the past, when yield potential increased dramatically. On the other hand, traditional breeding may benefit today by the contribution from molecular biology (Araus et al. 2002), which is likely to help in this field. Initially promising perspectives from new molecular technologies, however, have not yet yielded the expected results for improving complex traits related to crop productivity (Slafer 2003). Remarkable progress has been made with the discovery and transfer of major genes, almost exclusively linked to the control of biotic constraints, like the Bt for insect control and the glyphosate resistance for weed management. Molecular tools are still far from giving a good explanation of the causal relationships between genes and the phenotype of complex traits linked to productivity under field conditions, the initial step for their subsequent manipulation. This is particularly evident in the case of yield, which is formed continually from sowing to harvest and with virtually all genes contributing directly or indirectly to its determination in a quantitative manner. In this context, there is good consensus at present among breeders about the importance of an adequate phenotyping as the first task for the identification of genes responsible for a given trait. The second task is the detailed characterization of the target environment, generally neglected by breeders and physiologists (Acevedo and Fereres 1993). Both aspects, i.e. improved phenotype and environment data collection, will enhance the analysis and comprehension of the genetic bases of yield determination with respect to statistical approaches most currently used in breeding. This is a key step for the correct application of many identified QTLs and genes.

Here we have briefly reviewed (i) the importance of improving yield potential for further increasing actual yields in a range of conditions, and (ii) the significance of considering physiological attributes for achieving this goal. We finally discuss recent research on two developmental traits as tools for further raising yield potential in cereals. These are the particular extent of the stem elongation phase in wheat and the synchrony in the emergence of silks within ears in maize. We separately discussed physiology of grain yield in sorghum.

Relevance of further raising cereal yield potential

There is on-going discussion as to whether it is relatively more important to further improve yield potential genetically, with the concomitant increase of actual grain yield in the field, or agronomically, reducing the gap between this potential yield of modern cultivars and actual yields achieved by farmers. The relative importance of these two viewpoints would, at first sight, depend upon the magnitude of the gap between potential and actual yields. If the gap is small, little can be expected from improved management, and future improvements in actual yields may largely depend on further raising yield potential. This is the case in many irrigated high production regions of the world, like major rice-producing provinces of China, wheat production in the Yaqui Valley of Mexico, and maize contest-winners of the US corn-belt, where actual yields are reaching the 80% yield potential threshold that marks the start of on-farm yield stagnation (Cassman et al. 2003).

The issue is rather more complex for the environments in which actual yields represent only a rather small proportion of potential levels, which is the case for most cereal growing regions of the world. In these environments, the magnitude of the gap between potential and actual yields is frequently interpreted as an indication of the potential contribution that management improvement might make. However, the alternative view suggests that, independently of the magnitude of the gap, increases in yield potential are critical even in these circumstances. This view is based on the parallelism between improvement in yield potential and responsiveness to management improvement (Cassman et al. 2003). For instance Kirigwi et al. (2004) have shown that it is feasible to retain genes for relatively high yield under stress from selection carried out under stress-free conditions in wheat, and similar conclusions apply to other cereal crops like barley (Abeledo et al. 2003) and maize (Duvick 1992).

The fact that (i) there has been little or no increase in actual yields until there was a consistent increase in potential yield of cultivars released in different crops (e.g., Evans 1993), and (ii) cultivars released by breeding with higher yield potential

outyielded their predecessors in a wide range of environmental conditions (e.g. Russell 1991; Calderini and Slafer 1999; Tollenaar and Lee 2002) support this view. Thus, it may be expected that future genetic progress in yield potential (yield in favorable environments) should continue contributing to increases in actual yields in less favorable growing environments (see reviews in Reynolds et al. 2001).

Determination of cereal yield potential

In order to increase yield potential, the traditional approach has been selecting for yield *per se*. It seems that in the future, the traditional approaches may benefit from complementation with analytical tools. These analytical tools need to consider determinants of yield potential that must be functionally related to yield so that they may be reliably used in breeding or pre-breeding. The initially most popular approach of dividing yield into its numerical components, though apparently logical and simple, is unfortunately of little use due to the negative relationship expected among them under agronomic conditions (Fischer 1984).

A more functional approach has been the analysis of the timing when yield is chiefly being determined. In all crops yield is the end result of growth and development, determined by the genotype, the environment and their interaction. Yield can be affected at any time from sowing to maturity: at any stage of development one or more components of yield are being determined, either through their generation or their degeneration/death (Slafer and Rawson 1994). However, only a relatively small fraction of the whole growing period is actually critical to the determination of yield in most grain crops. This is, in general, the period when the number of grains per unit land area is largely determined in response to the growing/partitioning conditions of the crop. This is so, in turn, because grain yield is much more related to the number of grains per unit land area than to the average weight of the grains. The latter is far less responsive to changes in availability of assimilates, although here there are differences among crops (Borrás et al. 2004).

This critical period is always concentrated around the flowering stage, with specific differences likely dependent upon the floral biology and mating system. For instance in wheat, a cleistogamous species (pollination occurs before the opening of the flowers), most of the floret primordia that reach the stage of fertile floret become grains after anthesis. The critical period is when a proportion of the large number of floret primordia becomes fertile florets. This period is during stem elongation, a few weeks prior to anthesis (e.g. Fischer 1985; Kirby 1988). In maize, a monoecious crop (grains are set in the axillary, female inflorescences fertilized with pollen from the apical inflorescence, mostly from other plants in the population due to protandry), the critical period includes the periods immediately before and immediately after anthesis/silking, but grain set rather than the determination of the number of fertile florets is the relevant process (for a review on this topic see Otegui and Andrade 2000, and Westgate et al. 2004).

By improving either crop growth or partitioning to reproductive structures during their respective critical periods, the number of grains per unit land area (and yield) would be concomitantly improved both in wheat (e.g., Fischer 1985) and maize (Andrade et al. 2002). Consequently, various traits presumably associated with improved growth of harvestable organs during the critical period (e.g. reduced plant height, reduced tassel size) have been included in breeding programs, in order to identify prospective parents or to directly select the progeny (e.g., various chapters in Otegui and Slafer 2000, and Reynolds et al. 2001).

Developmental patterns have received far less consideration as potential traits to improve yield potential. Developmental attributes have mostly been studied in terms of their effects on anthesis time, strongly related to adaptation but not clearly related to yield potential. For instance, wheat breeding that increased crop yields noticeably during the second half of the 20th century worldwide (Calderini et al. 1999), only generated systematic changes in developmental patterns in countries with large areas of the crop under Mediterranean conditions of terminal drought, in which shortening the cycle improved stress avoidance (such as in Western Australia). In regions where mid-season stress or stresses occur irregularly during the season, improved yields have not consistently followed changes in developmental patterns of the crop (see Araus et al. 2002, for an extended discussion of this issue). However, in the last decade or so, several cases have emerged in which manipulation of particular developmental attributes (beyond general changes in time to anthesis) seemingly influences crop yield. These developmental attributes might be potential candidates for breeding for further increasing yield, with virtually no effect on adaptation. In the last sections of this paper we will concentrate on the likelihood of using particular developmental attributes in wheat and maize as tools to actually improve yield potential. They are the duration of the stem elongation phase in wheat and the synchrony in the emergence of silks within ears in maize.

Duration of late reproductive phases in wheat as an alternative to improve its yield potential

Brief hypothetical framework

It has been proven that (i) number of grains per unit land area in wheat is strongly associated with the dry matter accumulated

in the spikes at anthesis (see references above), a relationship that holds for a wide range of growing conditions, and (ii) spike dry-matter accumulation takes place only during a brief period within the phase of stem elongation (Kirby 1988; González et al. 2003b) in strong competition with the growing internodes (e.g., Fischer 1995).

Most breeding success in the past has been associated with improvements in the partitioning of dry matter to the growing spikes (as recently reviewed by Calderini et al. 1999), and most of this achievement has been accomplished by the introgression of major *Rht* genes for reduced stem growth, increasing thus the availability of assimilates for the developing spikes. As modern wheats have already reached an optimum height (Miralles and Slafer 1995), further reductions in height are likely counterproductive, and then the trait most successfully altered in the recent past seems no longer useful for further increases in yield potential (Slafer et al. 1999).

Increasing crop growth rate during the critical phase of stem elongation is likely the universal mechanism by which most management practices impact on grain yield of many annual crops (e.g., Fischer 1993; Andrade et al. 2002). Consequently, a lot of public and private research effort is aimed to improving knowledge of the developmental pattern of each cultivar in each environment (e.g., days or thermal time to anthesis), a key issue for matching the critical period with the best growing conditions. In the main wheat producing areas of Argentina, for instance, spring type cultivars predominate and sowing date is scheduled in order to place the anthesis of the crop as soon as late frosts do not represent a serious risk of spike damage. Spring types avoid the extra water uptake of longer cycles early in winter, which can be particularly disadvantageous in some areas (Savin et al. 1995), and early anthesis dates exploit mild temperatures during grain filling. The combined effect of cycle duration and planting date also lead to cereal harvest as soon as possible in December for the early sowing of second-planted soybeans, the yield of which is significantly reduced for each day delay in planting (Calviño et al. 2003). In this cropping scenario there is little room for significant changes in wheat cycle duration, and it seems likely that increasing crop growth rate genetically by improving either radiation interception or radiation use efficiency during the critical phase of stem elongation may be required to keep on increasing yield potential (Slafer et al. 1999).

It has been only relatively recently hypothesized that lengthening the stem elongation phase (independently of the previous phases) would bring about improvements in both spike dry weight at anthesis and number of grains to be filled from then on (Slafer et al. 2001). This hypothesis would potentially work in any condition in which wheat yield is clearly sink-limited during grain filling, and then increasing the number of grains per m^2 would result in actual increases in yield. This situation is seemingly generalized over many different growing conditions and cultivars (Borrás et al. 2004). Thus, if differences among genotypes in the length of the phase of stem elongation (due to either sensitivity to photoperiod or intrinsic earliness for the specific phase) may be found independently of the photoperiod sensitivity or the intrinsic earliness ranking of previous phases, the developmental pattern of a genotype might be tailored. In other words, for a specific length of the total phase to anthesis (critical for adaptation, and thus already optimized in most regions) a combination of different lengths of developmental phases occurring before and after the onset of stem elongation may be hypothetically arranged. The fact that developmental rates of different phases seem to be, at least partially, independently modulated by photoperiod (e.g., Slafer and Rawson, 1996; Miralles et al. 2000) and intrinsic earliness (Slafer 1996), supports the hypothesis.

Empirical evidence of genotypic variation in partitioning of total time to anthesis among phases occurring before and after the onset of stem elongation

We conducted a detailed study to try to uncover any variability existent within modern wheats cultivated in Argentina for the duration of the stem elongation phase (from the onset of stem elongation to anthesis) within commercial cultivars released in recent years and of similar time to anthesis when sown in their recommended dates (Whitechurch, Slafer and Miralles, unpublished). We preferred to test variation within modern cultivars as they are the core material used to pyramid yield increases.

Sixty-four cultivars grouped into subsets of similar emergence-anthesis durations were sown in field experiments and screened for their phenology. There were some clear examples of pairs of cultivars with similar times to anthesis combined with contrasting distribution of that time between phases elapsed before and after the onset of stem elongation. This variability is in agreement with that observable in barley when a screening is made with several cultivars (Kernich et al. 1997). In addition, there was variation among genotypes regarding the stage of the stem elongation period responsible of the observed variability, being sometimes from the onset of stem elongation to flag leaf emergence and in other times from then on (data not shown). A detailed understanding of the response may be relevant when considering possible effects on traits influencing canopy survival and/or photosynthetic activity after anthesis. For instance, lengthening the first stages of stem elongation may enhance rooting and access to N sources after anthesis, while lengthening the late stages of this period may act more directly on floret primordia survival. Testing the effects of these phenological changes on biomass partitioning and kernel set requires more than the simple comparison of cultivars, as discuss in the next section.

Responses of grain number to changes in duration of stem elongation

Even before exploring the existence of genetic variation in length of the stem elongation phase, independently of variation in duration of previous phases, we searched for the actual sensitivity of this late reproductive phase to photoperiod. A summary of those experiences has been reviewed in Slafer et al (2001). To recap briefly, we firstly dealt with the generalized assumption that only relatively early developmental phases are responsive to photoperiod. However a reappraisal of the literature data from studies in which photoperiod treatments were imposed directly rather than by changes in sowing dates clearly suggested that the late reproductive phase of stem elongation was highly sensitive to photoperiod (Slafer and Rawson 1994), and in addition quite variable in terms of intrinsic earliness (Slafer 1996). The suggestion of the strong responsiveness of the stem elongation phase to photoperiod was significantly supported by experiments specifically designed, both in controlled conditions (Slafer and Rawson 1996) and in the field (González et al. 2002), in which plants were exposed to different photoperiods throughout their development but the responses of different phases analyzed independently. In later studies we exposed the late reproductive phase to different photoperiods independently of the photoperiod experienced in the previous phases, in order to test direct responses (and sensitivity) of this critical phase. Both in controlled conditions (Miralles et al. 2000) and in the field (González et al. 2003a; Slafer and Abeledo, unpublished) the stem elongation phase responded to photoperiod regimes imposed exclusively at that stage, lengthening the phase as photoperiod decreased. It seems then that sensitivity to photoperiod may actually be used as a tool to further increase wheat yields, by specifically manipulating the sensitivity to photoperiod during the stem elongation phase. As direct phenotypic selection for this trait seems unrealistic, it is crucial to identify genetic bases for the sensitivity to photoperiod during the stem elongation phase. Only initial efforts have been made (and these only with the three major *Ppd* alleles) in this field so far, (Whitechurch and Slafer 2001, 2002) and this must be strengthened in the near future.

In all studies (under controlled or field conditions; with photoperiod regimes imposed throughout or only during the stem elongation phase), only changes in duration of the stem elongation phase were reflected in changes of the number of fertile florets or grains produced by the crop (Slafer et al. 2001; Fig. 2). In the phytotron study, plants of a photoperiod-responsive spring wheat (UQ189), grown in a naturally lit phytotron at constant (9, 13 and 19 h) and reciprocally interchanged photoperiods at the onset of stem elongation. The stem elongation phase was actually lengthened under shorter photoperiods and *vice-versa*, irrespective of the length (and photoperiod condition) of the previous phases; and these changes in duration of stem elongation translated into changes in the number of fertile florets through parallel changes in spike dry matter at anthesis (Miralles et al. 2000). In the field study, plants of different degrees of sensitivity to photoperiod x vernalization were grown under natural photoperiod until the onset of stem elongation, and from then to anthesis either maintained in that condition or exposed to a longer photoperiod in the field. Focusing on the cultivar that was insensitive to vernalization (to avoid the interaction here), there was a clear change in duration of the stem elongation phase due to exposure to different photoperiods during the stem elongation phase, and this change resulted in changes in number of fertile florets (Fig. 2b); once again mediated through changes in spike dry weight at anthesis (González et al. 2003a).

Synchrony in the emergence of silks within ears of maize as an alternative to improve its potential grain yield

Yield potential improvement in maize: controversies and needs.

From recent publications that included the analysis of trends in maize yield potential (Tollenaar and Lee 2002; Cassman et al. 2003) it can be concluded that there has been no real improvement in this trait during the last 30 years, because on-farm grain yields as high as 19.7 Mg ha^{-1} have been reported as early as in the 1970s. Neither recent grain yield contests for irrigated systems (Cassman et al. 2003) nor results from small-plot trials (Otegui et al. 1996) indicate an improvement in yield potential with respect to the 1970's records, which are close to the estimate of 25 Mg ha^{-1} computed by Tollenaar (1983) for the conditions of central North America. On the other hand, results from breeding studies indicate a sustained genetic gain in average on-farm grain yields, with no clear signs of having reached a plateau (Slafer and Otegui 2000). In other words, this contrast in trends between potential and actual maize grain yields is clear evidence of the main objective pursued by breeders during the recent decades and the approach they used for successfully achieving it: search for improved stress tolerance in order to obtain improved grain yield stability, based on a large number of testing sites that included those currently encountered by most commercial maize crops in a given region (Tollenaar and Lee 2002). This strategy is still successful because most average on-farm grain yields are yet far from the potential, especially in the developing world. Problems related to lack of improvement in grain yield potential could be expected in some irrigated systems, like those already quoted for some US corn-belt farmers (Cassman et al. 2003) or maize production in some high-yielding Mediterranean environments (e.g., Chile).

Grain yield and reproductive development in maize

One aspect has been consistent from most studies on grain yield improvement in maize: grain yield increases have been mostly related to an improved number of harvestable kernels per unit land area, indicative of a predominant sink limitation to

crop yield (Borrás et al 2004). This fact led to increased attention to attributes that control final kernel number. The main features of reproductive differentiation in maize have been thoroughly studied (Bonnett 1966), both for the apical meristem that gives place to the tassel (botanically a panicle) responsible for pollen production, and for the axillary buds that produce the ears (modified spikes), which bear the grains. This declinose monoecious characteristic of the species is the trait that most strongly conditions its reproductive success, because harvestable organs (i.e., the ears) start differentiation and growth after the tassels do, and remain under the dominance of the male structure until pollen is shed. Any growth restriction, therefore, will have a larger negative effect on the progress of the ears than on the evolution of the tassels.

Under stress conditions, silk emergence is delayed relative to pollen shed, which can result in lack of pollen for late-appearing silks on apical ears, reduced silk emergence from sub-apical ears, failure in ovary fertilization, and ultimately, reduced kernel set (for more on this topic refer to Otegui and Andrade 2000, and Westgate et al. 2004). Moreover, this unfavorable reproductive pattern is not offset by other phenotypic traits that usually add plasticity to a species adaptation to the environment, like tillering or branching. Commercial maize vegetative phenotype can be described as very *rigid* in this aspect. Consequently, close synchrony between pollen shed (i.e., anthesis) and silk emergence (i.e., silking, when the first silks emerge from the husks) is required for high kernel set in maize (Bolaños and Edmeades 1993), and a negative relationship exists between final kernel number and the extent of the anthesis- silking interval (ASI= date of silking – date of anthesis). Hall et al. (1982) hypothesized that the lack of pollen for late-appearing silks was among the causes of kernel number reduction under water stress conditions in maize, but their own results and subsequent research on kernel number determination demonstrated that kernel abortion still occurred when fresh pollen was added to late-exposed silks (Otegui et al. 1995). Therefore, factors other than greater pollen availability must be involved in improving final kernel number in response to a shorter ASI.

Under natural conditions, the delay in silk growth among ovaries along the ear, together with the position- dependent length the silk must attain to emerge (Bonnett 1966; Cárcova et al. 2003), determines a time lag between the first-appearing silks (from the lower half of the inflorescence) and the late-appearing ones (from the tip of it). This feature, together with the male-female asynchrony described above, results in pollination asynchrony among ovaries along the ear, and the natural embryo abortion of those ovaries located at the tip of the ear usually observed in most maize crops. The rate of kernel abortion is strongly dependent on plant growth rate around silking (Andrade et al. 1999, 2002), and this abortion can be partially overcome by increasing assimilate supply of plants during this critical period. Nevertheless, evidence indicates that assimilate availability per fertile floret seems not to be the only factor controlling kernel set when water and nutrients are not limiting growth. It is well known that kernel set in the subapical ear depends on synchronous silking and pollination of both ear shoots. Considering pollination synchrony within the ear, a significant reduction in kernel set has been observed when the pollination interval between early- and late-appearing silks in the apical ear was artificially increased (Cárcova and Otegui 2001). On the other hand, maize kernel set can be improved significantly (8–31%) through synchronous hand pollination, both between ears at low plant population and within the apical ear at high stand densities (Cárcova et al. 2000). The benefits of synchronous pollination on final kernel set have been thoroughly assessed (Cárcova 2003), with studies including several hybrids (two Americans and two Argentines, and among the latter their normal and male-sterile versions), environments (cool-temperate at 48°N in MN, USA, and temperate at 34°S in Argentina and for the latter, in four growing seasons), and plant populations (from almost isolated plants at 3 plants m⁻² to a high density of 9 plants m⁻²). On the other hand, uncertainty remains with respect to the translation of this increment in kernel number to an increase in grain yield. A thorough analysis of seed weight response to the post-flowering source-sink ratio in different species (Borrás et al. 2004) showed that maize kernel weight is particularly sensitive to reductions in this ratio. In other words, a further increase in the numbers of kernels in this crop will turn into an improved grain yield only if it is accompanied by an enhanced production of biomass after flowering. Up to present, improvements in post-silking biomass have been possible because of selection for enhanced green leaf area persistence (*stay-green*), a trait strongly related to grain yield in maize (Russell 1991; Duvick 1992) and in other source-responsive crops like sunflower (de la Vega and Hall 2002).

Promising traits to be considered when breeding for improved pollination synchrony among ovaries within the ear

Improved kernel set obtained with artificially forced synchrony in pollination timing, suggested that the rates of silk emergence and pollination might explain part of the genotypic differences observed in final kernel number. Thus, a better knowledge of the pattern of ear development and growth would help identify traits that integrate the effects of several basic processes related to kernel set. Lafitte and Edmeades (1995) observed that selection for improved performance under water or N stress brought about a reduction in the number of florets along the ear (i.e., shorter ears) and an increased biomass per floret, which apparently promoted greater kernel number per ear (i.e., increased kernel set) and prolificacy. They postulated that, because final kernel number per plant is always smaller than the potential number of fertile florets per ear (i.e., kernel set <1) in most maize crops, breeding for synchronous pollination should focus on the selection of short ears, which usually exhibit synchronous exposure of most silks in a short period of time. They hypothesized that this trend, however, can not be extended indefinitely, due to eventual yield restrictions under favorable growing conditions. In these circumstances,

prolificacy could not compensate for the reduced potential kernel number attainable with the apical ear (Andrade et al. 1999). An analysis of the evolution of potential ear size (i.e., spikelets per ear) performed on widely used commercial hybrids representative of different breeding eras in Argentina, revealed exactly the opposite trend to that suggested by Lafitte and Edmeades (1995)(Table 1). Grain yield improvement for this environment has been related to increased kernel number (Luque 2000), and this trend has been matched by an increase in potential ear size (Matthiess et al. 1999; Luque 2000), both in the number of spikelets per ear row and in the number of spikelet rows per ear. We hypothesized that the increased number of spikelet rows determines a large number of silks exposed synchronously in a few days after silking of each plant, and that the enhanced number of florets along the ear gives the genotype a better chance for increasing kernel number in good years than the alternative, an increase in prolificacy (Table 1).

Recently, Cárcova et al (2003) studied in detail the female developmental characteristics of two hybrids with very contrasting ear types, the short-eared DEA from France and the long-eared DK696 from Argentina. They observed that these hybrids had similar trends with respect to (i) the proportion of final ear size reached at silking, (ii) the dynamics of spikelet and silk initiation, and (iii) the pattern of silk elongation, which was similar among ovaries along the ear but acropetally delayed in time. Genotypes, however, displayed a different rate of ear and silk elongation, and convergence in silking among spikelets along the ear was attained (i) by synchronous silk initiation along the ear and a similar pattern of silk elongation among florets in the short-eared DEA, or (ii) by an increased silk elongation rate from the base to the tip of the ear in the large-eared DK696. The former is a development-based response pattern while the latter is a growth-related one, and consequently maybe more dependent on environmental conditions that control growth (e.g. water, light). Future studies should determine if synchronous silk initiation is always related to short ears or can be selected independently of ear size.

Table 1. Reproductive traits of a set of hybrids released at different years in Argentina (adapted from Matthiess et al. 1999).

Stand Density	Hybrid	Year of release	Silked ears per plant	Florets Kernel rows per ear per ear	Florets per kernel row	Grained ears per plant	Kernels per plant	
3 plants m ⁻²	DKF880	1965	1.90 a*	636 c	14 c	44 b	1.60 b	660 c
	M400	1978	1.65 b	678 c	14 c	47 b	1.45 b	718 c
	DK752	1993	2.00 a	973 a	19 a	51 a	1.85 ab	954 a
	DK757	1997	2.00 a	1012 a	20 a	51 a	1.50 b	925 ab
9 plants m ⁻²	DKF880	1965	1.35 b	543 d	14 c	38 c	0.90 a	339 e
	M400	1978	1.30 b	609 c	14 c	44 b	1.00 a	450 d
	DK752	1993	1.81 a	949 a	19 a	51 a	1.00 a	690 b
	DK757	1997	1.90 a	972 a	20 a	51 a	1.05 a	743 a

* Different letters within a column and stand density indicate significant differences ($P < 0.05$) among hybrids.

Finally, studies performed by Luque (2000) gave some clues of the degree of genotypic variability for traits related to ear growth and development. For a set of seven hybrids, that included among others those described in Table 1, and stand densities between 3 and 18 plants m⁻², he determined that (i) short ears do not necessarily confer improved biomass per floret, because there is variability for biomass partitioning to the ear, and (ii) improved kernel number obtained with new, large-eared hybrids, is not always related to an improved ASI. Apparently, the increased number of silks exposed soon after silking from large ears could compensate, at least partially, the negative effect on kernel set of a longer ASI. In his study, final kernel set was modulated by the ASI, the potential ear size (i.e., spikelets per ear) and the biomass achieved per floret. All these traits varied among genotypes, and no constant link was detected among them.

THE PHYSIOLOGY OF GRAIN YIELD IN SORGHUM

Opportunities exist to further increase grain yield under ‘water-limiting’ and ‘non-limiting’ conditions. For example, when water and nutrients are not limiting, sorghum plants that a) intercept more sunlight, b) use sunlight more efficiently to produce biomass, or c) allocate more biomass to grain, will yield more. Alternatively, when water is limiting, sorghum plants that a) access more water, b) use water more efficiently to produce biomass, or c) allocate more biomass to grain, will yield more. This discussion provides a physiological understanding of how grain yield can be further improved in sorghum.

Sorghum is a remarkable cereal. It contains biochemical, physiological and morphological characteristics such as C₄ photosynthesis, deep roots and thick leaf wax that enable growth in hot and dry environments. Although sorghum

germplasm collections show considerable diversity, much of this has been lost during domestication. Opportunities exist, therefore, to recapture some of this diversity in modern sorghum hybrids. This paper will explore the physiological basis of grain yield in sorghum, highlighting some of the traits that could be 'recaptured' to further improve yield under water-limiting and non-limiting conditions in Australia's northern grain belt.

Let's consider two frameworks to help us better understand sorghum yield under 'water-limiting' and 'water non-limiting' conditions.

Non-limiting conditions

First, in the absence of water or nutrient limitations, biomass accumulation is limited by the amount of radiation that is intercepted by the crop. Grain yield can be expressed in terms of the following framework:

$$\text{Grain yield} = \text{IR} \times \text{RUE} \times \text{HI}$$

where:

IR = intercepted radiation

RUE = radiation use efficiency

HI = harvest index (grain as a proportion of total above-ground mass).

This equation shows that grain yield can be increased by increasing any one of the three components (IR, RUE or HI), assuming no net reduction in the other two components. The total amount of radiation intercepted by the crop (IR) can be increased by either improving the ground cover of the crop, or extending the duration of radiation interception. For example, modifying canopy architecture (via either genetics or management) to maximise the amount of solar radiation intercepted by the leaves, without a net reduction in RUE or HI, will increase grain yield (all other things being equal). Genetic solutions include longer duration varieties (hence more leaves), more erect leaves to capture more radiation through better distribution of light, increased tillering, increased leaf appearance rate, and larger leaves. Management solutions include sowing time (to maximize duration of crop growth) and optimizing planting geometry, nitrogen fertilization and water supply to maximize canopy size. Alternatively, for a given canopy size and HI (all other things being equal), improving the efficiency with which solar radiation is converted to crop biomass or increasing the amount of biomass that is partitioned to above-ground biomass rather than the roots would increase grain yield. Finally, for a given amount of above-ground biomass (IR x RUE), yield can be improved by increasing HI.

Let's use this framework to explore how a trait may affect yield when water is not limiting. A positive correlation between plant height and grain yield has long been observed. Why do taller plants yield more under non-limiting conditions? To what extent are these yield increases associated with IR, RUE or HI? Taller plants usually have greater above-ground biomass and, if the HI is equivalent, will produce more grain yield. The higher above-ground biomass may be due to either higher RUE or greater partitioning to the shoot rather than the roots. However, more research is needed to clarify the yield advantage of taller sorghum plants.

IR may be increased through

- More rapid ground cover early in the season
 - Genetic: tillering, leaf appearance rate (LAR), leaf size, erect leaves (better light distribution)
 - Agronomic: planting geometry, N fertilization
- Longer duration
 - Genetic: later flowering
 - Agronomic: sowing date
- Note that maximum light interception is attained when the leaf area index exceeds 3

RUE is an intrinsic genetic value

- Differences in RUE reported in sorghum (associated with height)
- No consistent or significant RUE differences among 3 dwarf (short) hybrids have been reported

Can HI be increased?

- Already quite high at about 0.5
- Differences in HI related to height
- Higher yield of tall hybrids is probably associated with a higher crop growth rate (CGR) around flowering
- Some evidence of greater partitioning to the roots rather than the shoots in taller plants

Water-limited conditions

Sorghum is adapted to tolerate water-limited conditions. Let's consider a second framework to assess yield when water is limiting:

$$\text{Grain yield} = T \times \text{TE} \times \text{HI}$$

where:

T = transpiration (water use)

TE = transpiration efficiency

HI = harvest index (grain as a proportion of total above-ground mass).

This equation shows that yield can be increased by increasing any one of the three components (T, TE or HI) assuming no net reduction in the other two components. For example, the 'stay-green' trait increases yield by reducing T before flowering (via a smaller canopy) and increasing T after flowering (i.e. utilising the pre-flowering water savings to fill grain), effectively shifting water use to the grain filling period, thereby increasing HI and grain yield. In this scenario, T and TE remain largely unchanged (although T is relatively lower before flowering and relatively higher after flowering).

T increase

- Increase T by accessing more water
- Deeper roots
- Extraction of more water per soil layer

TE increase

- Intrinsic genetic value
- Hammer/Mortlock found range in TE across wide genetic background, but differences were generally small

HI

Water use pattern. Save water prior to flowering for use after flowering. Small water savings before flowering can lead to substantial increases in grain yield. Save water by restricting plant size (leaf area) through:

- Reduced tillering
- Reduced leaf appearance rate (hence fewer leaves)
- Reduced leaf size
- Decreased biomass partitioning to leaves and increased partitioning to stem will also improve lodging resistance
- Skip row

Note that many so-called 'traits' are linked into 'trait clusters', highlighting the importance of trait integration. For example, the 'leaf area trait cluster' comprises individual traits such as tillering, leaf appearance rate and leaf size. Furthermore, the genetic components of leaf area dynamics interact with management (sowing time, planting geometry, N fertilisation etc) and environmental (soil and climate) components. These interactions suggest that not every trait combination is useful for every stress pattern. Rather, certain 'gene x management' combinations will be more effective in some environments than others – we refer to this as 'specific adaptation'. Unravelling this level of complexity requires simulation modelling.

Let's consider an example. Modifying canopy architecture by reducing the 'leafiness' of the crop should be useful in terminal stress environments, i.e. in those environments in which the crop grows into increasing levels of water deficit. In this situation it would be beneficial to reduce the size of the canopy before flowering, either via genetics, management or a combination of both, thereby saving more water for grain filling. This strategy would be less useful in those environments where significant rainfall was expected during the grain-filling period. Simulation modelling enables combinations of genetics, management and the environment to be assessed in order to optimize canopy size for a particular farmer's property (specific adaptation).

This degree of integration also highlights the benefits of a multi-disciplinary and multi-organizational approach. Scientists (breeders, physiologists, molecular biologists and modellers) need to work with grain-growers to achieve these ends.

Optimization of plant population and planting geometry in relation to different resources

Yield of a crop is the result of final plant population which depends on the number of viable seeds, germination percent and survival rates. Establishment of optimum plant population is essential to get maximum yield. Under conditions of sufficient soil moisture and nutrients, higher population is necessary to utilize other growth factors efficiently. Once soil moisture and nutrients are not limiting, yield of crop is limited by solar radiation. The level of plant population should be such that maximum solar radiation is intercepted. In crops grown on stored soil moisture under rainfed conditions, plant population should not be high to deplete moisture before crop matures and not low to leave moisture unutilized.

Yield of individual plant and community

The full yield potential of individual plant is achieved when sown at wider spacing. When sown densely, competition among plants is more for growth factors resulting in reduction in the size and yield of the plant. Yield/plant decreases gradually as plant population/area is increased (Fig below). However, yield/area is increased due to efficient utilization of growth factors. Highest yield/area can, therefore, be obtained when the individual plants are subjected to severe competition.

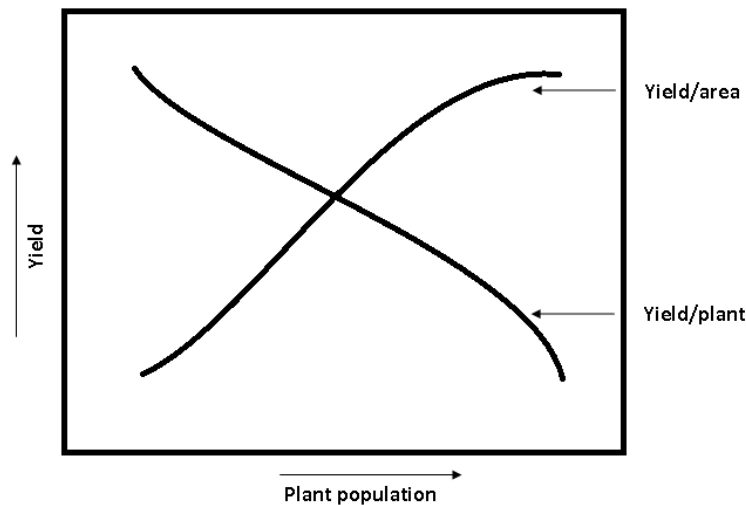


Fig 1. Yield of individual plant and community as influenced by plant population

Plant population and yield

Decrease in the yield of individual plants at higher plant density is due to reduction in the number of ears in indeterminate plants. In determinate plants, wherein the terminal bud ends in a flower or inflorescence, the reduction in yield is mainly due to the reduced size of ears or panicles. Highly branching or tillering plants behave as indeterminate plant and yield reduction is due to reduction in the number of seeds. Redgram produces about 20 pods/plant at 3.33 lakh/ha while it produces more than 100 pods/plant at 50000 plants/ha. Conversely, non-tillering or nonbranching plants produce less yield due to reduction in size of ears as in the case of maize and sorghum. Among all the yield attributes, test weight is the stable character under wide range of plant populations. Under very high population levels, plants become barren.

Efforts were made to quantify the relationship between plant population and yield. Holliday (1960) suggested two types of response curves, asymptotic and parabolic.

Asymptotic response

Where entire plant dry matter as in the case of fodder crops and tobacco is the economic product, the response to increasing plant population is asymptotic (Fig 2). When plants are widely spaced, dry matter of individual plants increases with increase in plant density. This indicates lack of appreciable competition between neighbouring plants. Further increase in density, increases the dry matter of individual plants at a diminishing rate, signifying that competition between plants is felt and that the dry matter production of individual plants is reduced. However, this reduction is more than compensated by the increase in the number of plants. A further increase in plant population results in a plateau i.e. with increase in plant population there is no increase in dry matter per unit area. It shows that increase in production due to increased plant

population compensates almost equally for the reduction in the production of the individual plant. The plateau continues for large increases in plant population. That is why, for fodder crops, dense stands are recommended to get maximum yield. The extra expenditure is the seed cost only. In addition, dense stands provide for lean stems and more leafy fodder compared to sparse population where stem dry matter is high. The type of response gives the asymptotic curve which is expressed as follow

$$Y = Ap + \frac{1}{1 + Abp}$$

Where, Y is dry matter yield/area; A apparent maximum yield per plant, p number of plants per unit area and b is linear regression coefficient.

The term $1/(1+Abp)$ represents the maxima in which the maximum plant yield (A) is reduced by increasing competition resulting from greater plant density. It is termed as competition factor. Maximum yield that is obtained in particular condition when the plants are widely spaced with practically no competition is denoted as A or apparent maximum yield per plant.

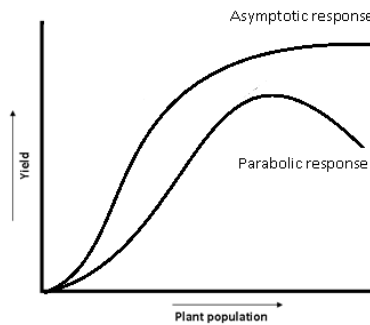


Fig 2 Asymptotic and parabolic response curves

Parabolic response

When the economic yield is the part of the total dry matter or the reproductive parts, parabolic curve is used to describe plant population yield relationship. In this case also yield increases with increase in population, then reaches a maximum. However, unlike in asymptotic curve, yield decreases with further increase in population (Fig 2). Holiday (1960) suggested that the curve can be fitted to the quadratic equation

$$Y = a + bp + cp^2$$

Where Y is yield/area, p plant population and a, b and c are regression coefficients.

There is a drawback in representing plant population- yield response as a quadratic function. With increase in plant population, after reaching a maximum, yield does not fall suddenly. There is a plateau for some range of plant population. The extent of plateau depends on elasticity of plants. This aspect is not considered in the quadratic equation.

Square root function

The disadvantage of quadratic function can be overcome by square root function.

$$Y = a + bp + c\sqrt{p}$$

It is almost similar to quadratic function except that root of p is taken instead of square (Fig 3).

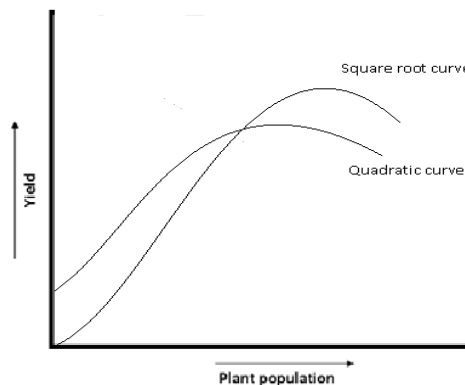


Fig 3 Square root and quadratic curves

Reciprocal functions

Reciprocal functions can also be used to express relation between population and yield. The increase of average yield of individual plant is directly related to plant density. In case of biological yield it is expressed as follows

$$\frac{1}{w} = a + bp$$

Where W is weight of individual plant, p population/area and a and b are constants.

To describe economic yield and plant density, the reciprocal equation is

$$\frac{1}{w} = a + bp + cp^2$$

Where a, b and c are constants.

Optimum plant population

Moderately dense stands or optimum plant population are necessary to obtain maximum yield. Optimum plant population depends on size of plant, elasticity, foraging area, nature of the plant, capacity to reach optimum leaf area at an early date and seed rate used.

Size of the plant

The spread or the volume occupied by the plant at the time of flowering has influence on the spacing to be adopted for these crops. Plants of sugarcane, redgram, cotton occupy larger space in the field compared to wheat, rice and sorghum. Even the varieties of the same crop differ in size of the plant. In redgram, LRG-30 grows to a height of 1.5-2.0 m with a horizontal spread of 1-1.5 m while the average height and spread of ICPL 87 is 70 and 30 cm, respectively.

Elasticity of the plant

Variation in size of plant between the minimum size of the plant that can produce some economic yield to the maximum size the plant can reach under unlimited space and resources is the elasticity of the plant. LRG 30 redgram can produce a few pods when the plant attains a minimum size of 20 g dry weight but it can attain a size to produce a dry weight of 2000 g per plant. Instead of the weight of the plant, it is more meaningful to consider elasticity in the number of branches and pods per plant. The elasticity of the plant for these characteristics can be estimated by coefficient of variation (CV). The higher the CV, more is the elasticity of the plants. The elasticity of redgram for branching and number of pods are 30 and 80%, respectively. Elasticity of growth and yield characters of plants are higher in indeterminate and long duration crops. The optimum plant population range is quite high for indeterminate crops. For the indeterminate redgram varieties, the optimum plant population ranges from 55 – 133 thousand plants/ha. The elasticity of plants is due to the branching or tillering. For determinate plants, the elasticity is less and optimum plant population range is small as in maize, sorghum. In castor closer spacing is followed in combination with nipping of the axillary buds to get uniform and early maturity. The removal of axillary buds reduces the elasticity of plants.

Soil cover

The crop should cover the soil as early as possible so as to intercept maximum sunlight. The intercepted solar radiation and dry matter production are directly related. Light energy is instantaneously available and it has to be instantaneously intercepted. Closely spaced soybean crop which attained 95% light interception within 54-55 days gave 26-32% higher yield compared to wider spaced crop.

Dry matter partitioning

Dry matter production is related to the amount of solar radiation intercepted by the canopy. As plant density increases, the canopy expands more rapidly, more radiation is intercepted and more dry matter produced, especially during early stages before the canopy closes (Fig 4).

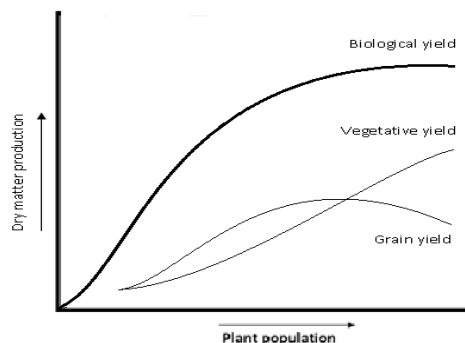


Fig 4. Relationship between plant population and dry matter production

Each plant must have certain amount of dry matter in vegetative tissue before any assimilate is allocated to fruiting structures. As density increases, the amount of dry matter in vegetative parts also increases. With regard to the biological yield, it increases with increases with increase in plant population upto a point and with further increase in plant population no additional biological yield can be obtained. Economic yield increases with increase in plant population upto a point and subsequently decreases with increase in population.

Optimum plant population and environment

Optimum plant population for any crop varies due to environment under which it is grown. It is not possible to recommend a generalized optimum plant population since the crop is grown in different seasons with different management practices.

Time of sowing

The crop is subjected to different weather conditions when sown at different periods. Among the weather factors, day length and temperature are the most important factors that influence optimum plant population. Photosensitive varieties respond to daylength resulting change in size of the plant. Red gram plant sown as winter crop will have half the size of those grown in monsoon season. Optimum plant population is 55000 plants/ha for monsoon which is increased to 3.33 lakh plants/ha for winter season crop. As low temperature retard the rate of growth, higher population is established for quicker ground cover. In sorghum, when the climate is favourable during pre-anthesis period, the optimum population is two lakh plants/ha and when it is not congenial for growth during pre-anthesis, it is four lakh plants/ha.

Irrigation

It is well known that plant population has to be less under rainfed conditions compared to irrigated conditions. However, it is applicable to crops grown on residual moisture and to some extent in seasons where prolonged dry spells between two rains occur. Under these conditions, evaporation is negligible as the surface soil is dry and transpiration is the main component in evapotranspiration (ET) and with higher population, transpiration is more resulting in stress in the last phase of the crop. Under higher plant densities, more water is lost through transpiration than through evaporation as soil temperature is less due to shading of plants. Under adequate irrigation or under evenly distributed rainfall conditions, higher plant population is recommended.

Fertilizer application

Dense plant stand is necessary to fully utilize higher level of nutrients in the soil to realize potential yields. Nutrient uptake increases with increase in plant population. Higher plant under low fertility conditions leads to development of nutrient deficiency symptoms. For example, rice does not respond to plant population without N application. With application of moderate dose of N (50 kg/ha), higher plant population gives more yield than lower plant population. However, by the application of higher dose of N (100 kg/ha), even moderate plant density also gives good yield due to its tillering nature. In non-tillering plants like maize, higher the fertility, more should be the plant population to get higher yield. Generally, close planting of the crop reduces weed infestation. But it creates problem of subsequent weeding operation with implements. Wider row spacing facilitates the use of inter-cultivation implements. Increasing plant population increases the proportion of ears or fruits in the upper layer of the canopy which facilitates ease in harvesting. Cotton sown with a closer spacing, produces mostly sympodial branches and most of the bolls appear in the top layer of canopy. Similarly, with higher population rice panicles appear in the upper layer of the canopy.

Planting pattern

Planting pattern influences crop yield through its influence on light interception, rooting pattern and moisture extraction pattern. Different planting patterns are followed to suit different weed control practices and cropping systems. Plant geometry refers to the shape of plant while crop geometry refers to the shape of space available for individual plants. Crop geometry is altered by changing inter- and intra-row spacing.

Square planting

It is reasonable to expect that square arrangement of plants will be more efficient in the utilization of light, water, and nutrients available to the individual plants than in a rectangular arrangements. In wheat decreasing inter-row spacing below the standard 15-12 cm i.e. reducing rectangularity, generally increases yield slightly. In crops like tobacco, inter-cultivation in both directions is possible in square planting and helps in effective control of weeds. However, square planting is not advantageous in all crops. Groundnut sown with a spacing of 30 x 10 cm (3.33 lakh plants/ha) give higher pod yield than with same amount of population in square planting. Pod yield is reduced either by increasing rectangularity or approaching towards square planting.

Rectangular planting

Sowing the crop with seed drill is the standard practice of stand establishment. Wider inter-row spacing and closer intra-row spacing is very common for most of the crops, thus attaining rectangularity. This rectangular arrangement is adopted mainly to facilitate intercultivation. Sometimes only inter-row spacing is maintained and intra-row spacing is not followed strictly and seeds are sown closely as solid rows.

Miscellaneous planting arrangements

Crops are sown with seed drills in two directions to accommodate more number of plants and mainly to reduce weed population. Crops like rice, finger millet are transplanted at the rate of 2-3 seedlings/hill. Transplanting is done either in rows or randomly. Skipping of every alternate row is known as skip row planting. When one row is skipped, and the population is adjusted by decreasing intra-row spacing, it is known as pared row planting. It is generally resorted to introduce an intercrop.

Concept of ideal plant type

The production of every plant is affected by the plant's type, climatic condition, soil type and management factors. The production of the plant might be increased by changing plant type and increasing the period of grain filling in a certain climatic condition where management and soil factors are not limited. There is a direct relationship between the plant's type and crop yield because the orientation and number of leaves play an important role in carbon fixation (photosynthesis).

In recent years due to all round efforts of agricultural scientists it has been possible to cultivate HYVs of cereal crops which are often been termed as "NEW PLANT TYPES".

1. **IDEOTYPE:** refers to plant type in which morphological and physiological characteristics are ideally suited to achieve high production potential and yield reliability. The concept of ideotype was given by Donald in 1968. He illustrated that there should be minimum competition between the crops and crop must be competent to compete with weeds. The single plant would give the better result in a group when the crop has at least competition with the same type of the crop. Ideotype is the model type which may also be defined as "a biological model which is expected to perform or behave in a predictable manner within a defined environment". On the basis of environment Donald and Hamblin (1976) identified two forms of ideotypes i.e. isolation ideotypes and competition ideotypes. Competition ideotypes are suitable for mixed cultivation.
2. NPT's are also called as **fertilizer responsive** varieties since these NPTs possess the trait of high responsiveness towards heavy fertilizer applications.
3. NPT's are also termed as adaptable varieties means the physiological attributes of variety responsible for
 - a) Controlling the assimilation of absorbed N in plant body.
 - b) Translocation and storage of photosynthetic products.
 - c) Possessing more activity of roots under heavy application of fertilizers.
 - d) Availability of resistance to lodging and diseases.

But, the term NPT seems to be more appropriate and reasonable as it can very easily express the extent of improvement incorporated over the old type varieties.

The so called improved tall varieties cultivated by farmers generally grow very tall and possess low yielding potentiality due to

1. Weak and tall straw, susceptible to lodging under heavy fertilizer application.
2. Inefficient leaf arrangement responsible for poor photosynthetic activity and less utilization of Solar energy.
3. Many associated attributes like unsynchronized susceptibility towards the attack of pests and diseases.

NPT's do not possess these defects and have been further improved to increase their production efficiency where the morphological frame work has been genetically linked with other yield contributing characters. Recent developments in plant breeding made significant contribution towards concept of NPTs. The successful efforts of altering the morphological architecture of crop plants and making them suitable for cultivation under high fertility status of soils have opened a new VISTA in developing the varieties suitable for good agronomy.

CHARACTERS OF NPT's: They should be

1. Morphologically be dwarf in growth habit with hard and stiff straw.
2. Erect and dark green leaves remaining active for longer duration.
3. Agronomically highly responsive to heavy fertilizer application.
4. Physiologically be well equipped for more dry matter production and high yields.
5. Adaptable under different agro climatic conditions and of short growing duration.

Example : NPT's made in wheat, rice, jowar, bajra and maize.

Important features of such NPT's of cereals in grain crops are:

1. **DWARFNESS:** NPT's are dwarf in nature due to **NORIN** in wheat and **DEE-GEE-WOO-GEN** in rice dwarf genes. NPT's are short, stiff, not more than knee high but could take more fertilizers without lodging.
2. **EFFICIENT LEAF ARRANGEMENT:** NPTs are narrow, thick, erect and dark green color with optimum LAI composed of properly arranged leaves, which remain active for longer period after flowering due to high sunlight interception they play important role in supporting grain formation resulting into more number of fertile grains per ear head.
3. **SYNCHRONOUS TILLERING:** The growth and development of NPTs are more or less rhythmic i.e., high germination %, formation of all tillers at a time (during a specific period) and timely maturity of all the tillers. So, they have highest synchronized coefficient as regards to the development and maturity of grains of different

ears of a plant. Synchronization of tillering has been found to be dependent on other factors like moisture, proper secondary regrowth and adequate nutrient availability during the period.

4. **LOW FLORET STERILITY:** Traditional tall varieties under heavy fertilizer application produce more sterile florets. NPT's have a very low floret sterility % due to synchronized tillering into uniform ear head formation supported by longer physiological activity of leaves at maturity. Low floret sterility in NPT's has also been attributed due to increased activities of roots at grain formation stage.
5. **SHORTER GROWTH DURATION:** NPT's have shorter duration than tall varieties. The optimum growth duration of a variety is more important for scheduling its irrigation and manuring for obtaining higher yield. At High N application longer growth duration and at low N application, short duration variety is preferred for obtaining higher dry matter production as well as more grain production efficiency i.e., grain yield/unit area/unit time. These short duration varieties can fit very well in under high cropping intensity programmes like multiple and relay cropping.
6. **ADAPTABILITY TO DIFFERENT CROP SEASONS:** All most all NPT's are photo insensitive and completely resistant to fluctuations in day length. They can be grown under all crop seasons provided inputs like fertilizers and irrigations are adequately made available, so higher yields can be obtained. However, some of the NPTs are thermo-sensitive and are affected by variation in temperature during season.
7. **ABSENCE OF SEED DORMANCY:** NPTs have no dormancy i.e. they do not require any rest period, called dormancy period. Freshly harvested seed can be used for sowing. This character is useful in seed multiplication programmes of HYVs, within a short span of time. This along with photo insensitivity makes them quite suitable for adaptation under high intensity cropping programmes.
8. **EFFECTIVE TRANSLOCATION OF FOOD MATERIAL FROM PLANTS TO GRAIN:** NPTs have higher potentiality to absorb and assimilate nutrient from soil throughout the growth duration which in combination with higher photosynthetic activities enable them for higher dry matter production. The built in efficient plant mechanism in NPT's coupled with fewer organs respiring at flowering stage permit more efficient use of respiration for growth and grain production. After flowering, this enables effective translocation of accumulated food materials of straw for grain formation.
9. **RESPONSIVE TO HEAVY FERTILISER APPLICATIONS:** NPT's possess the trait of high responsiveness towards fertilizer application. Their optimum N requirement is 2½ -3 times more than the requirement is so called improved local varieties. Similarly the P&K requirement of NPT's is also 1½ -2 times more in comparison to local types. Under low fertility status, their yielding ability is not fully utilized and very often they give quiet poor yield under sub optimum conditions, it is therefore necessary to supply adequate quantities of N, P&K in order to exploit their high yielding potentiality to the maximum. Research results (AICRP) revealed that on an average, NPT's require about 100-120 kg N, 50-70 kg P₂O₅ and 40-60 kg K₂O/ha under optimum conditions of soil moisture status.
10. **LODGING RESISTANCE:** NPT's are generally dwarf in growth habit with strong and stiff stem which provides them considerable resistance against plant lodging. Under heavy fertilizer applications, the tall varieties are bound to lodge resulting in substantial decrease in yield. Contrary to this, dwarf HY NPT's seldom lodge unless too heavy fertilizer application has been made coinciding with excessive water application. Because of incorporation of dwarfing genes in NPT's, they possess the trait of high responsiveness towards heavy fertilizer application without lodging.
11. **YIELDING POTENTIALITY:** The NPT's are known for their HY potential. NPT's are capable of yielding 2-3 times more grain yield in comparison to local tall improved types. This is probably due to their altered morphology which results into efficient utilization of water, nutrients and radiation and increased metabolic activities with high dry matter production. Their grain to straw ratio is approximately about 1:1. However, these strains are more susceptible to any degree of variation in manageable inputs. Inadequate and untimely supply of nutrients, irrigation and plant protection measures may result into partial or complete failure of crop.
12. **DISEASE SUSCEPTIBILITY:** The only drawback associated with NPT's is the disease susceptibility with luxuriant vegetative growth; the varieties offer scope for insect pests and diseases. However, attempts are being made to develop disease resistant NPT's.
 eg : Rice ----- BPH resistant varieties ----- MTU-2067, MTU-2077 and MTU-4870.
 Gall midge " ----- Pothana, Kakatiya, Phalguna.
 Wheat ----- Rust resistant varieties ----- Sonalika.
 Sorghum ---Striga resistant varieties -----N-13, SPV-462.

Ideotypes for some crops/situation

Wheat

According to Donald (1968), the ideotype for wheat crop has following features-

1. Short strong stem to avoid lodging.
2. Few small erect leaves to allow the sunshine into its canopy.
3. A large erect ear.
4. More number of fertile florets per unit area therefore more harvest index.
5. Presence of awns to increase the photosynthesis area.
6. A single culm to avoid wasteful vegetative growth.
7. Resistance to insect-pest and diseases.
8. Proper partitioning and translocation of assimilates.

Maize

The plants have erect upper leaves and the lower leaves gradually become horizontal to allow the sunshine into its canopy and for proper movement of air into the field. The height of the plant is to be 1.5 m in which cobs may be produced on the nodes near the tassel.

Gram

Pande and Saxena (1973) proposed the ideotype for gram having following features-

1. The vegetative growth must be stopped before the starting of reproductive stage.
2. The plant should have erect branching. (In the prevalent varieties of gram, the spreading and branching of its canopy is just like umbrella which interfere to penetrate the sunshine into its canopy causing humid conditions favourable for insect-pest and diseases).
3. To harness the long photoperiod and favourable temperature at the time of flowering, there should be 2-3 longer pods in the leaf axis and 2-3 seeds in each pod.

Arhar

The growth of arhar varieties in the beginning is too less i.e. in the first two months only one or two branches are come out. Therefore, arhar is unable to harness the solar energy properly in the first two months. The flower's drop is also a major problem. the filling of pods according to Hydro-dynamic model sets up the competition between vegetative and reproductive phases. considering all the views Pande and Saxena suggested ideotypes having following features-

1. The fast growth of plant's canopy at least in the beginning.
2. The reproductive phase starts after the closure of vegetative growth.
3. Long floral axis having 2-3 flowers in each trifoliate axis.
4. Synchronized flowering.
5. Active root nodules for the long time.
6. Resistance to insect-pest and diseases.

Rainfed upland rice

1. Short growth duration (85-100 days).
2. Effective deep root system.
3. Dwarf plant (<100 cm) with erect leaves and thick stem.
4. Early strong fertile tillering.
5. Synchronized flowering.
6. Good number of panicles (about 400/m²).
7. Higher number of grains per panicle.
8. Moderate seed dormancy.
9. Resistance to insect-pest and diseases.

Rainfed wheat

1. Large number of spikelets.
2. Large peduncle
3. Strong and deep root system.
4. Flat leaves parallel to soil and
5. A grain development period coinciding with mean max temperature of 25 °C.

Ideotype for Dryland Farming

1. Short growth duration.
2. Effective root system.
3. Drought tolerance.
4. High yield potential with altered morphology viz.
 - a. Plant with few leaves just sufficient to maintain photosynthetic output and growth (to minimize the use of water).
 - b. Leaves horizontally disposed for better light interception contrary to vertically disposed under irrigated conditions.

Crop modeling for desired crop yield

Agricultural models are mathematical equations that represent the reactions that occur within the plant and the interactions between the plant and its environment. Owing to the complexity of the system and the incomplete status of present knowledge, it becomes impossible to completely represent the system in mathematical terms and hence, agricultural models images of the reality. Unlike in the fields of physics and engineering, universal models do not exist within the agricultural sector. Models are built for specific purposes and the level of complexity is accordingly adopted. Inevitably, different models are built for different subsystems and several models may be built to simulate a particular crop or a particular aspect of the production system.

Features of crop models

The main aim of constructing crop models is to obtain an estimate of the harvestable (economic) yield. According to the amount of data and knowledge that is available within a particular field, models with different levels of complexity are developed. The most pertinent aspects of crop models are described below.

Empirical model

Empirical models are direct descriptions of observed data and are generally expressed as regression equations (with one or a few factors) and are used to estimate the final yield. Examples of such models include the response of crop yield to fertilizer application, the relationship between leaf area and leaf size in a given plant species. The limitation of this model site specific, it cannot use universally.

Mechanistic model

A mechanistic model is one that describes the behaviour of the system in terms of lower-level attributes. Hence, there is some mechanism, understanding or explanation at the lower levels. These models have the ability to mimic relevant physical, chemical or biological processes and to describe how and why a particular response results.

Static and dynamic models

A static model is one that does not contain time as a variable even if the end-products of cropping systems are accumulated over time, e.g., the empirical models. In contrast dynamic models explicitly incorporate time as a variable and most dynamic models are first expressed as differential equations:

Deterministic and stochastic models

A deterministic model is one that makes definite predictions for quantities (e.g., animal live weight, crop yield or rainfall) without any associated probability distribution, variance, or random element. However, variations due to inaccuracies in recorded data and to heterogeneity in the material being dealt with, are inherent to biological and agricultural systems. In certain cases, deterministic models may be adequate despite these inherent variations but in others they might prove to be unsatisfactory e.g. in rainfall prediction. The greater the uncertainty in the system, the more inadequate deterministic models becomes and in contrast to this stochastic models appears.

Simulation and optimizing models

Simulation models form a group of models that is designed for the purpose of imitating the behaviour of a system. They are mechanistic and in the majority of cases they are deterministic. Since they are designed to mimic the system at short time intervals (daily time-step), the aspect of variability related to daily change in weather and soil conditions is integrated. The short simulation time-step demands that a large amount of input data (climate parameters, soil characteristics and crop parameters) be available for the model to run. These models usually offer the possibility of specifying management options and they can be used to investigate a wide range of management strategies at low costs. Most crop models that are used to estimate crop yield fall within this category.

Optimizing models have the specific objective of devising the best option in terms of management inputs for practical operation of the system. For deriving solutions, they use decision rules that are consistent with some optimising algorithm. This forces some rigidity into their structure resulting in restrictions in representing stochastic and dynamic aspects of agricultural systems. Linear and non-linear programming were used initially at farm level for enterprise selection and resource allocation. Later, applications to assess long-term adjustments in agriculture, regional competition, transportation studies, integrated production and distribution systems as well as policy issues in the adoption of technology, industry re-

structuring and natural resources have been developed. Optimising models do not allow the incorporation of many biological details and may be poor representations of reality. Using the simulation approach to identify a restricted set of management options that are then evaluated with the optimising models has been reported as a useful option.

Some crop models reported in recent literature

Software	Details
SLAM II	Forage harvesting operation
SPICE	Whole plant water flow
REALSOY	Soyabean
MODVEX	Model development and validation system
IRRIGATE	Irrigation scheduling model
COTTAM	Cotton
APSIM	Modelling framework for a range of crops
GWM	General weed model in row crops
MPTGro	Acacia spp.and Leucaena Spp.
GOSSYM-COMAX	Cotton
CropSys	Wheat & other crops
SIMCOM	Crop (CERES crop modules) & economics
LUPINMOD	Lupin
TUBERPRO	Potato & disease
SIMPOTATO	Potato
WOFOST	Wheat & maize, Water and nutrient
WAVE	Water and agrochemicals
SUCROS	Crop models
ORYZA1	Rice, water
SIMRIW	Rice, water
SIMCOY	Corn
CERES-Rice	Rice, water
GRAZPLAN	Pasture, water, lamb
EPIC	Erosion Productivity Impact Calculator
CERES	Series of crop simulation models
DSSAT	Framework of crop simulation models including modules of CERES, CROPGRO and CROPSIM
PERFECT	
QCANE	Sugarcane, potential conditions
AUSCANE	Sugarcane, potential & water stress conds., erosion
CANEGRO	Sugarcane, potential & water stress conds
APSIM-Sugarcane	Sugarcane, potential growth, water and nitrogen stress
NTKenaf	Kenaf, potential growth, water stress

MODEL DEVELOPMENT

Strength

The strengths of models in general include the abilities to:

- Provide a framework for understanding a system and for investigating how manipulating it affects its various components
- Evaluate long-term impact of particular interventions
- Provide an analysis of the risks involved in adopting a particular strategy
- Provide answers quicker and more cheaply than is possible with traditional experimentation

Model calibration

Calibration is adjustment of the system parameters so that simulation results reach a predetermined level, usually that of an observation. In many instances, even if a model is based on observed data, simulated values do not exactly comply with the observed data and minor adjustments have to be made for some parameters.

Model validation

The model validation stage involves the confirmation that the calibrated model closely represents the real situation. The procedure consists of a comparison of simulated output and observed data that have not been previously used in the calibration stage. Ideally, all mechanistic models should be validated both at the level of overall system output and at the

level of internal components and processes. The latter is an important aspect because due to the occurrence of feedback loops in biological systems, good prediction of system's overall output could be attributed to compensating internal errors. However, validation of all the components is not possible due to lack of detailed datasets and the option of validating only the determinant ones is adopted. For example, in a soil-water-crop model, it is important to validate the extractable water and leaf area components since biomass accumulated is heavily dependent on these.

The methodology of model validation is still rudimentary. The main reason is that, unlike the case of disciplinary experiments, a large set of hypotheses is being tested simultaneously in a model. Furthermore, biological and agricultural models are reflections of systems for which the behavior of some components is not fully understood and differences between model output and real systems cannot be fully accounted for.

The validation of system simulation models at present is further complicated by the fact that field data are rarely so definite that validation can be conclusive. This results from the fact that model parameters and driving variables are derived from site-specific situations that ideally should be measurable and available. However, in practice, plant, soil and meteorological data are rarely precise and may come from nearby sites. At times, parameters that were not routinely measured may turn out to be important and they are then arbitrarily estimated. Measured parameters also vary due to inherent soil heterogeneity over relatively small distances and to variations arising from the effects of husbandry practices on soil properties. Crop data reflect soil heterogeneity as well as variation in environmental factors over the growing period. Finally, sampling errors also contribute to inaccuracies in the observed data. Validation procedures involve both qualitative and quantitative comparisons. Before starting the quantitative tests, it is advisable to qualitatively assess time-trends of simulated and observed data for both internal variables and systems outputs.

Inadequate predictions of model outputs may require "re-fitting" of the regression curves or fine-tuning of one or more internal variables. This exercise should be undertaken with care because arbitrary changes may lead to changes in model structure that may limit the use of the model as a predictive tool. In some cases, it is best to seek more reliable data through further experimentation than embarking on extensive modification of model parameters to achieve an acceptable fit to doubtful data. This decision relies on the modeller's expertise and rigour as well as on human resources and time available to invest in fine-tuning model predictions.

MODEL USES AND LIMITATIONS

Models are developed by agricultural scientists but the user-group includes the latter as well as breeders, agronomists, extension workers, policy-makers and farmers. As different users possess varying degrees of expertise in the modelling field, misuse of models may occur. Since crop models are not universal, the user has to choose the most appropriate model according to his objectives. Even when a judicious choice is made, it is important that aspects of model limitations be borne in mind such that modelling studies are put in the proper perspective and successful applications are achieved.

Misperceptions and limitations of models

Agricultural systems are characterised by high levels of interaction between the components that are not completely understood. Models are, therefore, crude representations of reality. Wherever knowledge is lacking, the modeller usually adopts a simplified equation to describe an extensive subsystem. Simplifications are adopted according to the model purpose and / or the developer's views, and therefore constitute some degree of subjectivity. Models that do not result from strong interdisciplinary collaboration are often good in the area of the developer's expertise but are weak in other areas. Model quality is related to the quality of scientific data used in model development, calibration and validation.

When a model is applied in a new situation (e.g., switching a new variety), the calibration and validation steps are crucial for correct simulations. The need for model verification arises because all processes are not fully understood and even the best mechanistic model still contains some empiricism making parameter adjustments vital in a new situation. Model performance is limited to the quality of input data. It is common in cropping systems to have large volumes of data relating to the above-ground crop growth and development, but data relating to root growth and soil characteristics are generally not as extensive. Using approximations may lead to erroneous results.

Most simulation models require that meteorological data be reliable and complete. Meteorological sites may not fully represent the weather at a chosen location. In some cases, data may be available for only one (usually rainfall) or a few (rainfall and temperature) parameters but data for solar radiation, which is important in the estimation of photosynthesis and biomass accumulation, may not be available. In such cases, the user would rely on generated data. At times, records may be incomplete and gaps have to be filled. Using approximations would have an impact on model performance.

Model users need to understand the structure of the chosen model, its assumptions, its limitations and its requirements before any application is initiated, e.g. using a model like QCANE, developed for cane growth under non-limiting conditions, would lead to erroneous output and analysis if it is used to simulate under water or nitrogen stress conditions. At times, model developers may raise the expectations of model users beyond model capabilities. Users, therefore, need to judiciously assess model capabilities and limitations before it is adopted for application and decision-making purposes. Generally, crop models are developed by crop scientists and if interdisciplinary collaboration is not strong, the coding may not be well-structured and model documentation may be poor. This makes alteration and adaptation to simulate new situations difficult, specially for users with limited expertise. Finally, using a model for an objective for which it had not been designed or using a model in a situation that is drastically different from that for which it had been developed would lead to model failure.

Model uses

The above points may give the impression that crop modelling has a bleak future but recent literature confirms the contrary. Simulation modelling is increasingly being applied in research, teaching, farm and resource management, policy analysis and production forecasts. These model can be applied into three areas, namely, research tools, crop system management tools, and policy analysis tools. A summary of some specific applications within the different groups follows:

As research tools

Research understanding: Model development ensures the integration of research understanding acquired through discreet disciplinary research and allows the identification of the major factors that drive the system and can highlight areas where knowledge is insufficient. Thus, adopting a modelling approach could contribute towards more targeted and efficient research planning. For example, changing the plant density in a sugar beet model resulted in model failure. This failure stimulated studies that gave additional information concerning biomass partitioning in the sugar beet.

Integration of knowledge across disciplines: Adoption of a modular approach in model coding allows the scientist to pursue his discipline-oriented research in an independent manner and at a later stage to integrate the acquired knowledge into a model. For example, the modular aspect of the APSIM software allows the integration of knowledge across crops as well as across disciplines for a particular crop. Adoption of a modular framework also allows for the integration of basic research that is carried out in different regions, countries and continents. This ensures a reduction of research costs (e.g., through a reduction in duplication of research) as well as the collaboration between researchers at an international level.

Improvement in experiment documentation and data organization: Simulation model development, testing and application demand the use of a large amount of technical and observational data supplied in given units and in a particular order. Data handling forces the modeller to resort to formal data organisation and database systems. The systematic organisation of data enhances the efficiency of data manipulation in other research areas (e.g., productivity analysis, change in soil fertility status over time)

Genetic improvement: As simulation models become more detailed and mechanistic, they can mimic the system more closely. More precise information can be obtained regarding the impact of different genetic traits on economic yields and these can be integrated in genetic improvement programs, e.g., the NTKenaf model. Researchers used the modelling approach to design crop ideotypes for specific environments.

Yield analysis: When a model with a sound physiological background is adopted, it is possible to extrapolate to other environments. The use of several simulation models to assess climatically-determined yield in various crops . The CANEGRO model has been used along the same lines in the South African sugar industry. Through the modelling approach, quantification of yield reductions caused by non-climatic causes (e.g., delayed sowing, soil fertility, pests and diseases) becomes possible. Almost all simulation models have been used for such purposes. Simulation models have also been reported as useful in separating yield gain into components due to changing weather trends, genetic improvements and improved technology.

As crop system management tools

Cultural and input management: Management decisions regarding cultural practices and inputs have a major impact on yield. Simulation models, that allow the specification of management options, offer a relatively inexpensive means of evaluating a large number of strategies that would rapidly become too expensive if the traditional experimentation approach were to be adopted. Many publications are available describing the use of simulation models with respect to cultural management (planting and harvest date, irrigation, spacing, selection of variety type) and input application (water and fertiliser).

Risks assessment and investment support: Using a combination of simulated yields and gross margins, economic risks and weather-related variability can be assessed. These data can then be used as an investment decision support tool.

Site-specific farming: Profit maximisation may be achieved by managing farms as sets of sub-units and providing the required inputs at the optimum level to match variation in soil properties across the farm. Such an endeavour is attainable by coupling simulation models with geographic information systems (GIS) to produce maps of predicted yield over the farm. But, one of the prerequisites is a systematic characterization of units that may prove costly.

As policy analysis tools

Best management practices: Models having chemical leaching or erosion components can be used to determine the best practices over the long-term. The EPIC model has been used to evaluate erosion risks due to cropping practices and tillage.

Yield forecasting: Yield forecasting for industries over large areas is important to the producer (harvesting and transport), the processing agent (milling period) as well as the marketing agency. The technique uses weather records together with forecast data to estimate yield across the industry.

Introduction of a new crop: Agricultural research is linked to the prevailing cropping system in a particular region. Hence, data concerning the growth and development of a new crop in that region would be lacking. Developing a simulation model based on scientific data collected elsewhere and a few datasets collected in the new environment helps in the assessment of temporal variability in yield using long-term climatic data. Running the simulations with meteorological data in a balanced network of locations also helps in locating the industry.

Global climate change and crop production: Increased levels of CO₂ and other greenhouse gases are contributing to global warming with associated changes in rainfall pattern. Assessing the effects of these changes on crop yield is important at the producer as well as at the government level for planning purposes.

UNIT IV

Scientific principles of crop production; seed production techniques in various crops; crop response production functions; concept of soil plant relations; yield and environmental stress

Scientific principles of crop production

Crop production is the conversion of environmental inputs like solar energy, carbon dioxide, water and nutrients in soil to economic products in the form of human or animal food or industrial raw materials. Goals of crop production are achieved through principles of Agronomy, Agronomy is derived from the greek words *Agros* meaning field and *nomos* meaning manage. It is branch of agricultural science which deals with principles and practices of soil, water, and crop management. Agronomy deals with methods which provide favourable environment to higher crop productivity. According to Norman (1980) it is a science of manipulating the crop environment complex with dual aims of improving productivity and gaining a degree of understanding of the process involved. The recent definition of agronomy is the successful, sustainable, profitable, nutritionally secured, efficient crop production with least or no environmental degradation.

Agriculture is a science of farming. Scientific principles are employed to find ways of making it as efficient possible. Through scientific principles plants and animals are transformed genetically and most favorable environment is provided to harvest higher yields of good quality with least expense of energy. The scientific principles of various branches viz. soil science, genetics and plant breeding, entomology, plant pathology, microbiology, agricultural engineering etc. were employed in agriculture. Agriculture like any other science is a body of truths synthesized, systematized and arranged in such a way as to show the operation of general laws and principles.

Agriculture is an art which embraces knowledge of the way to perform the operation of a farm in a skillful manner. The physical and mental skills are involved in agriculture. The skills may be acquired through years of experience viz. ploughing, stacking hay bundles, handling animals, sowing, transplanting, driving a tractor etc. Mental skills are those involved in decision making for example when to plough the land, selection of appropriate crops, seed selection etc. Agriculture is a business: agriculture is no longer a way of living or subsistence agriculture where production is intended to meet the home requirements. Agriculture is intended to earn more income. Land, labour, capital are judiciously used. Like in any industry the farming industry should forecast the demand, tailor the production with demand to earn more profits. It involves processing, value addition, transportation, packing, storage in scientific way. Knowledge of employee and employer relationship or human resource management, export and imports, taxation, customs, tariffs and trade are required. All these aspects demand business knowledge in addition to the production and managerial skills. Traditional agriculture is no longer relevant for success in agriculture. Commercial Agriculture or Corporate Farming, Agri-Business Development Corporations demand entrepreneurs in agriculture rather than technologists alone.

Producers aim to ensure that the safety and quality of their products will satisfy the highest expectations of the food industry and consumers. In addition, on-farm practices should ensure that crops are produced under sustainable economic, social and environmental conditions.

Good management of a cropping/farming system constitutes the grassroots of the system's economic, environmental and social sustainability. Therefore, it first pays attention to planning and managing well the overall farm system itself.

Farmers shall have taken into consideration applying the principles and practices to the whole farm system within a philosophy of continuous improvement, starting with the crop or livestock in scope. The following headings and bullets summarize the sections and objectives when applied to a whole farm system.

Sustainable Farming Systems

- Are varieties suited to the local climate, soil, pests & diseases being grown?
- Nutrients – how is crop nutrition calculated? How are nutrients stored considering environmental/safety risks?
- Pest management – Are all key pests known? Is IPM applied? Are pesticides stored safely & securely?

Economic sustainability

- Is yield increase possible? Is food safety and food quality understood? Is the farm system diverse enough? Is there access to market information?

- Is group use of equipment or group purchasing an option?

Social Sustainability

- Social & Human capital – including farm workers – Are workers treated fairly? Is training a priority?
- Local community /economy - Is there a positive impact in the local community from the farm system?

Environmental sustainability

- Soil fertility/soil loss – how is soil fertility maintained, is soil erosion an issue?
- Water – Is total water use for irrigation known? How is irrigation amount calculated? Is the water source for irrigation sustainable? Are the impacts of fertilisers and pesticides considered?
- Biodiversity – Are there natural habitats on farm? Are rare species of plant/animal threatened by growing the crop?
- Energy – Are the major energy inputs known? How can their impact on climate change be reduced?
- Waste – Are the principles reduce, reuse, recycle, dispose understood? Are pesticides/fertilisers disposed of safely?

Sustainable Farming System

Sustainable agriculture seeks, at least in principle, to use nature as the model for designing agricultural systems. Since nature consistently integrates her plants and animals into a diverse landscape, a major tenet of sustainable agriculture is to create and maintain diversity. Nature is also efficient. There are no waste products in nature. Outputs from one organism become inputs for another. One organism dies and becomes food for other organisms. Since we are modeling nature, let us first look at some of the principles by which nature functions. By understanding these principles we can use them to reduce costs and increase profitability, while at the same time sustaining our land resource base.

Diversity is nature's design

When early humans replaced hunting and gathering of food with domestication of crops and animals, the landscape changed accordingly. By producing a limited selection of crop plants and animals, humankind has greatly reduced the level of biological diversity over much of the earth. Annual crop monocultures represent a classic example. In response to this biological simplification, nature has struggled to restore diversity to these landscapes—that is her tendency. Our “war” with nature over the tendency to diversity is what we call “weed control” and “pest management.” Of course we could hardly produce any crops if we simply allowed our fields to return to natural vegetation, but we can realize some of the benefits of diversity by planting mixtures of different crops.

Cooperation is more apparent than competition

There is far more cooperation in nature than competition. Cooperation is typified by mutually beneficial relationships that occur between species within communities. In *The Redesigned Forest*, ecologist Chris Maser offers a glimpse of the cooperation inherent in a northern temperate forest when he describes a relationship that exists among squirrels, fungi, and trees. The squirrels feed on the fungus, then assist in its reproduction by dropping fecal pellets containing viable fungal spores onto the forest floor. There new fungal colonies establish. Tree feeder roots search out the fungi and form a symbiotic association that enables the tree roots to increase their nutrient uptake. The fungi, in turn, derive food from the tree roots. Each benefits from the other's presence or actions.

If we view competition as the driving force in nature, we fail to see the complex relationships and feel compelled to take actions that may have unforeseen impacts. The rancher who views coyotes as competitors (for calves and lambs) and kills them out may later find the predator helped keep rodent populations in check. With the predator gone, rodent numbers explode and cause more problems than ever before. The same is true with many insect pests of crops. When the only food for insects is crops, that is what they will eat. With no predator or parasite habitat present in a pure stand of crop, the pest insect could not possibly have it better. If we can shift our view of nature from a theme of competition to one of collaboration, we can act in ways that yield fewer negative consequences.

Stability tends to increase with increasing diversity

If left undisturbed and unplanted, an abandoned crop field will first be colonized by just a few species of plants, insects, bacteria, and fungi. After several years, a complex community made up of many wild species develops. Once a wild plant and animal community has reached a high level of diversity, it remains stable for many years.

When wild communities are in the early stages of development, or when they have lost diversity due to natural catastrophe or human actions, they are prone to major fluctuations, both in types of species present and in their numbers. Disease outbreaks in

plants and animals occur more frequently—as do outbreaks of weed, insect, bird, or rodent pests. One good example is the grasshopper plagues that follow regional weather shifts. Another is the shift in weed species dominance following a soil disturbance.

The more complex and diverse communities become, the fewer the fluctuations in numbers of a given species, and the more stable communities tend to be. As the number of species increases, so does the web of interdependencies. In both higher and lower rainfall years, there are fewer increases in any one species and fewer fluctuations in the community as a whole.

Pursuing Diversity on the Farm

So, then, how can we begin to model our agricultural pursuits after some of these natural principles? Can we look for patterns in nature and imitate them? Some pioneering farmers have been able to utilize nature’s principle of diversity to their advantage. Results of their efforts include lower cost of production and higher profits. Among the practices that promote diversity and stability are:

Enterprise diversification—Risk reduction through stability of income and yield are two of the reasons people diversify their crop and live- stock systems. Increasing diversity on-farm also reduces costs of pest control and fertilizer, because these costs can be spread out over several crop or animal enterprises.

Crop Rotation — Moving from simple monoculture to a higher level of diversity begins with viable crop rotations, which break weed and pest life cycles and provide complementary fertilization to crops in sequence with each other.

Farmscaping—Diversity can be increased by providing more habitat for beneficial organisms, habitats such as borders, windbreaks, and special plantings for natural enemies of pests.

Intercropping—Intercropping is the growing of two or more crops in proximity to promote interaction between them. Much of this publication focuses on the principles and strategies of intercropping field crops.

Integration—On-farm diversity can be carried to an even higher level by integrating animals with intercropping. With each increase in the level of diversity comes an increase in stability.

The diversity created by intercropping can be enhanced even further by integrating livestock (single or mixed species) into the cropping plan as harvesters. Grazing animals and other livestock can be managed on croplands to reduce costs, increase income, and increase diversity. There are ways of incorporating animals into cropping without the farmer getting into animal husbandry or ownership directly. Collaboration with neighbors who own animals will benefit both croppers and livestock owners. Grazing or hogging-off of corn residue is one example where a cost can be turned into a profit.

Item	Principles	Recommended Practices
Site selection and management	When planning and managing the farm activities, be aware of the site history (previous land use).	A risk assessment shall be undertaken for new production sites considering the following: <ul style="list-style-type: none"> <input type="checkbox"/> Taking into account the prior use of land e.g. historical/archaeological remains, any soil pollution issues or land change from forest to agricultural land, availability and quality of water resources, pest disease and weed levels and the potential impact of the production on adjacent crops and the adjacent area. <input type="checkbox"/> Sites should be checked against any off site contaminant (e.g. invasive species) or pollution risk and protected against those through adequate buffer zones when necessary.
	When planning and managing the farm activities, properly take into account the site specificities (such as topography, neighboring activities, ecological and social conditions).	A risk assessment shall be undertaken for on site/off-site impacts considering the following: <ul style="list-style-type: none"> <input type="checkbox"/> Soil erosion (storm events or dust from cultivation), water pollution (soil, from storing or applying nutrients, or pesticides or storage of fuel or waste storage/disposal), pesticide drift, natural habitat destruction, archaeological sites, tourist sites, hunting/poisoning or rare/endangered species, worker welfare, health & safety at work, food safety.
Sustainability management system	Maintain a functioning sustainability system on the farm, geared towards continuous improvement.	Records (Records belong to the farmers and shall only be disclosed with their approval.) <ul style="list-style-type: none"> <input type="checkbox"/> Reliable information on the following shall be recorded: <ul style="list-style-type: none"> - Yield - Varieties grown - Fertilisers applied, pesticides applied, irrigation applied - Gross Margin (if feasible) - Soil analysis <input type="checkbox"/> Reliable information on the following should be recorded:

		<ul style="list-style-type: none"> - Biodiversity - Techniques used - Energy use <p>Reviewing results</p> <ul style="list-style-type: none"> <input type="checkbox"/> Existing records and practices shall be examined critically by the farmer in order to improve the overall sustainability of the farm. <input type="checkbox"/> The farmer shall ensure that the all people working on the farm are aware of the relevance of their specific responsibilities and contribution to the economic, social and environmental sustainability of the farm. (see also 3.3 Training).
	Record reliable information on farm inputs and techniques used on the farm.	<ul style="list-style-type: none"> <input type="checkbox"/> Reliable information on the following shall be recorded: <ul style="list-style-type: none"> - Varieties grown - Fertilisers applied, pesticides applied, irrigation applied - Soil analysis - Techniques used - Energy use
	Take the opportunity of accessing valuable information and support services to continuously improve the farm overall sustainability.	<ul style="list-style-type: none"> <input type="checkbox"/> Regular advice shall be sought by farmers on a variety of issues, including: <ul style="list-style-type: none"> - How to get access to improved arable and vegetable production technologies, tools and best practices - How to access and use instruments and tools (e.g. financial planning) for improved financial management - Information about the market, sales and production of the product in order to better meet market requirements, and tools to optimise his/her economic return. <input type="checkbox"/> When sought, advice and information should be taken from reliable sources, e.g. qualified agronomists, training courses, farming magazines, and/or suitable internet sites.
Planting material	Consider the farm's structure & local situation when choosing planting material.	<p>Variety choice and use shall consider the following:</p> <ul style="list-style-type: none"> <input type="checkbox"/> Resistance or tolerance to commercially important pests and diseases, adapted to local conditions and meet customers specified requirements <input type="checkbox"/> Growing of any genetically modified plants for consumption must comply with all the regulations in place for both countries of production and consumption, and checked if they are accepted by direct customers and consumers.. <input type="checkbox"/> Varieties are planted at the optimal time of the season. <input type="checkbox"/> Invasive species should not be planted <input type="checkbox"/> Seed/Tubers/bulbs are true to type and the quality is checked before use and is traceable to source. <input type="checkbox"/> Records are kept of the variety name, batch number and seed vendor.
Integrated crop management	Use rotation practices for annual crops as an important tool of integrated crop management and as a diversified source of income for the farm.	<ul style="list-style-type: none"> <input type="checkbox"/> Rotation of crops shall be considered. <input type="checkbox"/> Whether rotation is or is not possible farmers shall record on a regular basis suitable indicators of soil health these could be for example: stable or increasing yield, stable or reducing fertiliser/pesticide inputs, stable or increasing organic matter levels, stable soil nutrient levels. <input type="checkbox"/> The planning of the crop shall take into account the previous crops protection against pests and diseases <input type="checkbox"/> Farmers should use diverse crop rotations and seek to employ these whenever possible to maintain condition, minimise risk of nitrate leaching and reduce pest and disease development to maximise plant health as well as to spread the farm income streams soil
	Use specific cultivation techniques to maintain or improve the physical and biological characteristics of the soil as well as to reduce mineralization and leaching of nutrients.	<ul style="list-style-type: none"> <input type="checkbox"/> If soil conditions allow, chopping and incorporation of crop residues as well as organic manure or compost shall be used to help improve soil fertility by increasing organic matter content, improving nutrient and water retention and reducing erosion.
	Balance fertilization in order to provide the appropriate allowance of nutrients to the crops, taking into account release from other sources such as organic manures, soil organic	<p>A cropping/nutrient management plan should consider the following:</p> <ul style="list-style-type: none"> <input type="checkbox"/> The nutritional requirements of the crop to deliver the quality and yield for customer requirement. <input type="checkbox"/> Soil types mapped for the farm so as to be used to plan nutrient requirements for rotations. <input type="checkbox"/> Soil chemical, biological composition analysis – to ensure nutrient availability is understood as effected by pH, organic matter or clay/sand content. <input type="checkbox"/> Application rates of either mineral or organic fertilisers applied in accordance with national and local legislation (e.g. nitrate sensitive areas) and meet the needs of the crop as well as maintaining soil fertility. Rates based on a calculation of the nutrient requirements of the crop and on regular analysis of nutrient levels in soil, plant or nutrient solution. <input type="checkbox"/> A simple nutrient input/output balance using best available information, considering nutrient

	matter etc.	<p>inputs, crop returned to the soil and crop off-take with the harvested part of the crop.</p> <ul style="list-style-type: none"> <input type="checkbox"/> Planting of catch crops to capture nitrates.
	Avoid using sludge. If sludge is used though, manage it very carefully on the basis of proper risk assessment.	<ul style="list-style-type: none"> <input type="checkbox"/> Untreated sewage sludge shall not be applied to land used to grow crops. <input type="checkbox"/> Any use of treated sewage sludge on land destined for agricultural use shall be very carefully managed in accordance with national and local legislation. <input type="checkbox"/> Farmers shall check whether their customers allow the use of treated sewage sludge.
	Protect crops against pest, diseases and weeds with as little as possible reliance on pesticides. In particular, strive to use Integrated Pest Management (IPM) systems.	<p>The IPM system shall consider the following:</p> <ul style="list-style-type: none"> <input type="checkbox"/> Responsibilities are clearly assigned for planning and carrying out pest control. <input type="checkbox"/> Choice of crop/variety appropriate for the location as well as disease and pest resistance <input type="checkbox"/> Use of cultural and physical controls: crop rotations (e.g. mechanical weeding), biological controls (e.g. beneficial insects) <input type="checkbox"/> Regular visual inspections, thresholds or other recognised prediction systems to be used to avoid unnecessary application of pesticides. <input type="checkbox"/> Use of selective pesticides (insecticides, fungicides, herbicides) rather than broad spectrum <input type="checkbox"/> Rotation of pesticide active ingredients to reduce resistance. <input type="checkbox"/> Use of engineering/application techniques e.g. seed dressings, to improve targeting of pesticide application. <input type="checkbox"/> Potential yield and quality loss must be assessed in determining treatment levels. Management tools (e.g. weather forecasts, crop stress) to be used before treatment to assess the risk.e.g. insecticides that only control the pest species, not the predators.
	Chose, handle and store agricultural inputs with great precaution as per label instructions.	<p>Pesticides shall be used as follows:</p> <ul style="list-style-type: none"> <input type="checkbox"/> The crop protection product utilized is appropriate for the target pest and nationally registered in the country of use. <input type="checkbox"/> Only using treatments legally approved in country of production, which also comply with destination country maximum residue level (MRL) legislation. <input type="checkbox"/> Use must not exceed maximum authorized doses, comply to label recommendations and must conform to pre-harvest intervals. <input type="checkbox"/> Effective instructions are provided and measures taken, including use of appropriate equipment (e.g. Personal protective Equipment (PPE)), to protect health and safety of farm workers who handle or are exposed to agrochemicals. Instructions should highlight the legal aspects, use, storage, environmental and safety aspects and other precautions. <input type="checkbox"/> Spray equipment must be maintained and calibrated on a regular basis. <input type="checkbox"/> Surplus spray mix and washings must be disposed of according to local legislation and prevent surface and groundwater contamination. <input type="checkbox"/> Non target areas should be protected with appropriate measures (e.g. buffer strips). <p>Pesticide Storage Crop protection products shall be stored safely and securely considering the following:</p> <ul style="list-style-type: none"> <input type="checkbox"/> Pesticide containers shall be disposed off properly and not be reused. Ideally, they shall be punched and taken off the farm by official companies or burned at high temperatures with secure and proven techniques. <input type="checkbox"/> Storage facilities must be constructed of suitable materials, well ventilated, well lit and located where risks to the environment or human health are minimised in case of fire, spillage, flooding or other emergencies. <input type="checkbox"/> Separate storage from living quarters, food, feed, fertiliser, fuel and waste. <input type="checkbox"/> Areas where pesticides are handled and stored are designed such that spillages can be contained and do not reach the environment or pose a risk to human health. <input type="checkbox"/> Pesticide contaminated equipment (e.g. sprayers, PPE, measuring equipment) is stored and handled as specified by the manufacturer, separately from food, feed, living quarters and food preparation <p>Fertilizers shall be used as follows:</p> <ul style="list-style-type: none"> <input type="checkbox"/> Fertilizers are only applied to the intended crop area, non crop areas should be protected <input type="checkbox"/> Procedures are in place to deal with accidents and spillages. <input type="checkbox"/> Measures to avoid nitrogen and phosphate being lost to the environment, e.g. avoid rainy periods, avoid frozen, cracked, water logged, compacted soils, or the application technique such as split applications, incorporation or direct injection. <input type="checkbox"/> Application equipment is maintained and calibrated on a regular basis.

		<ul style="list-style-type: none"> <input type="checkbox"/> All fertiliser should be recorded and records should include: crop name, location of application, date of application, product trade name, operator name, and product quantity. and consumption areas). <input type="checkbox"/> A record kept of pesticides currently in the store. <p>Fertiliser Storage Fertilisers shall be stored safely and securely considering the following:</p> <ul style="list-style-type: none"> ▪ Storage and all products stored must comply with national and local legislation. ▪ Storage facilities must be constructed of suitable materials (e.g. liquid fertilisers have different storage requirements to solids) and located where risks to the environment or human health are minimised, in case of fire, spillage, flooding or other emergencies. ▪ Fertilisers must not be stored with pesticides or fuel. ▪ A record kept of fertilisers currently in store. <p>Fuel Storage Fuels shall be stored safely and securely considering the following:</p> <ul style="list-style-type: none"> ▪ Storage facilities are constructed of suitable materials and located where risks to the environment or human health are minimised, in case of fire, spillage, flooding or other emergencies. ▪ Fuel must not be stored with pesticides and fertilisers.
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2. Economic Sustainability

Item	Principles	Recommended Practices
Safety, quality and transparency	Ensure the safety, quality and transparency of the products throughout the production methods and storage facilities.	<p>Food Safety & Quality Farmers shall ensure they understand their role and responsibilities for ensuring food safety and quality and are familiar with the principles of Hazard Analysis and Critical Control Points (HACCP). Typical (but not exhaustive) crop Safety and Quality Hazards are listed:</p> <p>Biological</p> <ul style="list-style-type: none"> <input type="checkbox"/> Pathogenic bacteria e.g. E.coli, Salmonella, Fungal toxins, Plant toxins – e.g. glycoalkaloids from solanaceous weeds <input type="checkbox"/> Fungal bodies or plant berries e.g. ergot, nightshade <input type="checkbox"/> GMO modified material <input type="checkbox"/> Fungal moulds and bacterial rots (spoilage) <input type="checkbox"/> Plant diseases <input type="checkbox"/> Insects <input type="checkbox"/> Animal or Human matter – e.g. faeces (e.g. temporary post harvest storage contamination from birds/rodents) <p>Chemical</p> <ul style="list-style-type: none"> <input type="checkbox"/> Pesticide residues – e.g. exceeding MRLs, or using pesticides not permitted in origin or destination country. <input type="checkbox"/> Nitrate levels – certain leafy crops such as spinach <input type="checkbox"/> Heavy metal levels e.g. Pb, Cd <input type="checkbox"/> Mineral oils – lubricants, hydraulic oil, diesel <input type="checkbox"/> Composition – e.g. protein, sugars, oil <input type="checkbox"/> Dry matter content <p>Physical</p> <ul style="list-style-type: none"> <input type="checkbox"/> Glass, Metal, Stones, Wood <input type="checkbox"/> Extraneous vegetable matter (EVM) – contamination with other plant parts <input type="checkbox"/> Foreign EVM – contamination with plant parts not from the crop <input type="checkbox"/> Physical damage and blemishes <input type="checkbox"/> Size/shape <input type="checkbox"/> Colour <input type="checkbox"/> Soil contamination

		<p>Farmers should put in place a HACCP system, by mapping out the crop production process on farm to ex farm, once crop Safety and Quality Hazards have been identified. The management system then defines limits for the hazard, monitoring processes and remedial actions to reduce the risk of the Hazard to acceptable on farm levels.</p> <p>Traceability</p> <ul style="list-style-type: none"> <input type="checkbox"/> The farmer shall consult with the customer as to the level of traceability and chain of custody required. (For example: This may be to the field, farm, farm store or co-operative level.)
Financial Stability	Seek to achieve long-term stability of the farm income for proper investments and workforce payment.	<p>The farm's forward business plan shall take in to consideration the following:</p> <ul style="list-style-type: none"> <input type="checkbox"/> market characteristics <input type="checkbox"/> how diverse are the income streams (i.e. heavily reliant on one crop, or balanced over a number) <input type="checkbox"/> customer demand (What are customers plans? Are there different ways of working together?) <input type="checkbox"/> optimal yields <input type="checkbox"/> profit (gross margin calculations understanding variable costs) <input type="checkbox"/> current capabilities and resources (land, skills, workforce) <input type="checkbox"/> investments necessary for continuous improvement plan/change management <input type="checkbox"/> fixed overhead costs (labour, machinery depreciation, land rent, energy, maintenance)
Market	Seek to get organised and to select efficient trading channels in order to optimize benefits.	<ul style="list-style-type: none"> <input type="checkbox"/> Farmers shall negotiate in open and honest terms with their customers (optimum in quantity and quality), and try to develop long-term trading relationships with them. <input type="checkbox"/> Farmers may consider getting organised in groups, to better access support services and improve the position in bargaining prices for crop inputs (e.g. seed, fertilisers, fuel, pesticides, machinery, technical advice) <input type="checkbox"/> Farmers shall liaise with customers on the optimum timing of harvesting/crop deliveries to ensure efficient trading channels and the best price for and share of the product value. <input type="checkbox"/> Farmers should actively seek feedback from direct customers on how to increase 'value' for each other.
Diversification	Seek to diversify the farm into other farming activities or/and possible non-farming activities if appropriate, in order to increase farm income and to reduce risk linked to market price fluctuations.	<ul style="list-style-type: none"> <input type="checkbox"/> Farmers shall assess the diversity of sources of income considering the following: <ul style="list-style-type: none"> <input type="checkbox"/> Is income dominated by one crop <input type="checkbox"/> Are there alternative crops would could be grown on the farm, either for on-farm consumption or to be sold externally <input type="checkbox"/> Is development of non-farming activities feasible. <input type="checkbox"/> Are customers a source of innovation?

Social Sustainability

It is recognized that the majority of the farms are family run and family labour helping on the farm is often an essential component for the sustainability of the farm. In these circumstances, some of the principles might not fully apply. In any case, farms should comply with their national labour legislation, and if none exists, refer to the ILO conventions.

Item	Principles	Recommended Practices
Working conditions	Provide a cordial and pleasant working environment, free of any type of discrimination and free of disciplinary practices.	<ul style="list-style-type: none"> <input type="checkbox"/> Discrimination on the basis of ethnic groups, national origin, religion, disability, gender, sexual orientation, worker organisations or political affiliation with regard to contracts, compensation, training, promotion, dismissal or retirement of its personnel should be strictly prevented. <input type="checkbox"/> Same rights and obligations should be conceded to women and men, consistent with in-country cultural practices and balanced with international Convention <input type="checkbox"/> Employees and workers should not be asked to leave deposits or identity cards behind. <input type="checkbox"/> Employees and workers should have the right to freely practice their religion or fulfil their needs relating to race, national origin, religion, disability, gender, sexual orientation, membership in worker organisations or political affiliation. <input type="checkbox"/> Decent working conditions and dignity should be provided to all workers regardless of their employment status. <input type="checkbox"/> Behaviour, including gestures, language, and physical contact that is of a sexually abusive, coercive and threatening nature must be prevented.
	Farm workers and their families (if applicable) have access to suitable sanitary, housing and transportation infrastructures and services.	<ul style="list-style-type: none"> <input type="checkbox"/> Workers and their families should be provided with suitable sanitary facilities and drinking water in sufficient amounts <input type="checkbox"/> Workers and their families, living on the farm, should have access to medical treatment, nutrition and accommodation <input type="checkbox"/> Suitable and hygienic facilities should be provided for the preparation, storage and consumption
	Provide recognised employment relationship to workers based on national law and practice.	<ul style="list-style-type: none"> <input type="checkbox"/> Workers should be encouraged to know their status and, consequently, their respective rights and obligations under law. <input type="checkbox"/> Working contracts or other appropriate working relationships should be established, in accordance with national law. <input type="checkbox"/> <input type="checkbox"/> Temporary workers should be managed in a way that is as close as possible with those applied to permanent employees.
	Ensure that workers' working hours comply with national and local laws. Overtime performed during peak season is acceptable but duly compensated.	<ul style="list-style-type: none"> <input type="checkbox"/> Daily working hours for registered employees should not exceed the maximum number of hours set by national regulations. <input type="checkbox"/> Registered employees should be conceded for every six working days at least one day of rest, covered by their salary. <input type="checkbox"/> Overtime work shall be demanded only in exceptional circumstances over a short-term period due to the business cycle, notably during the harvest season. Overtime should be compensated adequately. <input type="checkbox"/> Registered employees who have worked at the farm for more than one year should have a period of paid leave (in line with local law and conventions).
	Ensure that wages and benefits received by workers comply as a minimum with local and national legislation.	<ul style="list-style-type: none"> <input type="checkbox"/> Wages and benefits of permanent employees should meet or exceed the minimum required under local and national laws. <input type="checkbox"/> Workers, especially temporary ones, should be provided with clear information about the payment that they receive for their work. <input type="checkbox"/> All employees and workers should receive remuneration in accordance with their tasks and abilities while having equal work opportunities. <input type="checkbox"/> Employees and workers should be able to receive wages in legal tender/currency. Compensation with merchandise, vouchers, tokens or any other symbolic means may be agreed upon with the employee or worker without creating any form of dependency. <input type="checkbox"/> Deductions should not be made from wages for disciplinary purposes
	Ensure that working conditions comply with applicable laws as well as international Conventions and Recommendations	<ul style="list-style-type: none"> <input type="checkbox"/> Actions should be promoted on the farm, which help prevent accidents and injuries of farm employees and workers during their duties. This equally refers to accidents and injuries of farm employees and workers as well as their families when living on the farm. <input type="checkbox"/> Access should be guaranteed to hygienic bathrooms and potable water for all employees and workers. <input type="checkbox"/> Activities should be promoted for the prevention of diseases, like

	related to occupational health and safety.	vaccination, orientation in aspects of personal hygiene.
	Do not use any form of forced labour.	<input type="checkbox"/> Forced labour of any type must neither be used nor supported.
	Allow workers to form and join unions of their choice and to bargain collectively.	<input type="checkbox"/> Employees and (family) workers should have the right to form and join associations of their own choice without previous authorisation. <input type="checkbox"/> Employees and workers should be entitled to collective bargaining. <input type="checkbox"/> Labour organisations should be allowed to conduct their activities if employees and workers wish so. <input type="checkbox"/> Workers' representatives should not be discriminated against.
	Do not use child labour.	<input type="checkbox"/> Child labour shall neither be used nor supported. <input type="checkbox"/> For cultural and socio-economic reasons, children under the minimum working age referred by national laws are allowed to help their parents with crop production. It shall be ensured that they are not forced to work, do not work long hours and are not exposed to hazardous or heavy work. <input type="checkbox"/> The individual situation of the children involved should be considered in relation to all actions implemented in order to eliminate child labour. All measures taken shall be designed to actually improve the living conditions of the individual child. <input type="checkbox"/> Young workers under the age of 18 should not be exposed to situations in the workplace that are hazardous, unsafe or unhealthy, even more so than any other workers.
	Seek to assure children access to adequate education as well as to support the education of farm employees and workers.	<input type="checkbox"/> Children below the work minimum age referred by national laws, living permanently or temporarily on the farm, should participate in educational programmes comparable with the formal school system. <input type="checkbox"/> Education programmes for workers' children who are at school age should be promoted.
Training	Support the training of farm employees and workers on all aspects of sustainable agricultural practices.	<input type="checkbox"/> Make sure all people are sufficiently trained to carry out their tasks and their responsibility shall be well determined. <input type="checkbox"/> Choose competent sources for advice and interventions. <input type="checkbox"/> Knowledge and awareness of charters for good agricultural practice and guidelines should be promoted.
Local economy	Contribute to provide economic benefits to local communities.	<input type="checkbox"/> Farmers should consider the following: <input type="checkbox"/> Being active members in their community e.g. engaging and consulting with schools, churches, local government. Understanding the community's needs and therefore the mutual benefits between the farm business and the local community. <input type="checkbox"/> Farmers should look to collaborate with the local community on aspects of improving environmental protection, health and safety linked to farm business impacts on the local community. <input type="checkbox"/> Preference given to local communities with regard to recruitment of permanent and temporary personnel, thus contributing to the build-up of sustainable livelihoods.

4. Environmental Sustainability

Item	Principles	Recommended Practices
Soil	Maintain good soil fertility and prevent damage to the environment, soil erosion and pollution.	Cultivation methods and equipment shall consider the following: <ul style="list-style-type: none"> <input type="checkbox"/> Soil type <input type="checkbox"/> Cultivation is timed to match soil conditions, i.e. should be avoided when soil is wet <input type="checkbox"/> Farmers avoid cultivation of steeply sloping fields, follow contours with operations for soil preparation as much as possible or use terracing <input type="checkbox"/> All cultivation equipment is regularly checked and maintained, including tyre

		<p>pressures.</p> <ul style="list-style-type: none"> <input type="checkbox"/> Appropriate methods, e.g. planting hedges, using cover crops is used to maintain soil in steep areas <input type="checkbox"/> Minimal cultivation techniques - is considered to reduce compaction and loss of soil organic matter. For those soil types where minimal cultivation techniques are not appropriate or where tenacious weeds occur, some rotational ploughing may be necessary.
Water	Properly manage and optimise water use.	<p>The Farm enterprise activities shall not knowingly deplete available water resources, beyond the recharge capacity of the watershed/catchment, by direct abstraction and consider the following:</p> <ul style="list-style-type: none"> <input type="checkbox"/> An assessment of the hydrologic characteristics of the soil should be performed before adopting any irrigation system. Overall, soil water is managed by drainage maintenance in wet climates and by soil moisture conservation practices, e.g. rainwater harvesting, mulching, in dry conditions. <input type="checkbox"/> Water harvesting in balance with all catchment users requirements should be promoted. <input type="checkbox"/> Advice on abstraction should be sought from water authorities or a relevant consultant. Water extraction licences, where held, are complied with. <p>An irrigation management system shall be used to ensure that:</p> <ul style="list-style-type: none"> <input type="checkbox"/> Irrigation is only used when it can enhance the yield and quality of crops produced. <input type="checkbox"/> Timing and amount of irrigation is tailored to crop requirements. <input type="checkbox"/> Irrigation takes into account predicted rainfall and evaporation, using either daily rainfall records or weather forecasts to plan irrigation schedules) <input type="checkbox"/> The most efficient and commercially practical water delivery system is used. In addition, water saving practices should be adopted and water should be re-used or re-cycled where possible. <input type="checkbox"/> Irrigation water quality is monitored and managed where necessary <input type="checkbox"/> Irrigation water usage records are maintained.
	Properly manage the use of inputs and release of	<p>The Farm enterprise activities shall protect surface and ground water from direct and indirect pollution considering the following:</p> <ul style="list-style-type: none"> <input type="checkbox"/> Untreated sewage water shall not be used for irrigation
	wastewater in surrounding water sources.	<ul style="list-style-type: none"> <input type="checkbox"/> Sources of water are carefully and regularly assessed for their microbial, chemical and mineral content, and properly managed in accordance with the assessment results. <input type="checkbox"/> The use of inputs as well as release of wastewater is properly managed in order to preserve surrounding water sources <input type="checkbox"/> Manures and fertilisers are stored in a clean, dry location (preferably under cover), where there is no risk of contamination of watercourses, and separate from nursery stock; they are not be applied to water logged, steep or frozen ground where there is a risk of run-off. <input type="checkbox"/> Buffer zones adjacent to waterways are planted, maintained or restored, preferably with native species.
Biodiversity	Maintain or enhance biological diversity on the farm.	<p>Farmers are encouraged to have a biodiversity action plan for their farm which includes:</p> <ul style="list-style-type: none"> <input type="checkbox"/> A map of the location of areas or features important to biodiversity on and around the farm <input type="checkbox"/> An assessment of any particular biodiversity issues on and around the farm <input type="checkbox"/> Details of how provision is made for wildlife habitats and food sources through hedges, field margins, extensive pasture, etc. <input type="checkbox"/> Details of measures to protect important biodiversity features or areas <input type="checkbox"/> A practical plan to make progress in an area of conservation/protection/education <input type="checkbox"/> A periodic review to assess biodiversity improvements

		<p>The biodiversity action plan should also consider the following for guidance:</p> <ul style="list-style-type: none"> <input type="checkbox"/> The farm environment is enhanced for locally important, rare or endangered species by providing appropriate habitats and adopting appropriate cultural practices, and reducing the negative impact of operations such as using agrochemicals, ploughing, grass cutting and hedge cutting. <input type="checkbox"/> Areas of higher ecological value located on the farm are protected via the minimisation of human intervention and the implementation of measures for the conservation of biodiversity, soil, water, flora and fauna. In particular, field margins and buffer zones is maintained and dominated by native species. <input type="checkbox"/> Restoration of vegetation is encouraged in degraded areas that have been prone to loss of fertility or soil erosion, preferably by using native species. <input type="checkbox"/> Farmers are also encouraged to create biodiversity habitats, e.g. field margins or beetle banks, that may encourage natural enemies of pests and hence contribute to their control by biological rather than chemical means.
Air	Preserve or improve the air quality.	<p>The farmer shall identify all sources of emissions which effect air quality. The following should be considered as potential sources:</p> <ul style="list-style-type: none"> <input type="checkbox"/> Manure storage <input type="checkbox"/> Waste storage <input type="checkbox"/> Burning waste <input type="checkbox"/> Pesticide application. <input type="checkbox"/> Manure application <input type="checkbox"/> Dust from harvest or cultivation <input type="checkbox"/> Machinery exhaust fumes <input type="checkbox"/> Noise pollution from machinery particularly at night <p>If sources are identified that effect the quality of air on a regular basis, mitigation plans shall be put in place.</p>
Climate change	Minimize adverse impacts on the global environment and climate change.	<p>The farm shall strive to minimise greenhouse gas emissions:</p> <ul style="list-style-type: none"> <input type="checkbox"/> By reducing the use of non-renewable sources of energy and increasing the use of renewable sources of energy, and by optimising the use of energy-intensive inputs, e.g. inorganic fertilisers.
Energy	Properly chose and use energy resources.	<p>The farm should assess the different energy requirements on farm and implement practices to:</p> <ul style="list-style-type: none"> <input type="checkbox"/> Avoid wasting energy, e.g. by combining field operations and optimising haulage distances <input type="checkbox"/> Avoiding unnecessary operations and use appropriate machinery and equipment <input type="checkbox"/> Increase the use of renewable energy and fuels on-farm <input type="checkbox"/> Record and monitor fuel usage
Waste	Use crop by-products as much as possible on the farm.	<ul style="list-style-type: none"> <input type="checkbox"/> The farm shall continuously reduce, reuse and recycle the quantity of waste and by-products of harvesting and processing, e.g. by composting organic debris on-farm and re-using it for soil conditioning (where there is no risk of disease transmission).
	Properly handle, and if possible recycle waste generated by the farm.	<ul style="list-style-type: none"> <input type="checkbox"/> Untreated farm sewage water and other farm effluents shall not be used on the farm nor be discharged into natural superficial waters. <input type="checkbox"/> Treated sewage shall be spread in the field only under proper climatic and biological conditions, as per national and local legislation. <input type="checkbox"/> Inorganic waste that is not recyclable, including chemical and toxic substances shall not be burned. They shall be handled appropriately. <input type="checkbox"/> Used containers which have held hazardous substances, e.g. crop protection products and antimicrobials, shall be disposed of in a proper manner, and never used to store water, food or feed.. <input type="checkbox"/> All waste storage shall be assessed for risks considering the following: <ul style="list-style-type: none"> - Location of store

		<ul style="list-style-type: none"> - Does the store need to be secure - Capacity of the store - Is the store purpose built to contain the waste (e.g. is bunding required) - Storage of waste is segregated (e.g. hazardous from non-hazardous, waste is not stored with non-waste) - Procedures are in place to contain spills <input type="checkbox"/> A waste management plan is recommended, which: <ul style="list-style-type: none"> - Identifies all potential waste streams within the business - Identifies hazardous and non-hazardous waste - identifies the measures in place to reduce, reuse and recycle waste as well as to prevent pollution - outlines emergency action procedures in order to minimise the risk of pollution from accidents concerning hazardous waste.
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Seed production techniques in various crops

The seeds are evolved, tested and if found good they are multiplied and distributed to the farmers for commercial production of the crop. Therefore, according to the nature and precaution with which the seeds are produced, they are classified into the following groups:

1. Breeder's seed or nucleus seed

These seeds are produced at breeder's level as a result of hybridization, selection and mutation. When these seeds possess all the required genetic characters they are named as breeder's or nucleus seeds. For testing the genetic purity, yield potentials, disease reaction and adaptability the seed has to go for testing under a number of trials in different agroclimatic conditions or zones of the country. Each breeder's seed has to be tested in initial evaluation trial, National trial, Uniform Regional Trial, District Trial and finally under Mini-Kit programme. The varieties which qualify in all the trials are further produced. These seeds are of high genetic value and being very little in quantity are often costly.

2. Foundation seed

The foundation seed is a second grade seed in order of its genetic purity because there may be slight degeneration during the process of multiplication of nucleus seeds. The foundation seed is always produced by certain organizations viz. National Seed Corporation, Tarai Development Corporation and State Seed Corporation. A strict Seed plot technique which includes inspection, rouging, weed control, isolation etc is adopted during seed production process. The foundation seed is relatively less pure compared to the breeder's or nucleus seed.

3. Certified seed

The certified seeds are produced from foundation seeds mostly in two ways: in the first way the seed is produced at the seed farms of the National Seed Corporation or State Seed Farms. In the second way the seed is produced by certified farmers under growers' programme. During the production of seed the field is inspected by the seed inspector and the seed thus produced is processed, bagged and tagged in the presence of the seed technicians deputed by seed certifying agency. After proper labeling, the seed is sold to the farmers for commercial cultivation. The certified seed is relatively less pure compared to the previous two seed categories.

Basic Concepts of Seed Production

In order to produce seed which is true to type, one must become knowledgeable in the variety's reproductive process, as well as, the techniques used for maintaining genetic diversity and identity, seed harvesting, seed cleaning and seed storage.

Plants can be broken down into 2 main reproductive categories...Self-Pollinating and Cross-Pollinating.

- Self-Pollinating Plants ("selfers"): transfer of pollen from the male anther to the female stigma within the same flower or on the same plant.
 - These plants usually require smaller minimum population sizes (*minimum number of plants needed to ensure genetic diversity*) and shorter isolation distances (*distance needed between same species varieties to ensure no crossing*) than crossers.
 - Examples: beans, tomatoes, barley, lentil, oat, rice, soybean, wheat.
- Cross-Pollinating Plants ("crossers"): transfer pollen from the anther of one plant to the stigma of another plant. This process is usually accomplished naturally by wind and insects or can also be accomplished manually by hand-pollination.
 - Cross-pollinating plants evolve under conditions of constant gene recombination and suffer from "inbreeding depression" (*symptoms of decreased vigor and the appearance of negative recessive genes when inbred*).
 - When breeding cross-pollinating plants one must be cautious to prevent crossing varieties of the same species. This can be accomplished through various methods of isolation.
 - Genetic diversity must be maintained. *High genetic diversity ensures that all possible genes (characteristics) are being represented in the variety.*
 - Examples of cross-pollinated: onion, beets, corn, cucumber, cole crops, squash, radish, celery, rye, and buckwheat.

Annual Crops: Annual crops require only one growing season to produce seed and complete their lifecycle. But because you are growing the crop for seed rather than fruit, you may have to plant the crop earlier than usual and harvest much later.

Biennial Crops: Biennial crops require 2 growing seasons to produce seed and complete their lifecycle.

- These crops generally require a period of vernalization (*exposure to cold*) in order to flower. [Tip: Before exposing the vegetable to the cold (less than 45 degrees Fahrenheit), they should be partially developed].
 - Cabbage stems should be at least as large as a lead pencil in diameter.
- Average chilling temperature should be less than 45 degrees Fahrenheit and chilling should continue for at least 1 – 2 months.

Genetic Integrity: To prevent varieties from crossing, seed producers must use some means of isolation (cages, distance isolation, time isolation, or hand pollination) during periods when pollination can occur. Genetic diversity within a variety is maintained by including a minimum number of randomly selected parents into the breeding population. This number will vary by crop species.

Ways to protect a varieties genetic integrity:

1. **Control of seed source:** Multiplication of seed material from an appropriate class viz. breeder's, foundation, registered and certified procured from an appropriate source is essential.
2. **Nature of preceding crop:** In order to maintain genetic purity of the seed there are certain requirements pertaining to the nature of preceding crop which may not deteriorate the seed quality and help in growing healthy seed crop. Scientific crop rotation should be followed but if the same crop was grown in previous season, under special case, then the fields should be irrigated at least three weeks before sowing to allow germination of shattered seeds of the previous crop and they should be destroyed during seed bed preparation like in case of rice, barley and wheat. The seed crop of sorghum should never have Johnson grass. Thus the volunteer plants of same variety or the crop should be destroyed under all the circumstances.
3. **Isolation:** isolation is an effective distance upto which the pollens may be carried by various agencies like wind, insect etc. from commercial crop to the seed crop and result into natural crossing or cross pollination. The seed crop must be grown beyond this distance.
4. **Rouging:** A rogue is a plant which is "off-type" (*different from the variety*) or is otherwise undesirable. Presence of off type plants causes a potential threat to genetic contamination, purity, however, removal of these plants before flowering or before heading may not jeopardize the genetic purity of the seed. The off types may be produced because of presence of some recessive genes in the variety at the time of release or they may arise by mutation. The off-types may also grow as volunteer if the same crop or variety is grown in previous year or these had been mechanical mixture due to use of same seed drill/threshing machine.
5. **Seed certification:** To ensure good quality pedigree seed it has to be certified by any registered seed certifying agency like NSC, TDC, state Seed Corporations etc.
6. **Adoption of appropriate agronomic practices:** These practices include selection of suitable agro-climatic zone, selection of well leveled fertile plots free from water logging, hardpan in sub-soil zone and excessive salt; seed treatment, efficient water and nutrient management, use of all preventive measures against diseases and insect-pests and other cultural practices, timely harvesting, threshing, drying, grading, bagging , storage under regulated moisture and fumigated conditions. These practices help in raising a healthy seed crop for onward distribution to the cultivators for raising a good crop of higher productivity.

Reproductive Isolation

1. Isolation strips: plot of a crop which separates seed plots, preventing crossing and mechanical mixtures.
 - This strip would theoretically catch windblown pollen and distracts insects from visiting the plots on either side of it.
2. Distance Isolation: Try to follow this general rule, selfers should be isolated by at least 150 feet and an isolation strip. Wind pollinated crossers should be separated by at least 1 mile (but up to 5 miles), insect pollinated crossers should be separated by at least ¼ mile and some other barrier (or 1 mile in open land). Once again these figures vary depending on the source of your information.
3. Caging and Artificial Barriers: Cages can be constructed with PVC and fabric row covers. Brown paper or fine meshed bags can also be used. Non-porous bags are not recommended because they can lead to rot.
 - When these methods are used it is required that either plants are hand-pollinated or pollinators must be introduced into the caged/bagged environment.

4. **Time Isolation:** You can plant different varieties of the same species in the same year as long as the times they flower do not overlap. For annuals, this could mean starting one variety early in the season and then starting another several weeks later. For biennials, you could have multiple varieties of the same species (such as onions) growing in the same place but only one that is in its second year and going to flower.

Hand-pollinating

Basically, you are transferring pollen from one flower to the stigma of another and then you must cover the pollinated flower to isolate it from being pollinated by a different variety.

1. The flower to be pollinated is emasculated (*stripped of anthers or male parts*).
 - This should be done BEFORE the male parts begin to release pollen (typically just before the flower opens).
2. To transfer the pollen, either...
 - Remove the entire flower and touch the anthers to the stigma.
 - Place a bag over the flower heads and shake to collect the pollen and then transfer the pollen with a feather or fine brush.
3. After pollination has occurred, the flower should be covered with a bag or taped (squash flowers and other large flowers).
4. Remove the bag or tape after approximately one week.

Minimum Population Size: This refers to the smallest number of plants that can be grown of one variety to ensure genetic integrity. There is a more in-depth minimum population size sheet at the end of this section.

- In general,
 - 200 plants for cross-pollinated varieties.
 - 60-80 plants for self-pollinated varieties.

These figures often vary depending on who you talk to.

Seed Harvesting

- **Labels and Records:** Label seeds and seed lots! Labels should be affixed to whatever the seed is being stored on or in during processing.
- **Harvesting Methods:**
 - **Dry Seeds:** Let the plant material completely dry either in the field or after you harvest in mesh bags or on mesh tarps (turn frequently to ensure proper drying).
- Harvest when the seeds begin to rattle in their pods but, keep a daily check to ensure the pods don't open and you don't waste any seed.
 - **Wet Seeds:** Harvest entire fruit and scoop out seeds and place in container.
- Most fruits should be allowed to slightly over-ripen (but before decay) before you harvest for seed.
- Seeds should be harvested from as many plants as possible throughout the growing season to help ensure genetic integrity.

Seed Cleaning

When seeds come out of the field, they may contain many types of particles (the desired seed, weed seed, plant material, etc.). In addition to the many different types of particles, the desired seed may have broken or other unviable seed mixed in to the lot. By removing these undesirable seeds and particles, you will improve the vigor and germination rate for your lot. When removing the undesirable seed from your seed lot, there are many differences in the seed used to make separations.

1. **Size** (large vs. small and length, width, and thickness). The most popular way to separate particles of different sizes is by scalping (using a screen which allows the desired seed fall through the screen holes while removing the larger particles) or sifting (dropping out smaller particles by using a screen in which only the particles smaller than the seed are allowed to pass). Both of these separations can be made manually by using separating boxes or mechanically using devices like the Clipper Office Tester (see equipment section). Making length separations can be done by using an indented cylinder or disc machine.
2. **Weight** (heavy vs. light and differences in specific gravity and surface area). This separation is best done with a box fan, an air column or aspirator (see equipment section). These work by passing a stream of air past the seed allowing

the light (often unviable) seed to be blown out of the seed lot. This method will also remove any light chaff that remains within the seed lot.

3. **Shape** (round vs. non-round). This separation can be done with a spiral separator (round seeds will roll faster than flat or non-round seeds).
4. **Surface Texture** (rough, smooth or pointed). A flat piece of roughed-up cardboard works well for this separation. Round seed will roll to the bottom when placed at a slight angle while flat seed will be “caught” on the roughed cardboard. Also a velvet roller works well (see equipment section).
5. **Color:** This separation is most often done by hand-picking although there are color separation devices; they are not commonly used by small-scale seed producers.

Other things to keep in mind when cleaning seed:

- Labels, Records and Mechanical Mixing: Affix labels to all seed containers and spaced far enough apart to ensure there is no mechanical mixing of seed lots.
- Cleaning Supplies: Dry seed should be free of seed pods, hulls, and stalks by being smashed in a tarp, bag or mechanical thresher (clipper mill, belt thresher, brush mill, etc.) and then screened. Screens are used to separate out material that is larger or smaller than the seed being cleaned.
 - Wet vegetable seed cleaning supplies include buckets for fermenting, hand mashers (4 x 4 with a handle), a wet vegetable seed separator (See Seed Cleaning Equipment section) and sieves and colanders.
- Always dry seeds completely before storing!

Cleaning Dry Seed

- Seed pods can be dried then smashed in a number of ways...stomping and smashing in a threshing box, or using a mechanical thresher is common. Once all the seeds are released from the pods, you can separate the seeds from the pods by using handscreens or a “Clipper Mill” (See Equipment section).
 - A threshing box can be built by making a 3 x 3 box (without a top) and placing a corrugated plastic mat at the bottom of it.
- Once the larger pods are removed, lighter chaff can be removed by winnowing or using an air column (See Equipment section). Finer removal of chaff can be accomplished by using a velvet roller (See Equipment section).
- Once all chaff has been removed, seeds should be stored in a dark, clean, dry, pest-free environment.

Wet Seed Cleaning

- Seeds can be removed from fruit by cutting the fruit open and scooping out the seeds or by using a “Wet Vegetable Seed Separator” for tomatoes, peppers, and cucumbers. (See Equipment section).
- After seeds are removed, some species (tomatoes, for example) can benefit from a fermentation process.
 - Fermentation Process: Place seeds (covered with pulp/gel) into a container and cover seeds with an equal amount of water for approximately 2 days. You should stir this mix at least twice a day.
- Once the fermentation process is finished (there will be a pungent odor and layer of mold growing on the top of the bucket), seeds should be rinsed thoroughly. Strainers and fryer baskets come in handy during this step.
- After seeds are rinsed, they can be dipped in a 20% Clorox solution (this process protects the seed from Tobacco Mosaic Virus) and then rinsed again with clean water to protect the seeds against certain viruses.
 - The seeds only need to be dipped for enough time to ensure that all the seeds have contacted the bleach solution.
- Once seeds are treated, they should be dried completely prior to storing.

Drying Seeds

- Drying seeds at 10 – 25 degrees Celsius (50 – 77 degrees Fahrenheit) and at 10 – 20 % relative humidity using either some type of desiccant (silica gel or activated alumina) or a dehumidified drying chamber (set at the **lowest** heat setting or no the “no heat” setting) is ideal but air drying is common as well. Desiccants should be replaced every 3 to 5 years and dehumidifiers should be carefully watched so that seeds are not damaged by the heat.
- Seeds should be dried as soon as possible after harvest to avoid fungal and viral growth.
- Drying time is variable depending on the seed and the conditions in which the seed is being dried.
- If you can push your nail into the seed, it is probably not dry enough to store!!!
- Ovens are not recommended for drying seeds since heat can damage many seeds

Seed Storage

- Optimal storage is airtight, low humidity, and low temperature.
 - Except for peas and beans which like some “open air”.
- Containers should ideally be moisture proof and sealable (keep in mind that most plastics are not moisture proof).
- Metal, foil-lined heat sealable envelopes are often used at seed banks.
- Cold storage in a chest type deep freezer is invaluable for extending the lifespan of seeds. Low temperatures slow the process of seed decay. But be careful, most seeds can tolerate freezing but, it may damage others. Test a small sample of seeds first before putting the whole seed lot into freezer storage.
- Leak, onion, corn and parsnip seed is short-lived, the seed will most likely only last 1 – 2 seasons.
- Always remember that **before** opening any seed container that has been in a freezer, let the container acclimate to room temperature! If you just open the container straight from the freezer, condensation will form on the interior walls of the container and you will have to dry the seed again (possibly damaging it).

Germination Testing

- Germination testing is important to both the seed regenerator and the seed producer.
- Always try to germinate a random sample of the seeds you are wanting to plant.
- For long term storage, initial germination should be at least 85% for cereals, and 75% for vegetables.
- Wild species often have lower germination rates.

Seed production of major field crops: Cereals

Rice

Rice is a self pollinated crop but sometimes or rarely cross pollination is also reported. The extent of cross-pollination ranges between 0.1 to 4%. Therefore, an isolation distance of about 3.0 metres between commercial and seed crop is sufficient.

Raising of seedlings

To avoid varietal admixture one should choose a site for nursery where rice was not grown in the previous year. Sowing of seed should be done between 25th May to 10th of June for long duration varieties and between 10th to 25th June for short duration varieties. About 50-60 beds of 6 m x 1.5 m size are required for raising seedlings to transplant one hectare area. About 450 g of single super phosphate and 20 g of zinc sulphate/bed should be mixed into the soil at the time of final tillage operation in the beds. Seeds of required grade or type viz. nucleus/breeders/foundation should be taken after approval from the certification agency. A seed rate of 25-30 kg/ha for fine rice varieties (about 400-500 g/bed) should be treated with ceresin/agrosan G.N./bavistin at the rate of 2.5 g/kg of seed, soaked and sprouted and then sown in the beds either by broadcasting or by line sowing. Proper weed and water management practices should be adopted for obtaining healthy seedlings. They should be uprooted carefully and transplanted at the age of three weeks in early varieties. Weak, diseased or phenotypically different seedlings should be discarded.

Post-planting care

Like commercial crop the seed crop should also be fertilized with recommended dose of NPK and Zn. The field should be well puddle before transplanting. Two-three healthy seedlings should be transplanted in row at 20 cm x 15 cm in case of early and medium varieties and 20 cm x 20 cm or 30 cm x 20 cm in case of long duration ones. Two-three weedings or application of butachlor or other herbicide, as in case of commercial crop should be done to take care of weeds. Proper measures for insect-pests (stem borer, brown plant hopper, Gandhi bug etc) and diseases (blast, bacterial leaf blight, brown spot, seedling blight and foot rot etc) and micronutrient deficiency (khaira disease) should be taken.

Roguing

Roguing of wild rice plants, disease affected plants especially those infected with tungro virus and false smut and off-types thrice – once at panicle initiation, next at flowering and final near maturity keep seed free of admixtures.

Harvesting and threshing

The seed crop should be harvested when the seeds are at about 20% moisture. Threshing should be done over thoroughly cleaned floor. The grains should be winnowed and dried to about 10-12% moisture for storage.

Seed certification

Seed certification is a process designed to secure, maintain and make available high quality seed and propagating materials of superior crop plant varieties so grown and distributed as to ensure desirable standards of genetic identity, physical purity, seed conditions and quality. Certification of seed is performed in following four phases:

1. In all the cases, where the fields are under foundation or certified seed production, the individual who has taken up the production must submit documentary evidence including the certification tag, purchase records etc. to the certifying agency when demanded.
2. This is done in order to verify conformity to prescribe field standards. The objective of field inspection is to ensure that necessary steps to overcome genetic and physical contamination have been taken in time to make them effective. The field inspection gives the following information:
 - a) Whether the seed crop is grown in compliance with other special requirements for the crop concerned.
 - b) Whether the roguing is done to confirm the standards prescribed for the seed production. Roguing refers to the removal of all the contaminating factors such as pollen shedders in bajra and sorghum, shedding tassels in maize, crosses, off-types, diseased plants/ears, objectionable weeds and inseparable other crop plants.
 - c) Whether the plants are true to the varietal characteristics described for them.
 - d) Whether the crop is planted in prescribed ratio of female (seed) and male (pollinator) parents in the case of hybrid seed production. The prescribed ratios of female and male is given as under:

The recommended number of male border rows and the ration of male and female rows

Crop	Minimum No. of border rows	Planting ratio	
		No. of female rows	No. of male rows
Bajra	8	4	2
Maize- single crosses	4	4	2
Other hybrids	2	6	2
Sorghum	4	4	2

- e) Where the seed crop is provided with prescribed isolation as mentioned below:

Minimum isolation distance in meters (as per Field Inspection Manual Published by NSC 1972) for field crops

Crop(s)	Minimum isolation distance (m)		Remarks (to be isolated from)
	Foundation	Certified	
Cereals – barley, oats, paddy, wheat	3	3	
Berseem, Lucerne	400	100	
Castor	300	150	
Cotton	50	30	
Groundnut	3	3	
Jute	50	50	Other varieties
	3	3	Other species
Maize – inbred lines/single crosses	400	-	From any maize of same kernel colour or texture
	400	-	Any maize with different kernel colour and texture
Other hybrids	-	200	Any maize with same kernel colour and texture
	-	300	Any maize with different colour and texture
Composite/open pollinated variety	400	200	Other variety
Mesta – <i>Hibiscus cannabinus</i>	200	100	Other varieties of the same species or other variety not pure

Crop(s)	Minimum isolation distance (m)		Remarks (to be isolated from)
	Foundation	Certified	
Hibiscus sabdariffa	100	50	-do-
	-	10	Other species
Pearl millet	1000	200	Other varieties
	1000	25	Same variety but not pure
Rape, Mustard	200	100	Other varieties of the same species
Sesamum	100	50	Other varieties/same variety but not pure
Sorghum Hybrid	300	200	Other varieties
	300	25	Same variety but not pure
	400	400	Johnson grass (<i>S. halepense</i>)
	400	200	Forage sorghum
Open pollinated	200	100	Other varieties/same variety but not pure
	400	200	Johnson grass (<i>S. halepense</i>)
	400	200	Forage sorghum
Soybean	3	3	Other varieties/same variety but not pure
Sunhemp	200	100	-do-
Teosinte	200	100	Any maize/other varieties

The inspections are usually made at:

- a) Pre-flowering stage – this includes seedling stage, vegetative stage, flowerbud initiation stage and all such stages prior to emergence of flowers.
 - b) Flowering stage – When the flowers have opened, the stigma is receptive and anthers are shedding pollens.
 - c) Post-flowering stage – The stage when receptivity of stigma and the pollen shedding of anthers have ended. This includes milk stage and dough stage both.
 - d) Pre-harvest stage – The stage when the seeds becomes harder and reach to physiological maturity.
 - e) Harvest stage – The stage when the seeds are physiologically matured and sufficiently dried to permit safe and easy harvesting.
 - f) Whether the seed crop is harvested properly to avoid mechanical admixture.
3. Testing of each seed lot and seed sample
It is done for germination, purity etc.
 4. Tagging, labeling and sealing to identify the seed

The colour of the prescribed certification tag shall be white for foundation seed, and for certified seed. These colours are prescribed by the Central Certification Board. The seed inspector sends the report in sheets of different colours:

First copy	Pink	To head office
Second copy	Green	To grower
Third copy	Yellow	To regional office
Fourth copy	White	To be kept by the inspector

The container of the certified seed shall carry a seal of such material and in such a form as the certification agency may determine and no container carrying a certification tag shall be sold as certified seed if the tag or seal has either been tampered with or removed.

Hybrid seed production

Hybrid seed is seed produced by cross-pollinated plants. In hybrid seed production, the crosses are specific and controlled. The advantage of growing hybrid seed compared to inbred lines comes from heterosis. To produce hybrid seed, elite inbred varieties with well documented and consistent phenotypes (such as yield) are crossed and the resulting hybrid seed is collected. Another factor that is important in hybrid seed production is the combining ability of the parent plants. Although two elite inbred parent plant varieties may produce the highest yields of their crop, it does not necessarily mean that crossing these inbreds will result in the highest yielding hybrid. Combining ability is the term used to describe the level of heterosis that the parents will generate in the resultant seed. Higher combining ability between the parents results in increased performance in the resulting hybrid seed. Hybrids are bred to improve the characteristics of the resulting plants, such as better yield, greater uniformity, improved color, disease resistance, and so forth. Today, hybrid seed production is predominant in agriculture and home gardening, and is one of the main contributing factors to the dramatic rise in agricultural output during the last half of the 20th century. In the US, the

commercial market was launched in the 1920s, with the first hybrid maize. All of the hybrid seeds planted by the farmer will be the same hybrid, which causes the first generation of seed from the hybrids planted to be inbred. This is why hybrid seed is generally not saved from subsequent generations and is purchased for each planting. Hybrid seeds are much dearer than normal seeds, due to the technology, time and effort put in to produce them.

Crop response production functions

Over time, research aimed at illuminating the relationship between crop yield and any agricultural inputs (fertilizer water etc) has been guided, often implicitly, by various notions of what constitute a ‘optimum’ or ‘desirable’ level of that input use. The general definitions can be identified: (1) The work of agronomists and other production oriented scientists is frequently directed at the goal of establishing the level of input necessary to achieve maximum yield per ha. This particular goal is implicit in all efforts intended to ensure that resource (input) does not become limiting. (2) Another measure of desirability frequently encountered in the literature is that of maximum input use efficiency. Maximum input use efficiency is said to exist when the crop yield per unit of input is maximized. (3) Yet another definition of desirable levels of input use is advanced by economists who argue that input to be used efficiently should be applied upto the point where the price of the last unit of input applied is just equal to the revenue obtained as a result of its application. A simple model of production can be used to demonstrate that these various goals are usually inconsistent with each other.

A production function or total physical product curve in which yield (Y) is a function of the amount of input (I), with all other variables held constant, can be defined as follow:

$$Y = f(I) \dots\dots\dots 1$$

Two related concepts can be introduced. The average physical product (APP) which is simply output divided by input, can be written as

$$APP = Y/I \dots\dots\dots 2$$

The marginal physical product (MPP) is defined as the change in yield or output associated with the addition of one or more units of input. It can be written as

$$MPP = dY/dI \dots\dots\dots 3$$

The analytics of optimization can be used to demonstrate the inconsistency between maximum yield and input use efficiency. The total physical product or yield is maximized when the MPP is equal to zero. Maximum input use efficiency requires that the derivative of the APP be equal to zero, or

$$I^{-1}[(dY/dI) - (Y/I)] = 0 \dots\dots\dots 4$$

Equation (4) shows that as long as some positive quantity of input is applied, Input use efficiency or the APP is maximized where it is equal to the MPP. As a consequence, maximum input use efficiency (maximum APP) and maximum yield could only be equivalent if the APP is maximized at zero. Yet the APP cannot be zero except where there is no production at all.

Economic analysis, on other hand, defines the most efficient level of resource use in terms of value. The efficient use of land, water and other resources depends upon their value in a given activity relative to their value in achieving other purposes. Economically, efficient input use requires that the farmer apply input so long as the additional revenue generated exceeds the additional cost of that input.

A review of Agronomic and Physiological Production Functions

The scientific literature on production functions fits more or less into three classifications: (1) early related studies, (2) physiological approaches and (3) semiempirical approaches. We are restricting to crop water production functions.

Early related studies

Since the beginning of the twentieth century, researchers have been studying the relationship between crop yield and water use. De Wit (1958) analyzed the findings of the early investigations in an effort to further identify the factors that determine transpiration and yield under field conditions. He concluded that the relationship between dry matter yield (Y) and transpiration (T) for arid and semiarid regions of the world was linear with the following form:

$$Y = m(T/E_0) \dots\dots\dots(5)$$

Where m is a coefficient accounting for such factors as crop (and variety of crop), availability of water and weather conditions not accounted for by E_0 . He also concluded that this relationship was equally valid for container and field grown crops. For humid regions, he suggested that $Y = nT$.

Physiological approaches

Plant responses are the result of the complex interaction of many physiological processes, each of which may be affected differently by water deficits. Hsiao et al (1976) pointed out that what is known of water stress relationships in crops was learned almost exclusively from empirical work from thousands of irrigation trials conducted over many decades. They presented a simplified diagram of the general effects of water stress on yield that makes evident the multiplicity of interactions among water stress, growth, development, ontogenic stages and yields. That diagram is reproduced in Fig 1. Begg and Turner (1976) classified the effects of water deficit on crop growth and development into three main categories: morphological, physiological and ontogenic effects on the sensitivity of crops at different stages of development.

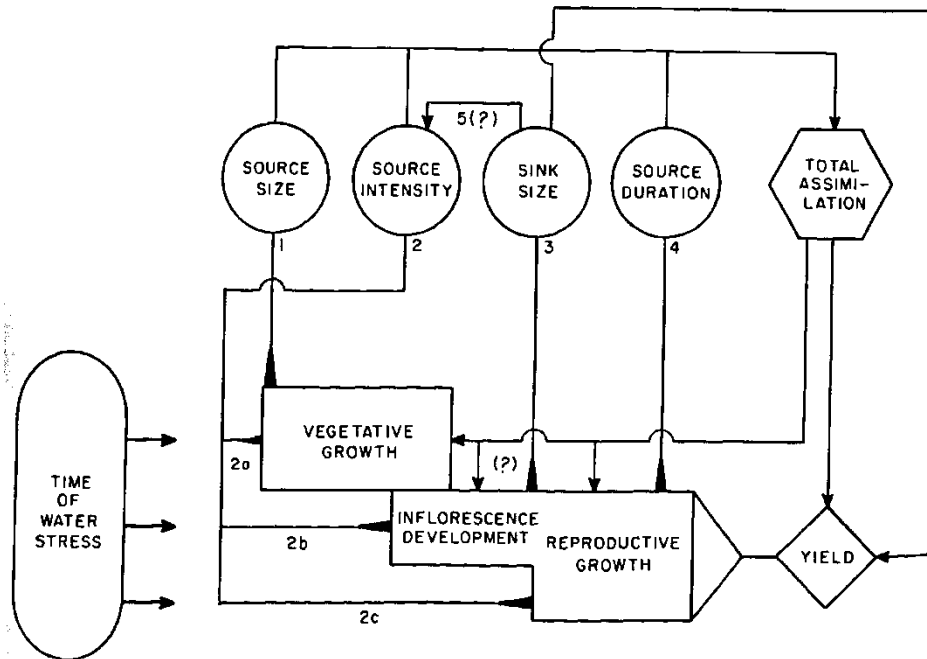


FIG. 1. General effects of water stress on yield as viewed in the context of temporal variations in CO₂ assimilation, source-sink relationships for assimilates, and plant ontogeny. The effects are considered to vary with time, and the cumulative effects would be the integrals over time. Arrows represent negative effects. For example, stress during the vegetative growth stages can reduce source intensity (line 2a), which in turn can lead to a reduction in total assimilation (line 2a), which in turn can lead to a reduction in total assimilation and yield. Question marks represent effects which are not well established. For example, it is not certain that a reduction in total assimilation would generally inhibit or reduce inflorescence development (after Hsiao *et al.*, 1976b).

In considering the effect of water stress on productivity, two phenomena are of primary importance: dry matter production (or the cumulative net assimilation of CO₂) and the partitioning of assimilates. The partitioning of assimilates among the plant parts determines how much of total dry matter actually ends up as yield. In spite of the importance of assimilate partitioning among

plant parts, the question of how the translocation of assimilates is affected by water stress has not been answered and quantitative relations between stress and translocation remain to be determined (Hsiao et al 1976).

Rijtema (1973) suggested that light energy be used as the principle variable in production models because of its importance in production and the ease and accuracy with which it can be measured under field conditions. The other partial processes involved with photosynthesis are incorporated as correction factors. Among the plant physiological studies, De Wit (1965) proposed the daily production rate during each growth stage as

$$P = FP_0 + (1 - F)P_c \dots\dots\dots (6)$$

Where P is the production in kilograms of carbohydrate per day pr hectare, P₀ the production on completely overcast days, P_c the production on very clear days, and F is the function of daytime during which the sky is clouded. The production calculated in this way is the potential production (P_{pot}) of a standard crop as defined by De Wit (1965). Rijtema (1973) used the De Wit (1965) production model to study the effects of light and water potential on dry matter production of field crops. Rijtema's production function has the form

$$P = \alpha[4.9/(r'_a + r'_s + r'_m)S_cP_{pot} \dots\dots\dots (7)$$

Where α is an efficiency factor to account for respiration losses. The ratio $4.9/(r'_a + r'_s + r'_m)$ is a factor to correct for differences in the resistances in the diffusion pathway, and S_c if the fraction of soil cover. The term r'_a stands for a combination of both stomatal and cuticular resistance, r'_s for atmospheric resistance and r'_m for mesophyll resistance. Ritjema found that there was good agreement between the dry matter production, measured at periodic harvests and the values predicted by his model.

Bierhuizen and Slatyer (1965) observed that the ratio of transpiration to apparent photosynthesis (T/P) increased linearly with the leaf air vapour pressure difference and decreased with increasing wind speed.

Semiempirical approaches

The semiempirical approaches are usually characterized by efforts to relate crop yield to either (1) soil moisture content or moisture tension, (2) transpiration or evapotranspiration, or (3) applied irrigation water.

1. Crop yield as a function of evapo-transpiration

Stewart et al (1977) reported generalized production function based on findings from three experiments in which corn, sorghum, beans and alfalfa were grown over a number of years.

$$1 - Y_a/Y_m = \beta(1-ET_a/ET_m) \quad (\text{Stewart's model } S_1) \dots\dots\dots(8)$$

Where Y_a is the actual yield, ET_a the actual seasonal ET, Y_m the maximum yield, ET_m the seasonal ET for maximum yield, and β the constant (yield reduction ratio).

Doorenbos and Kassam (1979) utilized this model to develop a method of quantifying the relationship between yield and water. Here Y_m is calculated by De Wit's approach modified with several correction factors. Maximum ET is determined by methods outlined by Doorenbos and Pruitt (1977) and ET_a is estimated with an elaboration of procedures covered only briefly in the same 1977 publication.

Hanks (1974) utilized De Wit's equation (Eq 1) in developing a model relating yield to relative transpiration:

$$Y = (T/T_p)Y_p \quad (\text{Hank's model } H_1) \dots\dots\dots (9)$$

Where T is the seasonal transpiration, Y the yield, T_p the maximum seasonal transpiration and Y_p the yield at T_p. seasonal transpiration is calculated using soil, plant and climatic factors and is assumed to be independent of evaporation. A through testing of the model demonstrated its ability to predict dry matter yield as influenced by irrigation management for many different crops and situations (Hanks and Mill, 1980).

2. Crop yield as a function of applied water

Stewart and Hagan (1973) suggested that although ET is the field level water parameter associated most directly with yield, the depth of irrigation water applied (IRR) represents water purchased and is most concern to planners and irrigators. There exists evidence that the form of the yield v/s IRR function is convex in contrast with the straight line form of the yield v/s ET function. For example, Howe and Rhoades (1955) examined 13 irrigation treatments on corn in a very fine sandy loam soil and found a sigmoidal relationship between dry matter production and applied water. Stewart and Hagen (1973) showed that the functional relation between yield and the seasonal irrigation depth of the field water supply (which includes rainfall and available soil moisture at planting) is convex (a second degree polynomial). They defined irrigation efficiency as

$$IRR\ EFF = \frac{ET\ (from\ IRR)}{IRR} \times 100 \dots\dots\dots (10)$$

These authors argued that if irrigation efficiency were 100% (all of IRR used as ET), the $Y = f(IRR)$ function and the $Y = f(ET)$ function would be identical. Therefore, the convex form $Y = f(IRR)$ indicates that irrigation efficiency decreases as ET_{max} is approached.

3. Growth stage effects

Jensen (1968) developed a production function which divided the growing season into stages, with ET in each stage having a unique effect on yield. The function expresses relative yield (actual yield divided by potential yield, (Y_a/Y_{max})) as a function of relative ET (actual ET divided by ET when soil moisture is nonlimiting) as follows:

$$\frac{Y}{Y_p} = \prod_{i=1}^n \left(\frac{ET_a}{ET_p} \right)^{\lambda_i} \quad (11)$$

where λ_i is the relative sensitivity of the crop to water stress in the i th growth stage. In this case, ET_p should be interpreted as equivalent to ET_{max} . This function requires that the yield be zero if ET is zero in any one stage. The accuracy of this model depends crucially on the accuracy of the sensitivity indices λ_i .

Stewart and Hanks both developed a second formulation of their models (S_1 and H_1) that permits the incorporation of variable responses to stress occurring in different growth stages. Hanks' model uses a functional form almost identical to Jensen's, except that relative seasonal transpiration is the independent variable rather than ET:

$$\frac{Y}{Y_p} = \frac{T^{\lambda_1}}{T_{p1}} \frac{T^{\lambda_2}}{T_{p2}} \dots \frac{T^{\lambda_n}}{T_{pn}} \quad (\text{Hanks' model } H_2) \quad (12)$$

where λ_n is a weighting factor expressing sensitivity to water stress in the n th stage. Here T_p should be interpreted as T_{max} , and Y_p as Y_{max} .

Stewart used a different coefficient for each stage and postulated an additive effect:

$$Y_a = Y_m - Y_m(\beta_1 ET_{D_1} + \beta_2 ET_{D_2} + \dots + \beta_n ET_{D_n})/ET_m \quad (\text{Stewart's model } S_2) \quad (13)$$

where ET_{D_i} is the ET deficit in stage i and ET_m is for the entire season. Hiler and Clark (1971) proposed a stress day index incorporating both leaf water potential and soil water potential to measure the water stress imposed on a crop throughout the growing season in an additive fashion.

Economic Production theory

Existing economic studies of water production functions fall into two categories. The empirical studies follow conventional economic theory in abstracting from or ignoring the issue of the timing of input application. A crucial premise of these studies is that conventional economic theory provides an adequate framework for analyzing crop–water production relations. Characteristically, the work involves the use of statistical methods to estimate production functions from empirical data. Inasmuch as the preponderance of empirical data is available in undated form, these studies invariably rest on the assumption that the timing of water applications is always optimal.

The second group of studies, characterized here as theoretical studies, are based on the proposition that the economic theory of crop water production must be a specialized theory, one that specifically includes the effects of timing. This work tends to be more theoretical than empirical because of the relative dearth of experimental data on the effects of timing. In this section, the principal studies in each of these categories are reviewed in some detail.

A. EMPIRICAL STUDIES

The empirical studies are well exemplified by the research of Koster and Whittlesey (1971). These workers developed production functions which express seasonal yield as a function of two inputs, seasonal applied water and seasonal nitrogen fertilizer application. The timing of application was not considered. Three polynomial forms of the production function were statistically evaluated, with the square-root form showing the best fit. Hexem *et al.* (1976) reported work with Mitscherlich and polynomial functions that reemphasized the view that polynomial forms appear to best capture the relationships between yield, water, and fertilizer embodied in the empirical data.

The work of Hexem and Heady (1978) represents the single most important contribution of empirical studies. This work contains a comprehensive review of both the conventional economic theory of production and the basic statistical techniques that are commonly utilized to estimate production

functions. The empirical findings of field experiments on corn, wheat, cotton, and sugar beets at different sites in Arizona, California, Colorado, Kansas, and Texas are formulated and reviewed in an economic context. The reported relationships generally specify yield as a function of applied water and nitrogen fertilizer in polynomial forms. A good deal of variability in both the estimated coefficients and the functional forms is reported from year to year and from site to site. The authors suggested that much of this variability may be attributed to differences in environmental conditions over time and between sites, as well as to management and cultural practices. Subsequently, the results of efforts to develop generalized production functions for each of the four crops are reported. Several functions perform reasonably well in predicting the yields actually realized at different sites, but the work is far from conclusive.

This study has made three principal contributions. First, this work contains an analysis of a wider range of water/crop production data for different crops in an economic context than has been attempted elsewhere. Second, the estimation of generalized production functions represents the most ambitious effort to date to account for the transferability of production function knowledge from site to site. Third, the estimation of generalized production functions represents the only effort to estimate water production functions utilizing a number of variables that account for differences in soil, climate, and cultural practices. The major shortcoming of this study, as well as of other empirical economic studies, is the failure to deal in any systematic way with variations in the timing of irrigation applications. The theoretical studies address this issue more explicitly.

B. THEORETICAL STUDIES

The second class of economic studies encompasses all work which is premised on the notion that the issues of application timing and the interrelation between applied water and actual plant water use are special and important enough to warrant a modification of standard economic theory. Some of this literature is strictly theoretical and some of it includes empirical analyses, but all of the production functions used are especially adapted to account for the timing of water applications.

The first major attempts to include time as a variable in economic studies of crop water use resulted from the postulate of Taylor (1952), that the integral of soil moisture stress in the root zone over the growing season would be an excellent predictor of plant growth. Clearly the timing of water application affects the fluctuation in soil moisture tension over time. Beringer (1961) described Taylor's integrated moisture stress and applied some basic economic analysis, but added little that was new to the concept. Neither

Taylor nor Beringer specified a production function based on this index, although Beringer suggested the functional form

$$\text{Yield} = f(S^{-1})$$

where S is the index of soil moisture stress. If S were integrated moisture stress, then, implicitly, each incremental growth period would be treated as equally affected by stress.

A related analysis which employs mean moisture stress as the independent variable was developed by Moore (1961). Moore assumed that there is a separate and independent production function for each irrigation cycle. Each production function is based on known soil moisture release curves that depict the amount of moisture available to a crop between field capacity and the permanent wilting point. Actual plant growth is a function of the amount of soil moisture depletion. It is assumed that plant growth is linear over all irrigation cycles and, consequently, that the effect of moisture stress on yield in any one cycle is the same as that in any other cycle. The yield response function thus takes the form

$$Y = \sum_{i=1}^n \left(\frac{t_i}{T} Y_{\max} \frac{1}{RG_{\max} - \text{TMP}} \int_0^{\text{TMP}} RG \, d\text{SMD} \right) \quad (14)$$

where Y is the actual yield, t_i the time in the i th cycle, RG the relative growth rate (%), SMD the soil moisture depletion (%), TMP the terminal moisture depletion (%), Y_{\max} the potential yield, T the time in the growing season, and $RG_{\max} = 100\%$.

The production function is formulated in an economic context by estimating the costs and revenues associated with each level of soil moisture depletion in any single irrigation cycle. The optimal level of irrigation is then established at the point where the marginal cost of irrigation is equal to the marginal revenue foregone with respect to soil moisture depletion. In most instances, optimality will require different levels of soil moisture depletion for different irrigation cycles. In this way, both the optimal timing of application and the optimal quantities to be applied can be derived.

Bielorai and Yaron (1978) used soil moisture tension in developing a similar approach for characterizing production functions that is less information intensive. A soil moisture variable, which is a function of time and soil depth, is used to express the moisture status of soil over time. When soil moisture falls below a predetermined "critical level" during the day, yield is affected by some increment. Seasonal yield is expressed as a function of the number of "critical days." The theoretical construct reported in this study was based on empirical work on grapefruit and peanuts developed by Yaron *et al.* (1972). In this latter work, yield was estimated as a function of several different measures of soil moisture status and soil salinity. The work was

especially notable because water quality was explicitly considered as an independent variable.

Economic notions of costs and returns were not introduced in either of these studies; rather, the studies were designed to demonstrate that soil moisture status and its impact on yield can be modeled with a limited amount of empirical data. The conclusion of the work is that irrigations should be scheduled so that the number of critical days is minimized or eliminated altogether. This conclusion appears to rest on the presumption that yield ought to be maximized, although the analysis could be expanded to introduce notions of optimality. No effort was made to consider the implications of interstage dependency.

The soil moisture functions discussed so far have all implicitly allowed the timing of water application to affect crop yield through adverse changes in soil moisture status. But none have allowed the plant's growth response to moisture stress to vary according to its stage of growth. This improvement was made in a study by Mapp *et al.* (1975). Their production function expressed yield reduction in each of three stages as a linear function of the soil moisture depletion and evaporative stress in that stage. The linear model performed reasonably well in a series of 20-year simulations, although the yield response to water stress at lower applications levels was consistently underestimated. However, the model or some variation of it appears to hold promise as a means of evaluating the economics of irrigation strategies.

A large body of the economic literature dealing with crop-water production functions has focused specifically on the question of the optimal application of water over the growing season. This literature recognizes the fact that irrigation scheduling requires knowledge of plant response to water stress (and therefore water use) at different times of the season. Dated or multistage production functions are clearly a necessary requirement if the problem of irrigation scheduling is to be modeled accurately.

Virtually all economic studies of scheduling incorporate dynamic programming to determine the optimal allocation of water. There appears to be a consensus that dynamic programming represents the state of the art for analyzing optimum water allocation among a discrete number of growth stages. However, since there are very few empirically derived multistage production functions, these allocation models generally rely on assumptions about the dated effects of water stress.

The first major study using dynamic programming was that by Flinn and Musgrave (1967). Their model, which is based on the results of Denmead and Shaw, accounts explicitly for the effect of climatic conditions on crop yield. Both the functional relationships and the "experimental" data were derived from a simulation model for a hypothetical crop and thus it is difficult to assess the accuracy of this portion of the model. The authors assumed,

however, that growth occurs only on those days when actual ET equals potential ET. In contrast with Moore's work, which employs a linear growth curve, in this study a sigmoid growth curve is used to compute the yield contribution from each stage. Cost and revenue functions were included in the model and maximization of profit was assumed to be the objective. The number of irrigations in each stage was treated as the decision variable. The model is not fully complete, however, because it was based on the assumption that the quantity of water applied per irrigation was fixed and interstage dependence or "conditioning" was ignored.

Hall and Butcher (1968) developed a dynamic programming model to allocate irrigation water over n plant growth stages, not necessarily of equal duration. They assumed that if soil moisture were to fall below field capacity in any stage i , then yield would be reduced by a factor a_i which is itself a function of soil moisture. The a_i functions were not specified, but could presumably differ to reflect the differing effects of moisture stress at successive growth stages. The production function was written as

$$Y = (a_1 a_2 \cdots a_n) Y_{\max} \quad (15)$$

where Y_{\max} is the maximum potential yield for the season. The multiplicative effect of this model reflects the important fact that if water input falls to zero in any stage, the plant dies. This is an improvement over formulations like Flinn and Musgrave's, in which the stage effects are strictly additive, implying that the total absence of water in any stage would only result in some discrete reduction in yield. A major weakness of this study is the authors' failure to deal systematically with the relationships between applied water, soil moisture, and evapotranspiration.

Two similar works, published in 1971, utilized Markovian analysis to model the effect of climatic data expressed in terms of historical probabilities (Burt and Stauber, 1971; Dudley *et al.*, 1971). Burt and Stauber defined two state variables as (1) crop condition and (2) remaining water supply. Transitions between values of the state variables were expressed as probabilities and the production function was assumed to have the form

$$\psi(Y) = h \sum_{i=1}^M \phi_i(W_i) \quad (16)$$

where $\psi(Y)$ is a monotonic transformation of yield that permits use of a dynamic linear program for computational purposes, W_i is a variable of climatic and cultural factors (including AW) in stage i , and h and ϕ_i are simply called "arbitrary functions."

An advantage of this general production form is that it allows the yield response function in each stage (ϕ_i) to be different, whereas other production functions generally allow only coefficients of the same functional form to

change between stages. It appears that interstage dependence can be included in this model by allowing W_i to be dependent on water stress in previous periods, but this has not been done. Again, interstage dependence and the problems with using applied water as the independent variable have not been addressed by the authors.

Dudley *et al.* (1971) also used the two-state-variable stochastic approach, with the state variables defined as (1) soil moisture and (2) remaining irrigation water. Their growth model is identical to Flinn and Musgrave's, with growth set equal to zero on any day where actual ET falls below potential ET. Actual ET is derived from soil moisture by

$$ET_a = P \times \text{potential ET} \quad (17)$$

where P is a "soil factor" which is a function of soil moisture and evaporative conditions.

Although Dudley *et al.* (1971) did not model interstage dependence, they acknowledged the need for it and suggested the inclusion of a third state variable to express and account for the previous history of applied water and growth. They also assumed that the water applied at each irrigation will be that necessary to return the soil to field capacity. Both Dudley and co-workers and Burt and Stauber employed dynamic programming techniques to solve their model and assumed that growers maximize profit.

Yaron *et al.* (1980) extended the dynamic programming methodology to include the salinity of the soil and irrigation water. Their profit-maximizing model employs two state variables: the soil moisture level at the beginning of each day and the salinity of the soil solution at the beginning of each day. These two components are used to calculate the total soil water potential. The yield of the crop is then expressed as a function of the number of "critical days," days where the soil potential exceeds a critical level. The production function incorporates days of stress rather than water used as the independent variable:

$$Y = A \prod_{j=1}^J F_j^{X_j} \quad (18)$$

where A is the maximum yield, X_j the number of "critical days" in each subperiod J , and F_j the coefficient of yield reduction per critical day. Transformation functions, which estimate the changes in soil water content and soil solution salinity, were taken from other published work. The production function model is identical to the one tested by Bielorai and Yaron (1978) and incorporates the effects of water quality.

Dynamic programming appears well suited for analyzing the problems of irrigation scheduling. Unfortunately, the development of the methodology has outpaced the development of data, particularly those needed to estimate

multistage or dated production functions. One small group of theoretical studies does focus on the specification of the dated production function, however. The two studies which compose this group have both combined theoretical specifications of the production functions with empirical analysis of data. A further distinction of these two studies is that they use ET or relative ET as the independent variable rather than applied water.

Gowon *et al.* (1978) used experimental data on corn from Davis, California, to statistically estimate a three-stage production function based on Hanks' model of production (see Stewart *et al.*, 1977a). This model is

$$\text{Yield} = (\text{relative ET}_1)^{\alpha_1}(\text{relative ET}_2)^{\alpha_2}(\text{relative ET}_3)^{\alpha_3} \quad (19)$$

where $\alpha_1, \alpha_2, \alpha_3$ are exponents for each stage of growth, which are estimated by regression analysis. The elaboration and interpretation of the results are incomplete and it is therefore difficult to assess the potential of this work.

Probably the most important work on dated production functions published to date was that carried out by Minhas *et al.* (1974). They developed (1) a production function based on relative ET which fits experimental data and (2) a theoretical approach to derive relative ET from available soil moisture. This is the only study to deal with the relationship between the various independent variables used (ET, soil moisture, applied water). Unfortunately, the derivation appears to be too complicated for practical use. The production function has the following form:

$$Y = a[1 - (1 - x_1)^2]^{b_1}[1 - (1 - x_2)^2]^{b_2} \cdots [1 - (1 - x_3)^2]^{b_3} \quad (20)$$

where Y is the yield, X_j the relative evapotranspiration in period j , and a and b_j are parameters. The parameters were estimated by regression analyses of experimental data, and the relative ET_i is simply the actual ET in stage i divided by the potential ET in the same stage. This function has two useful properties:

- (1) It is multiplicative over the stages, meaning that yield falls to zero if ET falls to zero in any stage.
- (2) The marginal product of the relative ET_i goes from ∞ to 0 as the relative ET_i goes from 0 to 1.

Empirically, the relative ET function performs reasonably well in predicting the actual ET of water for wheat in India and alfalfa in Ohio. The authors cautioned, however, against a generalization of their findings, since their data base was quite limited and sketchy. Although this work is highly promising from a conceptual standpoint, it remains to be seen how well it will stand up to a more comprehensive empirical evaluation. Additionally, it is possible that this formulation will prove to be quite information intensive.

Concept of soil plant relations

People are dependent on soils- and to a certain extent good soils are dependent upon people and the use they make of them. Soils are the natural bodies on which plants grow. Society enjoys and uses these plants. Standard of living is often determined by the quality of soils and kind and quality of plants and animals grown on them. Plants are dependent on favourable combination of some six environmental factors: light, mechanical support, heat, air, water and nutrients. With the exception of light, soil can supply each of these factors. But only when they are supplied in the right combination is best plant growth obtained. The factor that is least optimum will limit this growth. The principle, called the law of the minimum may be stated in a practical way as follows: The level of plant production can be no greater than that allowed by the most limiting of the essential plant growth factors. One of the principal reasons for studying soils is to ascertain which factor is least optimum and how its limitation to plant growth can be removed.

The uptake of essential elements is determined not only by the availability of the soil-held nutrients but by their being in proximity to the root surface. Nutrients are supplied to the root surfaces in three ways: First, as roots penetrate the soil they come in contact with soil colloids on which nutrients are held. This is termed root interception. Second, some nutrients move to the roots with water as it is absorbed by plants. Such movement is called mass flow. Third, as nutrients are absorbed by plant roots, a concentration gradient is set up between the zone immediately around the root surfaces and the soil zone farther away. In response to this gradient, diffusion of ions towards the root surfaces takes place. For cations such as K^+ and Ca^{2+} diffusion is by far the most important means of supplying nutrients to plant roots. Diffusion is also important for anions such as NO_3^- , although mass flow also can be quite significant for these negatively charged ions.

Root uptake of nutrients by plants requires intimate root-soil association. But research has clearly demonstrated that the plant does not simply absorb in a passive way essential nutrients presented to it. In the first place nutrient solubility is markedly affected by root exudates and by microbial activity in the vicinity of the roots (rhizosphere). Furthermore, entrance of soluble nutrients into root cells is stimulated by plant root metabolism. Chemical carriers (probably proteins) transport ions across membranes into cells. A combination of active transport and ion diffusion makes possible the movement of ions from the soil solution to the vessels that can carry the nutrients upward in the plant. Respiration by the root cells supplies energy for this nutrient absorption. Respiration by the root cells supplies energy for this nutrient absorption. Thus plant and microbial processes, coupled with the soil processes, implement the effective utilization of essential elements for crop production.

Soil-plant nutrient relations

Soil-plant interrelations are dynamic and subject to both inputs (fertilisers, pollutants, soil chemistry) and losses (erosion, leaching, harvesting). Metal ions are released into soil solution via weathering and solubilisation of soil minerals (Section 16.1) as well as via decomposition of organic matter.

Available ions are those that a particular root system can acquire. Strictly speaking, only ions in soil solution would be considered available, but due to a dynamic equilibrium that exists between the soil solution and other ion pools from which ready transfer into the soil solution can occur, ions adsorbed onto exchange sites can also be considered as available, or at least as influencing the available fraction.

Factors affecting ion supply to plant roots include ion activities in the soil solution, usually referred to as intensity, and the degree and rate of replenishment of the soil solution ion pool from other pools (ions adsorbed on solid soil particles or labile organic compounds and ions present in other readily soluble compounds), usually referred to as capacity. The capacity factor therefore determines a buffer power for a particular metal. The relationship between capacity and intensity factors for each particular metal is heavily dependent on pH.

Cation exchange capacity (a)

Clay particles are negatively charged and therefore surrounded by a swarm of (positively charged) cations. Clay minerals owe a part of their negative charge to isomorphous substitution (cations of higher charge, like Al^{3+} , are replaced by those of lower charge, like Mg^{2+}) thus leaving a surplus of (non-neutralized) negative charges which are satisfied with adsorbed, exchangeable

cations. In addition, soil colloids (e.g. humus, hydrous oxides) that exhibit protonated complexing functional groups (–OH, –COOH) also contribute to the cation exchange capacity of soils:

M^{1+}	+	M_2X	\leftrightarrow	M^{2+}	+	MX
(solution)		(solid)	\leftrightarrow	(solid)		(solution)

Since dissociation of –OH and –COOH groups (especially those on organic matter) is pH dependent, cation exchange capacity increases with an increase in pH. With an increased cation exchange capacity, metal cations are attracted to these negative sites on solid particles, soil solution is depleted and therefore metal availability reduced.

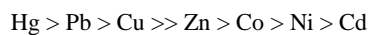
Retention of cations in soils (b)

Cations are held more strongly (less reversibly) when pH increases from 5 to 7. Cu, Zn, Ni, Cd and other metals become significantly less soluble and less exchangeable when pH increases from 5 to 7. Retention of metals in soil can occur through several processes: (1) cation exchange (non-specific adsorption), (2) specific adsorption, (3) organic complexation and (4) co-precipitation. In a given situation most, if not all, of these processes contribute to metal retention in soils.

In order to maintain electroneutrality, negative charges on solid particles (soil colloids) are balanced by an equal amount of cations; an exchange refers to the exchange between counter-ions balancing the surface negative charge on the soil colloids and ions in soil solution. Such an exchange is reversible, stoichiometric and diffusion controlled. Moreover, there is a certain degree of selectivity of the adsorbent. The higher the valency of an ion, the greater its replacing power (H^+ behaves like a polyvalent cation). By contrast, with greater degrees of hydration, a given ion will exhibit a lower replacing power.

Adsorption by cation exchange represents electrostatic binding through the formation of outer-sphere complexes with the surface functional groups. An outer-sphere complex means that at least one molecule of a solvent comes between the functional group and the ion.

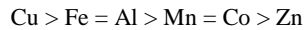
Specific adsorption is pH dependent and related to the hydrolysis of the heavy-metal ion. In specific adsorption partly covalent bonds are formed with the lattice ions. Partly covalent bonds are inherently stronger than electrostatic binding involved in the non-specific cation exchange (e.g. Zn can be adsorbed on Fe and Al oxides 7 and 26 times more strongly than their corresponding cation exchange capacity at pH 7.6 would imply). Metals most able to form hydroxy complexes are specifically adsorbed to the greatest extent:



Specific adsorption may also include diffusion of metals into mineral interlayer spaces and their fixation there. Such diffusion increases with an increase in pH.

Organic matter may either increase or decrease availability of micronutrients, Al and heavy metals. Reduced availability is due to complexation with humic acids, lignin and other organic compounds of high molecular weight (insoluble precipitates are thus formed). Conversely, increased availability may result from solubilisation and thus mobilisation of metals by low molecular

weight organic ligands (e.g. short-chain organic acids, amino acids and other organic compounds). Stability constants of chelates with several metals occur with increasing order as:



Co-precipitation represents formation of mixed solids by simultaneous precipitation as occurs with Fe and Mn oxides.

Soil-plant pH (c)

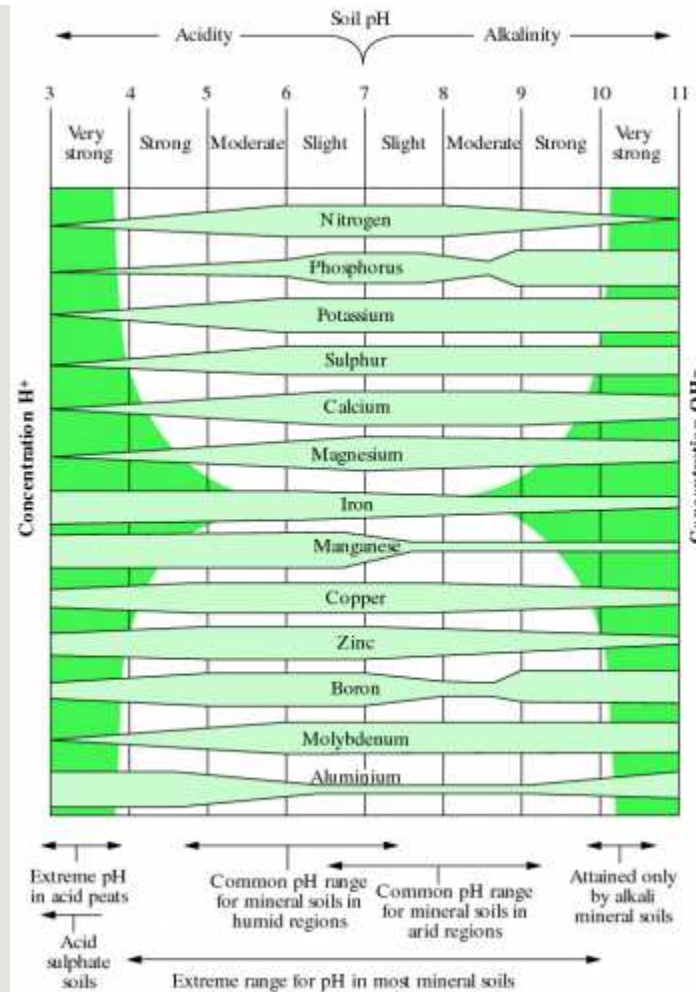


Figure 1 A highly diagrammatic picture of soil nutrient availability (and element toxicity) as a function of pH. Increasing acidity or alkalinity correspond to logarithmic increase in concentration of H^+ and OH^- respectively (vertical bars). Horizontal bars represent relative availability (or toxicity) at any particular pH. Most agricultural soils will be slightly acid (pH around 5.5 to 6.5) and essential nutrients are all readily available within that range. Of particular note, highly acid soils are conducive to both Al and Mn toxicity and to Mo deficiency. Highly alkaline soils are conducive to B toxicity but to Fe, Zn and Mn deficiencies. (Based on various sources including Handreck 1978 and Marshner 1995)

The pH value most relevant to soil and plant chemical processes is pH of the soil solution. A soil is acidic if the pH of its aqueous solution phase is <7 and alkaline if that pH exceeds 7. Nutrient element availability varies accordingly (Figure 1), and beyond the range of pH 4–8 plant growth becomes a function of pH *per se*, plus pH effects on nutrient ion availability.

In chemical terms, pH represents a measure of H^+ activity in a soil solution which is in a dynamic equilibrium with a negatively charged solid phase. H^+ ions are strongly attracted to these negative sites and have sufficient power to replace other cations from them. A diffuse layer in the vicinity of a negatively charged surface has higher H^+ activity than the bulk soil solution.

Soil pH varies in time and space. Diurnal fluctuations of as much as one pH unit may occur, as well as spatial variations (horizontal and vertical down the soil profile). Soil pH also varies over seasons. During seasons with low to moderate rainfall when evapotranspiration greatly exceeds precipitation, salts are not being removed by deep percolation and increased salts tend to reduce pH by forcing more of the exchangeable H^+ ions into the soil solution. Conversely, during wet seasons, salts are removed from the topsoil and pH goes up. This season to season fluctuation in total salt content should not be confused with long-term soil acidification (Section 16.5).

Relationships between pH and ion toxicity (d)

Soil pH is a dominant influence on solubility and therefore availability and potential phytotoxicity of metals (Figure 16.2). Low pH favours free metal cations and protonated anions, higher pH favours carbonate or hydroxyl complexes. Therefore, availability of micronutrient and toxic ions (which are present in soil solution as cations) increases with increasing soil acidity. By contrast, availability of those present as anions (MoO_4^{2-} , CrO_4^{2-} , SeO_4^- , SeO_3^- and $B(OH)_4^-$) increases with increasing alkalinity (see Case study 16.1).

Rhizosphere (e)

Plant growth is dependent on availability of water and nutrients in the rhizosphere, the soil–root interface consisting of a soil layer varying in thickness between 0.1 mm and up to a few millimetres depending on the length of root hairs (Section 3.3). Availability of nutrients in the rhizosphere is controlled by the combined effects of soil properties and interactions between plant roots and adjacent microorganisms in the surrounding soil.

Chemical conditions in the rhizosphere are usually very much different from those in the bulk soil further away from roots. Root-induced changes in the rhizosphere pH are a result of the balance between H^+ and HCO_3^- excretion, evolution of CO_2 by respiration and loss of various organic compounds known collectively as root exudates.

The balance between H^+ and HCO_3^- excretion depends upon the cation/anion uptake ratio. Greater excretion of H^+ accompanies a greater absorption of cations than anions and results in rhizosphere acidification. Conversely, when uptake of anions exceeds uptake of cations, excretion of HCO_3^- exceeds that of H^+ . The chemical form of soil N (ammonium v. nitrate) is an influential factor for the cation/anion ratio. Ammonium-fed plants take up more cations than anions, and they usually have a more acidic rhizosphere than bulk soil, while nitrate-fed plants take up more anions than cations and show the opposite relationship between rhizo-sphere and bulk soil pH. Plant effects on rhizosphere pH also vary with genotype, which can in turn influence nutrient ion availability (Section 3.3.1).

Overall, plants and soils must be regarded as interacting components in any ecosystem, and because plants take up more basic than acidic components, any net increase in ecosystem biomass will result in some degree of soil acidification.

Soil-plant-water relationships

Soil-plant-water relationships treat those properties of soils and plants that affect the movement, retention, and use of water. These properties must be considered in designing and operating conservation irrigation systems. In planning an irrigation system, an agronomist/engineer is concerned primarily with

1. the water-holding capacity of a soil, particularly in a plant's root zone;
2. the water-intake rate of the soil;
3. the root system of the crop to be grown; and
4. the amount of water that the crop uses.

But he must also have a working knowledge of all soil-plant water relationships in order to plan efficient irrigation for particular crops grown on particular soil and to adjust the design to various conditions. This general knowledge also enables him to assist an irrigator in managing the system efficiently.

Soils

Soil is a three phase system comprising of the solid phase made of mineral and organic matter and various chemical compounds, the liquid phase called the soil moisture and the gaseous phase called the soil air. Besides a storehouse of plant nutrients and a reservoir that holds the water needed for plant growth, it is a habitat for bacteria and an anchorage for plants. The amount of water a soil can hold available for plant use is determined by its physical properties. This amount determines the length of time a plant can survive without water being added. It determines both the frequency of irrigation and the capacity of the irrigation system needed to ensure continuous crop growth.

Physical properties of soil

Mineral soils are porous mixtures of inorganic (mineral) particles, decaying organic matter, air and water. They also contain a variety of living organisms. The parent material of mineral soils consists of loose unconsolidated fragments of weathered rocks or unconsolidated sediments of various kinds. Physical and chemical weathering give rise to a horizontal layering in the soil mass. These different soil layers can be seen in trenches, eroded banks, and road cuts. Collectively these layers (horizons) from top to bottom are called the soil profile. Their arrangement and the kinds of material in the layers affect both root growth and the movement and retention of water in the soil.

Two important physical properties of soils are texture and structure. Soil texture refers to the relative proportion of the various size groups of mineral particles in a given soil. Soil structure refers to the manner in which the soil particles are arranged in groups or aggregates. Together, soil texture and soil structure help to determine the supply of water and air in a soil.

Unlike texture, structure of the surface soil can be changed. Excellent structure develops in the surface layer of soils high in organic matter and on which a perennial grass is growing. Cycles of wetting and drying or of freezing and thawing improve structure in the plough layer. On the other hand, cultivation of medium or fine textured soils when their moisture content is high tends to destroy structure. Irrigation water containing large amounts of sodium causes very undesirable structure by dispersing the soil aggregates.

The physical condition of the soil in relation to plant growth and ease of tillage is commonly called tilth. It depends partly on granulation and on stability of the granules. Tilth is commonly evaluated as good, fair, or poor, according to the ease with which the soil can be worked and the rate at which it takes in water. Soils in good tilth are mellow, crumbly, and easily worked; they take up water readily when dry. Soils in poor tilth generally are hard, cloddy, and difficult to work; they take up water slowly and run together when wet. Good soil tilth can be developed and maintained on most soils by using good soil management practices.

Soil water

Since a constant supply of water in the soil is necessary for plant survival and growth, the irrigation agronomist/engineer is concerned with how water moves in a given soil, how much water a soil can hold and how much of it is available to plants, and how the water supply can be replenished. The first two are related to size and distribution of the soil pores and to size of the soil

particles and their attraction for moisture. The amount of water a soil holds also depends on the amount of organic matter in the soil. Generally, the finer the soil particles and the larger the amount of organic matter, the more water a soil holds.

Kinds of water in the Soil

The soil pores, spaces between the particles, form a network of connected cavities of every conceivable shape and size. When water is added to a dry soil by either rain or irrigation, it is distributed around the soil particles where it is held by adhesive and cohesive forces; it displaces air in the pore spaces and eventually fills the pores. When all the pores, large and small, are filled, the soil is said to be saturated and is at its maximum retentive capacity.

The water in the large pores that moves downward freely under the influence of gravity is called gravitational water or free water. When the supply of water to the surface is cut off, water continues to drain from the large pores for a few days. In well-drained soils, the free water near the surface usually has moved out before crops are damaged. The large pores are again filled with air; water in the small pores moves because of capillary forces and is called capillary water. It moves more slowly than free water; it can move in any direction but always in the direction of the greatest tension.

Evaporation from the surface and absorption of moisture by growing plants further reduce the amount of water in the soil until water no longer moves because of capillary forces. It is held so tightly as very thin films around the soil particles and in minute wedges between the particles at their points of contact that it cannot be used by plants and they begin to wilt. Eventually the soil is so dry that plants die if water is not added to the soil. The remaining water is held on the particle surfaces, particularly the soil colloids, so tightly that much of it is non-liquid and moves as a vapour. This is called hygroscopic water.

Of these three forms of water, gravitational, capillary, and hygroscopic, the irrigation agronomist/engineer is concerned primarily with gravitational and capillary water since hygroscopic water is not available to plants.

Movement of water in the Soil

The movement of water in the soil is complex because of the various states and directions in which water moves and because of the forces those cause it to move. Because of gravity, water moves downward. Because of adhesive and cohesive forces, it moves in small pores by capillarity. Because of heat, it vaporizes and diffuses through the soil air.

The rate at which gravitational water percolates through the soil is determined chiefly by the size and continuity of the pore spaces. Water usually moves freely through the large pores in coarse-textured soils. It moves less rapidly through fine-textured soils because of the resistance to flow in small pores, which may also be blocked by swollen colloidal gels and trapped air. Percolation is retarded by a slowly permeable layer such as a claypan or ploughpan. A sand lens temporarily halts percolation; but once water penetrates such a layer, it continues to move downward.

Irrigation water moves as a front--from a saturated soil layer to an unsaturated layer. Movement of the front is unsteady; water builds up behind the front until the large pores are filled and then moves to the next layer of large pores. In moist soils water movement is more uniform than in dry soils.

The movement of capillary water is affected by soil texture. The forces that cause capillary movement in small pores result largely from the difference in tension between films of different thickness around soil particles; the movement is from thick films to thin films. If these forces are expressed in terms of tension, water moves from an area where tension is low to an area where tension is high. At saturation, capillary movement is most rapid in sandy soils and slowest in clay soils. But in drier or unsaturated soils capillary water moves slowly in sands and more rapidly in clays.

Heat causes water to move as a vapour. As water vapour diffuses through the soil air near the surface, it either condenses in another part of the pore space or escapes into the atmosphere. As water is evaporated from the surface, capillary water rises and replaces part of the evaporated water. This continues until the upper few inches of the soil become dry and capillarity is broken. Water then leaves the soil only by vaporizing at the upper capillary fringe and diffusing through the overlying dry soil.

How Water Is Held in the Soil

Work must be done (energy used) to remove water from a soil. The force (tension) with which water is held depends on the amount in the soil—the smaller the amount, the greater the tension. The forces that determine tension are adhesion, the attraction

of soil-particle surfaces for water, and cohesion, the attraction of water molecules for each other. By adhesion water is held tightly at the soil-water interface. By cohesion these water molecules hold other water molecules. Because of these forces water fills the small pores in the soil and is in fairly thick films in the large pores. As the films become thicker, however, the water molecules at the outer surface, the liquid-air interface, are held less tightly. They can move in response to the pull of gravity and to the pull of less thick films nearby. Thus not much work or energy is required to remove water from a soil near saturation. But as more and more water is removed, more and more energy is required.

Soil-moisture tension

Soil-moisture tension is a measure of the tenacity with which water is retained in the soil and shows the force per unit area that must be exerted to remove water from a soil. It is usually expressed in atmospheres, the average air pressure at sea level, but other pressure units can be used. At a temperature of 21 °C (69.8 °F),

1 atmosphere = a pressure of 14.71 pounds per square inch,

= a column height of 76.39 centimetres of mercury

= a column height of 34.01 feet or 1,036 centimetres of water.

An expression of soil-moisture tension does not indicate the amount of water a soil contains nor does it indicate the amount of water that can be removed at that tension. These amounts, which depend on both texture and structure, must be determined. Generally sandy soils drain almost completely at low tension, but fine-textured clays still hold a considerable amount of moisture even at such high tensions that plants growing in the soil wilt.

To show the amount of moisture a given soil holds at various tensions, moisture-extraction curves (moisture characteristic curves) must be developed. This can be done by plotting tension in atmospheres against moisture content in percentage by weight. Tension values indicate the ease or difficulty with which moisture can be removed from a soil and moisture percentage indicates the amount of water still in the soil.

Soil-moisture tension as discussed in the preceding paragraphs is based on pure water. Salts in soil water increase the force that must be exerted to extract water and thus affect the amount of water available to plants. The increase in tension caused by salts is from osmotic pressure. If two solutions differing in concentration are separated by a membrane impermeable to the dissolved substance, such as a cell membrane in a plant root, water moves from the solution of lower concentration to the one of higher concentration. The force with which water moves across such a membrane is called osmotic pressure and is measured in atmospheres.

In many irrigated soils, the soil solution contains an appreciable amount of salts. The osmotic pressure developed by the soil solution retards the uptake of water by plants since the total moisture stress is the sum of the soil-moisture tension and the osmotic pressure of the soil solution. Plants growing in a soil in which the soil-moisture tension is 1 atmosphere apparently can extract enough moisture for good growth. But if the osmotic pressure of the soil solution is 10 atmospheres, the total stress is 11 atmospheres and plants cannot extract enough water for good growth.

Available Water

In designing an irrigation system and in making recommendations for improved techniques of applying water, the agronomist/engineer needs to know how much of the water in a soil is available to plants. The soil is like a tank and holds just so much available water. Its capacity is limited by the total amount of water it can hold between field capacity and the permanent wilting point. In addition to soil-moisture tension and the osmotic pressure of the soil solution, availability of water also depends on the temperature of the soil. Low soil temperatures decrease availability.

Field capacity is usually considered as the amount of water a well drained soil holds after free water has drained off or the maximum amount it can hold against gravity. The large pores in the soil are filled with air, the micropores are filled with water, and any further drainage is slow. In this condition, the soil is said to be at field capacity.

Soil-moisture tension in a salt-free soil at field capacity ranges from less than 0.1 to nearly 0.7 atmosphere, depending on soil texture. Sands are at field capacity when tension is near 0.6 atmosphere and loamy sands when tension is near 0.1 atmosphere.

Silt loams are at field capacity when tension is about 0.3 atmosphere. Clays and clayey soils are at field capacity when tension is about 0.6 atmosphere.

Field capacity of a soil can be determined, after it has been thoroughly wetted by rain or irrigation water, by covering a small area to prevent evaporation and determining the moisture content after drainage has taken place. One method is to take soil samples, weigh them, dry them in the oven, and reweigh them.

The permanent wilting point, also known as permanent wilting percentage, is the soil-moisture content at which plants can no longer obtain enough moisture to meet transpiration requirements; they wilt and remain wilted unless water is added to the soil. The moisture tension of a soil at the permanent wilting point ranges from 7 to 32 atmospheres, depending on soil texture, on the kind and condition of the plants, on the amount of soluble salts in the soil solution, and to some extent on the climatic environment. Since this point is reached when a change in tension produces little change in moisture content, there is little difference in moisture percentage regardless of the tension taken as the permanent wilting point. Therefore 15 atmospheres is the pressure commonly used for this point. During periods of low humidity, high temperature, and high wind velocity many plants with a large leaf surface show wilting even though the moisture content of the soil is higher than that at the permanent wilting point. This occurs because the transpiration rate exceeds the rate at which the plant can extract moisture from the soil. When a plant wilts, growth stops. Irrigation water, therefore, should always be applied to a soil before the moisture content of the root zone is reduced to the permanent wilting point.

The wilting range is the range in soil-moisture content through which plants undergo progressive degrees of permanent or irreversible wilting, from wilting of the oldest leaves to complete wilting of all leaves. At the permanent wilting point, which is the top of this range, plant growth ceases. Small amounts of water can be removed from the soil by plants after growth ceases, but apparently the water is only slowly absorbed and is only enough to maintain life until more water is available. The bottom of the range is called the ultimate wilting point. When the moisture level reaches this point, wilting is complete and plants die. Although the difference in the amount of water in the soil between the two points may be small, there may be a big difference in tension. At the ultimate wilting point soil-moisture tension may be as high as 60 atmospheres.

Since the moisture available for plant growth is the capillary water between field capacity and the permanent wilting point, the available water holding capacity of a soil can be determined by subtracting the amount of moisture remaining in the soil at the permanent wilting point from the amount held at field capacity.

Soil texture is of primary importance. For soils low in soluble salts, the finer the texture, the greater the available moisture holding capacity. But some sandy soils actually hold more available water than some clays, chiefly because in fine-textured soils so much water is held on the particles. Even at the permanent wilting point, the moisture content of some clays is fairly high.

Well-drained sandy soils have a low available water holding capacity. At field capacity, most of the pore space in sandy soils is filled with air and thus there is little available moisture. Silty soils generally have a good available water holding capacity since a soil made up of silty particles of about the same size releases most of its moisture at tensions ranging from one-third atmosphere to 15 atmospheres. But in some silty soils the spaces between large particles may be filled with smaller particles, resulting in a low available moisture holding capacity. Some silt loams hold more than 2 inches of available moisture per foot of soil, but some silty soils are very droughty. Clays and clay loams are usually high in available water - about 2 inches per foot of soil—and still hold a considerable amount of unavailable moisture at the wilting point. Organic soils hold a considerable amount of water at field capacity, but since much of the water is not available, they also have a high moisture content at the wilting point.

So far in this discussion, field capacity has been considered the upper limit of available moisture. This is not entirely true. In sprinkler and surface irrigation, water applied to the surface of the soil moves downward as a front, saturating the upper layers in most soils before the irrigation application is completed. Plant roots in the upper soil layers take up some of the water between saturation and field capacity. The amount plants use depends on how fast the soil drains to field capacity and on how often it is irrigated. Under good irrigation management on most soils, the length of time in which plants can use the extra moisture before the soil reaches field capacity is limited. For design purposes, therefore, this water is not considered.

Water intake

The movement of irrigation water from the surface into and through the soil is called water intake. It is the expression of several factors, including infiltration and percolation.

Infiltration

The downward flow of water from the surface into the soil is known as infiltration. Water enters the soil through pores, cracks, worm and decayed-root holes, and cavities introduced by tillage. In many places infiltration is restricted by surface sealing or crusting.

Percolation

For irrigation water to be effective in replenishing the soil's water supply, it must be able to move down, or percolate, through the soil to a predetermined irrigation depth. This movement of water through the soil profile is known as percolation. The percolation rate is governed by the permeability of the soil or its hydraulic conductivity. Both terms are used to describe the ease with which soil transmits water.

Permeability is the quality of soil that enables it to transmit air and water. It is independent of the viscosity of water. The relative permeability of soils is described in general terms as rapid, moderate, and slow.

Hydraulic conductivity is determined by both the soil and the fluid transmitted. It expresses the readiness of a soil to let a particular fluid flow through it for a given potential gradient. It is the coefficient "k" in Darcy's Law ($v = ki$) in which v is the effective flow velocity and i is the hydraulic gradient. The values of k depend on the properties of the fluid as well as on those of the soil, and they reflect any interactions of the fluid with the porous medium, such as swelling of a soil and the attendant reduced porosity.

Since water percolates chiefly through the large pores in a soil, percolation depends on the relative number and continuity of these pores. A soil that has high porosity and coarse open texture has a high hydraulic-conductivity value. For two soils of the same "total" porosity, the soil with small pores has lower conductivity than the soil with large pores because of the resistance to flow in small pores. A soil with pores of many sizes conducts water faster if the large pores form a continuous path through the profile. In fine-textured soils, conductivity depends almost entirely on structural pores. In some soils, particles are cemented together to form nearly impermeable layers commonly called hardpans. In other soils, very finely divided or colloidal material expands on absorbing water to form an impervious gelatinous mass that restricts the movement of water.

The quality of the water transmitted, particularly its salinity and alkalinity, has a marked effect on hydraulic conductivity. A change in the viscosity of water has an effect. A chemical change in water may greatly affect hydraulic conductivity without changing viscosity. The addition of a small amount of sodium chloride to the soil water, insufficient to make any noticeable difference in viscosity, may affect soil structure so much that hydraulic conductivity is greatly reduced.

Factors Affecting Intake Rate

The intake rate of a soil is a measure of its capacity to take in and absorb irrigation water applied to the soil surface during the period of time in which water is applied. The amount of moisture already in the soil greatly influences the rate at which water enters the soil. The soil takes in and absorbs irrigation water rapidly when water is first applied to the field surface. As the irrigation application continues, the surface soil gradually becomes saturated and the intake rate decreases until it reaches a nearly constant value.

The intake rate of any soil is limited by any restriction to the flow of water into or through the soil profile. The soil layer with the lowest transmission rate, either at the surface or below it, usually determines intake rate. The most important general factors that influence intake rate are the physical properties of the soil and in sprinkler irrigation the plant cover. But for any given soil other factors may affect the intake rate.

SURFACE SEALING. The formation of a thin compact layer on the ground surface rapidly reduces the rate of water intake through the surface. This layer results from a breakdown in structure, in part because of the beating action of raindrops or sprinkler drops and in part because of the action of water flowing over the surface whereby fine particles are fitted around larger particles to form a relatively impervious seal.

The effect of surface sealing on intake can be greatly reduced, if not eliminated, by protecting the soil surface with mulch or some other permeable material. Grasses or other close-growing vegetation will help to prevent surface sealing. The hardened or compact surface of a soil subject to surface sealing can be broken up by a light cultivation before irrigation water is applied.

SOIL COMPACTION. On some wet soils tillage operations may cause compaction and the formation of a ploughpan just below cultivation depth. A ploughpan impedes water movement and reduces the intake rate. The intake rate is materially reduced in furrows where tractor wheels operate. Subsoiling helps to improve the movement of water through a ploughpan and thus the intake rate, particularly in soils that have a relatively impermeable sublayer that can be broken up. The soil takes in more water through the enlarged openings and continues to take in water so long as they remain.

SOIL CRACKING. On heavy clay soils that crack on drying, irrigation generally can be accomplished by rapidly filling the cracks before the soil starts to swell. The amount of water that can be applied depends on the number and size of the cracks. As soon as the soil particles become wet, they begin to swell; eventually the cracks are closed so that further intake is either impossible or extremely slow.

TILLAGE. The intake rate may be increased by ploughing, cultivating, or any other stirring that increases the size of openings. But the beneficial effect of cultivation on soil porosity and intake lasts only until the soil settles back to its former condition of density because of subsequent rain or irrigation. The intake rate of loose, porous sands is not likely to be increased by any artificial disturbance. On some soils, cultivation reduces intake by closing up the natural surface openings that lead into the body of the soil. The most important effect of tillage on water movement is to break up a surface seal.

CROP ROTATIONS. If coarse organic materials are evenly incorporated into the soil, porosity remains high for comparatively long periods, depending mostly on the rate of decomposition of the materials. The intake rate can be maintained and even increased by using a cropping system that provides for incorporating crop residues in the upper few inches of the soil, growing grasses and legumes, and using any other methods that increase the organic-matter content of the soil. If a good crop rotation is followed, the proportion of stable soil aggregates is increased, which means large pores and consequently a high water-intake rate.

SOIL AND WATER SALTS. Any salts contained in irrigation water accumulate in irrigated soils and in time may change their character. This accumulation is serious in the arid West where almost all water is supplied by irrigation. In humid areas rainwater percolating through the soil leaches out most accumulated substances. But, in arid regions it is often necessary to overirrigate (leach) periodically to remove soluble salts from the soil.

Some soluble salts in irrigation water such as potassium nitrate may be directly beneficial to crops. Under some conditions, calcium and magnesium have a beneficial effect on the physical condition of the soil. High concentrations of sodium chloride or sodium sulfate, however, have a detrimental effect. If the sodium concentration is high, soil structure breaks down and eventually the soil colloids are dispersed, resulting in a tough or rubbery condition. Tilth and permeability are reduced. This sealing is noticeable even in some sandy soils.

The physical properties of some alkali soils, including intake, can be improved by adding chemicals or soil amendments through which exchangeable sodium is replaced by calcium. A comparatively economical and often used soil amendment is calcium sulfate, or gypsum. In some soils, its use results in improved permeability and aeration and thus better root development and plant growth. Other chemicals that can be used on some soils are sulfur and aluminum sulfate.

SEDIMENTS IN IRRIGATION WATER. In some places, fine silt and clay particles carried in suspension affect the quality of irrigation water. Whether this is detrimental or beneficial depends on the amount of silt transported, the length of time the silty flow continues, and the texture of the soil to which the water is applied. Occasional deliveries of silty water may be beneficial on coarse sandy soils inasmuch as the sediments improve the physical condition of the root zone, thereby reducing the rate of water movement. They also add some plant nutrients such as potassium, calcium, and phosphates to the soil. But silty water applied to fine-textured soils generally makes the surface of the soil still more slowly permeable and difficult to cultivate.

SOIL EROSION. As erosion progresses, the intake rate of many soils is reduced since less permeable material such as a dense clay subsoil is uncovered. In other soils erosion exposes coarse-textured layers such as sand and gravel. Here the intake rate is increased and irrigation efficiency is greatly reduced.

LAND LEVELING. The moving and mixing of soil in land leveling may change the water-intake rate of any given area. The effects are similar to those of erosion in that either more permeable or less permeable soil material is uncovered. Earth-moving equipment used in land leveling may compact the soil and thereby reduce the intake rate. Subsoiling is often necessary after land leveling.

TEMPERATURE. Tests show that water intake is greater during summer rains than during winter rains. Apparently the temperature of irrigation water has some effect on intake rate since the coefficient of viscosity of water decreases rapidly as temperatures increase. This effect is not considered significant by most authorities.

Plants

Almost every plant process is affected directly by the water supply. Water constitute about 80-90% of most plant cells and tissues in which there is active metabolism. The factors influencing the water relations of plants and thus their growth and yield responses, may be grouped into the following:

- (i) Soil factors – soil moisture content, texture, structure, density, salinity, fertility, aeration, temperature and drainage.
- (ii) Plant factors – type of crop, density and depth of rooting, rate of root growth, aerodynamic roughness of the crop, drought tolerance and varietal effects.
- (iii) Weather factors – sunshine, temperature, humidity, wind and rainfall.
- (iv) Miscellaneous factors – soil volume and plant spacing, soil fertility, and soil and crop management.

The size of the soil reservoir that holds water available to a plant is determined mostly by that plant's rooting characteristics. The distribution of its roots determines its moisture-extraction pattern.

How Plants Get Their Moisture

Most plants have an enormous absorbing root surface. Near the growing tip of each root or rootlet, there are many root hairs in close contact with soil particles and with the air spaces from which roots get their oxygen. Through osmotic and other forces, root hairs extract moisture from the film of water that surrounds each soil particle.

Two phenomena seem to explain how a plant gets the enormous amount of water it takes in and transpires: (1) Capillary movement of water to plant roots and (2) growth of roots into moist soil.

As roots take up moisture, tension around the soil particles increases and water moves toward these points of plant absorption. How effective capillary movement is depends on how much water can be delivered to the soil around the roots and how fast it gets there. But since there is little root extension when the soil-moisture content is low, it is likely that near the wilting point any water that reaches plant roots must move to them.

During favourable growing periods, roots often elongate so rapidly that satisfactory moisture contacts can be maintained even when the soil moisture content declines and without much help from capillary movement.

Where a good root system has developed during favourable growing periods, a plant can draw its moisture supply from deeper soil layers. Thus if the roots in the upper part of the soil have depleted the moisture there to below the wilting point, plant needs can still be met provided roots have already grown into deeper layers that contain an adequate moisture supply.

Kinds of Root Systems

The kind of root system a plant develops is fixed by heredity. Each species has its own characteristic growth habit. Some plants have a tap root that penetrates deeply into soil under favourable conditions. Other plants are slow growing and develop shallow primary roots and many lateral roots.

Most of the roots of spinach and celery are in the surface foot of soil, and those of potatoes are within the upper 2 feet. Corn, cotton, and tomatoes permeate an open soil to a depth of 4 feet or more. Alfalfa and asparagus roots penetrate good soils to a depth of 8 to 10 feet or more. Cucumber roots extend laterally 5 or 6 feet in the ploughed layer. Asparagus roots make little lateral spread in comparison with their depth.

CONSUMPTIVE USE

Consumptive use, often called evapotranspiration, includes water used by plants in transpiration and growth and that evaporated from the adjacent soil and from precipitation intercepted by plant foliage. It is expressed in acre-feet or acre-inches per acre or in depth in feet or inches.

Transpiration is the process by which water is removed from the soil by a plant, moved through the plant to the leaves, and lost to the atmosphere in vapor form. For irrigation, the moisture used in plant growth and that retained by the plant is included. Evaporation from the soil surface is not included in transpiration but is included in consumptive use.

Transpiration occurs mostly from the leaves of a plant, but a small part of the emitted moisture comes from the younger stems. It occurs mostly during the daylight hours, and only a small amount, possibly 5 to 10 %, occurs during the night. The rate of transpiration is lowest just before sunrise and usually reaches a maximum shortly before noon. Transpiration accounts for a substantial part of the total consumptive use of a crop.

Some of the factors that affect the rate of transpiration are moisture available in the soil, kind and density of plant growth, amount of sunshine, temperature, and soil fertility. In summer when exceedingly hot winds blow over a field, transpiration may take place more rapidly than moisture can be absorbed by plant roots even when the soil contains an ample supply of moisture. When this occurs, plants wilt. In some the foliage may be dried beyond recovery.

Evaporation is the diffusion of water as a vapour from a surface into the atmosphere. Factors that affect the rate of evaporation are the nature of the evaporating surface and differences in vapour pressure as determined by temperature, wind, and atmospheric pressure. In determining consumptive use, evaporation includes both evaporation from the ground surface and evaporation of the water intercepted by vegetation.

In irrigated fields, frequent shallow irrigations tend to increase water loss by soil evaporation. If less frequent heavy irrigations are used, the soil surface is wetted less often and water penetrates to a greater depth in the soil. Consequently, a larger part of the irrigation water is available for crop use. In fields of hay, pasture, or other close growing crops, evaporation from the soil is reduced not only because the plants transpire a large proportion of the soil moisture but also because they shade the soil.

Soil texture affects evaporation. Evaporation is higher in soils in which capillary movement of water to the surface is rapid. Conversely, evaporation is not so high in soils through which water percolates freely. Losses of water from soil by evaporation vary greatly not only in different areas but also at different times and under different conditions in the same area. Appreciable wind movement, high temperature, and low humidity generally result in a high rate of evaporation if there is enough moisture at the soil surface.

After irrigation, evaporation from the surface of the soil is high so long as the topsoil remains saturated; the rate is about the same as that from a water surface of the same temperature. Depletion of the moisture in the topsoil rapidly reduces the rate of evaporation. The evaporation rate between irrigations depends somewhat on tillage operations, cultivation, and mulching as well as on soil texture, weather conditions, kind of crop, stage of crop growth, and the method, frequency, and depth of irrigation. As plants develop and provide increasingly more shade, the amount of evaporation is progressively reduced.

Daily Consumptive Use

Daily consumptive use, that in a 24-hour period, varies as the factors that influence evaporation and transpiration vary. Consumptive use is low at the start of the growing season, increases as plant foliage develops and days become longer and warmer, generally reaches a peak during the fruiting period, and then rapidly declines to the end of a crop's growing season. From the time seed is planted until plants emerge, soil-moisture loss is by evaporation. As plants emerge, transpiration begins and increases in amount as they develop. After the plants die, transpiration ceases and further soil-moisture loss is by evaporation. If all the physical and climatic conditions remain the same, daily consumptive use drops in hay and pasture fields immediately after cutting or grazing because of the reduction in transpiration. If the field is irrigated immediately after cutting, however, there is no reduction in daily consumptive use and the rate may even increase because of high evaporation.

Seasonal Consumptive Use

The total amount of water used in evaporation and transpiration by a crop during its growing season is called seasonal consumptive use. It is expressed usually as acre-inches per acre or as depth in inches but sometimes as acre-feet per acre or depth in feet. Seasonal consumptive use values are needed to evaluate and determine seasonal irrigation water supplies.

Peak-Period Consumptive Use

The average daily water-use rate during the 6 to 10 days of the highest consumptive use of the season is called the peak-period use rate and is the design rate to be used in planning an irrigation system. The peak-use period generally occurs when the crop is starting to produce its harvest, vegetation is most abundant, and temperatures are high. Since the average consumptive-use rate is higher for a very short peak-use period (2 or 3 days) than for a longer peak-use period, the design rate varies with the amount of water that can be used from the root zone (the normal depth of water application per irrigation). In shallow soils, in soils with a low water-holding capacity, or for plants with shallow root systems, the depth to which water is applied is shallow and irrigation frequency during the peak-use period ranges from 3 to 6 days. The peak-use period for plants with a moderately deep root system growing in deep soils with a good water-holding capacity may range from 8 to 15 days. The average use rate for these short periods is considerably higher than the average rate for the month of greatest moisture use and is generally less than the peak daily-use rate. Deep-rooted crops, such as alfalfa, growing in deep soils have a large reservoir to draw on, and the irrigation interval may range from 3 weeks to 1 month; the design rate is equal to or possibly slightly higher than the average rate in the month of greatest moisture use.

The peak-use period for various crops in a given area may occur at different times in the growing season. Early-maturing crops have their peak-use period in late spring or early summer and late-maturing crops, in late summer or early fall. Knowing when these peaks occur is important in working out a cropping plan in which the peak-use periods are staggered, thus reducing the total capacity requirement of the irrigation system. If two or more crops are grown in the same field, such as a permanent cover crop in an orchard or grain with a new alfalfa seeding, the peak moisture requirement of the crop or crop combination that uses more water must be met.

Water movement along soil-plant-atmosphere system

The complete path of water from the soil through the plant to the atmosphere forms a continuous system which may be analysed by evaluating the potential difference between soil and atmosphere in contact with root and leaf, respectively. The path of water may be divided into four sequential processes as follows: the supply of liquid water to the root surface, the entry of water into the root, the passage of water in the conducting elements and the movement of water vapour through and out of the leaves. The rate of water movement is everywhere proportion to the potential gradient and inversely proportional to the resistance to flow. It is desirable to consider water absorption in the total soil-plant-atmosphere system instead of the roots alone. In this system one can partition the system in such a manner so that the involvement of different plant parts is taken into account.

Yield and environmental stress

The environment comprises all entities, natural or manmade, external to oneself, and their interrelationships, which provides value, now or perhaps in the future, to humankind. Environmental concerns relate to their degradation through action of humans.

Any environmental factor (biotic or abiotic) potentially unfavorable to plant is termed as **stress**. The effect of stress on plant condition is called **strain**. According to Newton's law of motion, a force is always accompanied by a counterforce, for an action there is always equal and opposite reaction. Stress is the action and whereas strain is the reaction. A body of a plant subjected to stress is in a state of strain.

Strain may be elastic or plastic strain.

Elastic strain: Up to a point, a strain may be completely reversible and when the stress is relieved, the plant becomes normal.

Plastic strain: Beyond the point of elastic strain, the strain may be partially reversible or partially irreversible, which is called plastic strain or permanent set.

The word stress mean hardship; biotic stress mean hardship due to living (insect-pests, diseases, weeds etc) things; abiotic stress means hardship due to non living things (Fig 1). From agricultural point of view moisture, temperature, radiation and wind are important abiotic factors. Of these, moisture is the most important factor. If moisture availability is normal, stress due to other factors can be tolerated. Stress may be due to excess or deficit of the factor.

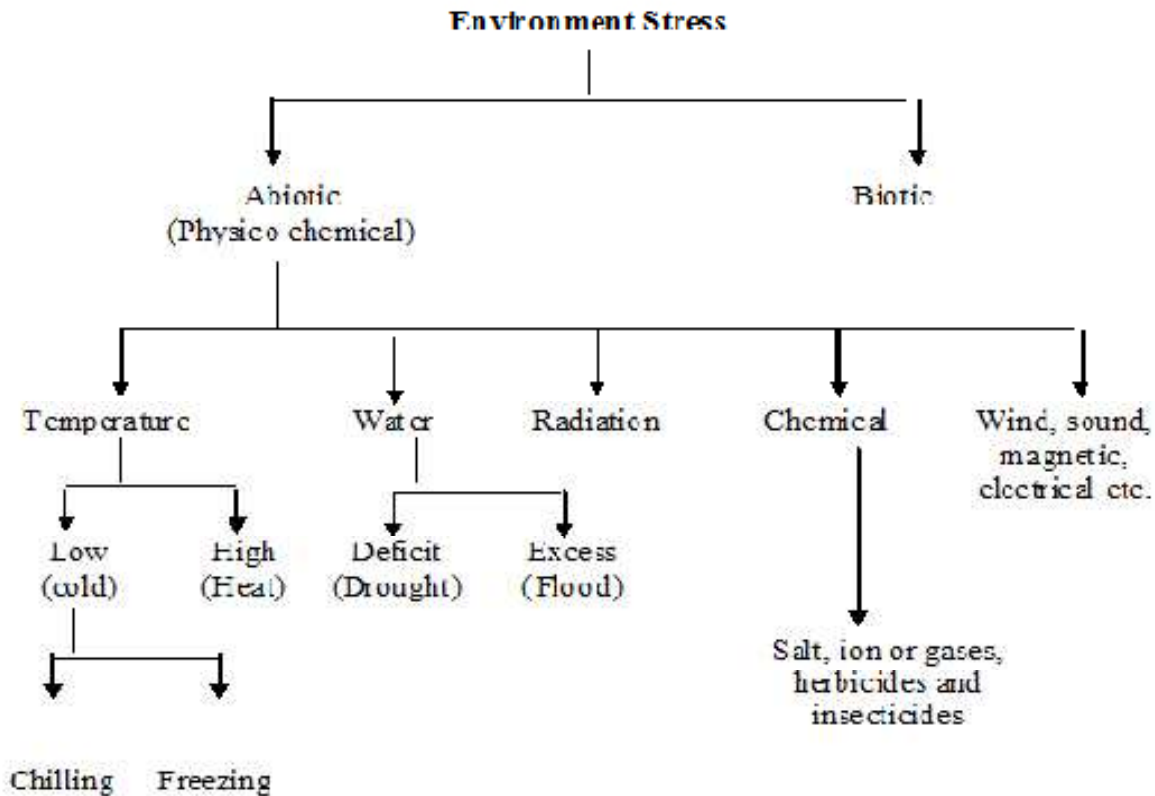


Fig 1 Classification of environmental factors causing stress



Low water stress



Excess water stress

Fig 2 Example of stress due to excess or deficit of the factor

Weather is the most variable factor not only in rainfed but in irrigated agriculture as well. Various approaches often referred to as contingent plans, have been evolved over the years for efficient weather management. The infrastructural requirements have to be developed and established by the government and other agencies as people themselves will not be in a position to adopt contingency measures more effectively because of their poor resource base. Some of the management options that can be adopted to mellow down the adverse effects of excessive rainfall, heat wave, less availability of surface irrigation, deficiency of nutrients, non availability of fertilizers, disease epidemics, insect-pest incidence etc. are discussed under this heading.

Management of stress due to excessive moisture

Excess moisture or waterlogging occurs due to heavy and continuous rains or due to faulty irrigation. Waterlogging causes several changes in the soil and plant resulting in poor growth and in some cases, death of the plants. The damage depends on crops, stage of crop, period of waterlogging and climatic conditions. Tomato, tobacco, chillies, brinjal, pulses are most susceptible to waterlogging. Rice is the most resistance crop for waterlogging. Germinating seeds are sensitive to waterlogging due to lack of oxygen. Seedling stage of the sensitive crops are highly susceptible to waterlogging. Pearl millet is susceptible to waterlogging during seedling stage while it can tolerate waterlogging at later stages. Yield of cereals is depressed if the soil is waterlogged during panicle development. Pulses are susceptible at initial period of reproductive stage. Temperature is the important climatic factor influencing the effect of damage due to excess moisture. Injury due to waterlogging is severe under warm weather conditions. Flooding is more harmful on sunny days than on cloudy days. Flopping or wilting of tobacco takes place only when sunshine occurs after prolonged wet spell.

Waterlogging causes injury to the plant due to low oxygen and accumulation of toxic substances in the soil. the relative importance of these factors for the injury is difficult to explain. Oxygen is depleted completely as the air is exchanged with water. Small pockets of oxygen present in the soil is consumed by microorganisms within hours after flooding. Subsequently toxic substances like hydrocarbon gases, hydrogen sulphide, carbon dioxide etc. Develop due to reduced conditions. Leaching of nitrates and denitrification increases resulting in nitrogen deficiency.

Several morphological, anatomical and physiological changes take place in plants subjected to waterlogging. The important changes are shoot elongation, senescence, abscission and production of adventitious roots. The proportion of

aerenchymatous tissue in the root system increases. Respiration in the roots changes from aerobic to anaerobic respiration with the result that toxic substances accumulate in roots and damage the root tissue. Ethanol production increases and activity of alcohol dehydrogenase increases in roots of waterlogged plants. Ethanol in large quantities is harmful to plants. Permeability of roots decreases due to shortage of oxygen. It results in decreased water uptake and wilting symptoms appear even though soil contains excess water. Permeability of nutrients is also reduced due to some extent by supplying nitrogen fertilizers.

Many parts of low and mid hills of Himachal Pradesh are characterized by medium to high rainfall (1150 to 2700 mm/annum). Distribution is highly monomodal (65 to 80% of the annual rainfall occurring during June to October). High rainfall is a bane rather than a boon. Because of characteristic physiography, state has high soil erosion problems. Rice and maize are main crops during summer/kharif and wheat, potato, sarson in rabi season. Irrigation is limited. Agriculture mainly is rainfed. Stress due to excess moisture is caused by:

1. high rainfall that results in serious soil erosion problems
2. floods in the valley and plain areas of the state that results in serious damage to crops and animals and
3. excess irrigation cause rise of water table, water stagnation and drainage problems in some pockets

Management problems are complex and difficult. Management problems range from soil erosion control (soil and water conservation), water harvesting in situ, storage, diversion and recycling of water and disposal of excess water at different elevations, construction of terraces and sunken and raised beds (buns), practice of agri-hort, agri-pasture, pond based water management system and irrigation and drainage problems in rabi and summer seasons. Management problems vary in different parts. For hills and hill slopes agroforestry and silvipastures can be practiced. In Shivalik areas, *Leucaena leucocephala* in the upper portion and Napier/Setaria/Panicum in the lower portion has been found successful. *Eucalyptus* and Poplar are very successful, however, govt should gear up its efforts in the revival of abandoned tea gardens. Ginger, turmeric, cardamom, colocasia and fruits like oranges, plum, litchi, mango, kiwi etc are fitting crops. Medicinal plants such as Herd, Behra and aonla should find place in sloppy lands.

Management of swampy and waterlogged lands

The swampy lands were initially low lands and fertile lands from rice point of view. Over irrigation, continuous accumulation of water and no drainage have transformed these low lands into waterlogged and swamps, where even cultivation of rice is not done. The swampy land though exist in negligible percentage may be utilized for cultivation of fish, lily and lotus and after reclamation for rice in kharif and berseem in rabi.

Water logging may be temporary for sometime and some weeks or months. Water remains locked due to impedance. Once the excess water drained, the land becomes normal and amenable to normal culture. Permanent water logging makes a land swamp, which can not be made normal land. Swamp may be same as marsh. To manage water logged lands, it is necessary to classify them with extent of waterlogging-howmuch and how long. Waterlogging lands may be rainfed or irrigated. The waterlogging lands may be classified as shallow water (0-30 cm), intermediate water (30-50 cm), semideep water (50-100 cm) and deep water (>100 cm standing water). For all ecosystems, management principles are, crop improvement-breeding selection and evaluation; crop management-selection of variety, planting time, population density, crop geometry, fertilization and crop protection-management of water, weeds, insect-pests and diseases.

Iron toxicity occurs also in waterlogged soils. Rice grown in iron toxic soils show bronzing symptoms. Soils with low levels of nutrients such as K, P, Ca, Mg, Si and Mn and Zn or with respiration inhibitors such as H₂S may cause iron toxicity even with concentration of Fe as low as 30 ppm (60 kg/ha). Iron toxicity problems can be ameliorated by:

- providing deep surface drains
- diverting soluble Fe⁺⁺ iron from the field by repeated drainage
- checking seepage carrying soluble Fe from the upper levels
- Application of liberal dose of K
- Application of lime and
- Growing iron tolerant varieties

Consequent upon introduction of irrigation a different ecosystem develops. Management principles remain same but the system becomes more intensive if irrigated areas are same but the intensity varies.

Management of flood affected areas

Floods refer to great flow of water. It occurs due to heavy rainfall in a short time beyond the capacity of soil to absorb and streams, channels, nallas and rivers to carry. Monsoon rainfall pattern brings more than one flood each year and damage crops and properties. Damage to crops depends on at what stage of crop growth and how long the flood occurs. Classification based on the intensity of floods is helpful for planning to meet the contingencies. If the rainfall is more than the rate of infiltration, it accumulates on the top of the surface and flows down. If there is no way out to flow or drain down, it accumulated and causing water logging. Floods cause water logging even if drainage is free. To manage such situations from crop production point of view delineation of flood prone areas may be accomplished. With weekly rainfall data over years (usually 30 years or more) flood weeks can be calculated and on this basis, areas likely to be affected by floods can be delineated. For such areas measures to grow crops can be devised. Few such measures are early planting/sowing, manuring, growing flood resistance varieties, planting aged seedlings, vegetative propagation, sowing sprouted seeds on puddle soil, raising seedling in polyhouses, stocking more seeds, desilting the leaves and sowing of green gram, blackgram and other pulses after recession of floods to compensate from rice crop loss.

Low water stress

Moisture stress does not affect all aspects of plant growth and development equally. Some processes are highly susceptible while others are far less affected. The final yield of the crop is the integrated result of these effects of stress on water relations, photosynthesis, respiration, nutrition, growth and development. Moisture regimes during flowering and grain development determines the number of fruits and individual grain weight, respectively. During ripening, which involves dehydration and certain biochemical processes, moisture regime has very little effect on yield components. For many crop plants, especially cereals, moisture stress at panicle initiation is critical. As the panicle is the organ that is growing most rapidly, it is most affected by stress due to restriction in cell expansion. Anthesis is another moisture sensitive stage as moisture stress at this stage causes drying of pollen and loss of viability of pollen. Stress during grain development also reduces yield due to reduction in leaf area and photosynthesis. However, vegetative and grain filling stages are less sensitive to moisture stress.

The effect of water stress on yield depends largely on what proportion of the total dry matter produced is considered as useful material to be harvested, when the yield consists mostly aerial parts like forage crops, tobacco etc., the effect of moisture stress is the same as those on total growth. When the yield consists of underground storage organs as in potatoes, sugarbeets etc., it will be as sensitive as total growth. When the yield consists of seeds as in cereals, moisture stress at flowering is detrimental. When the yield is fibre or chemicals where economic product is a small fraction of total dry matter, moderate stress on growth does not have adverse effect on yields.

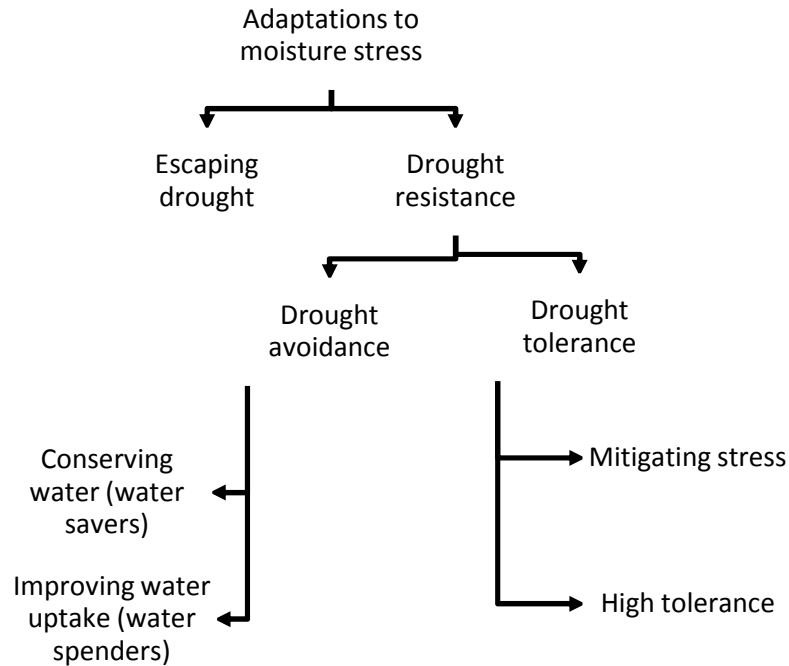


Fig Different mechanism for overcoming moisture stress

In brief the desirable plant characteristics for a drought resistance crop are:

1. Rapid germination and early establishment of deep roots
2. Rapid phenological development
3. Developmental plasticity
4. Parahelonomic movements
5. Stomata sensitive only to large vapour pressure deficits and insensitive to low leaf water potential
6. Ability to adjust osmotically
7. Large transfer of assimilates from stem to grain, and
8. Dehydration tolerance, particularly at seedling and grain filling stages

In addition to the above, characteristics like efficient root system, capacity of roots to grow in dry soils and high rate of photosynthesis with thick small leaves are also desirable for drought resistance.

Important natural resources are rainfall, soil and plants. Resource development and their efficient use are two important aspects to achieve good and stable yields under dryland conditions. The rainfall received in arid and semiarid regions is to be stored either on the soil or in the soil. Soil resources are improved or developed by:

1. Understanding the soil by proper grouping or classification,
2. Rectifying the defects of the soil either by leveling, application of amendments etc and,
3. Increasing storage capacity of the soils.

Plant resources are developed by selecting or breeding drought resistance varieties suitable for arid and semiarid environments.

Management of Acid soils

Acid soils are widespread in high rainfall area. Soil reaction affects concentration of different ions in soil solution and so their availability to the plants. In acid soils concentration of Fe and Mn and Al is more; that of Ca, carbonate, Mg and Mo is less. Fixation of P as iron and Al phosphate render it unavailable to crop plants. It becomes necessary to increase supply of P and calcium to increase crop growth by liming.

High temperature and high wind velocity

Moderate radiation (400-500 ly/day) and 25-35°C temperature with mild wind velocity (20-30 km/h) are congenial for good growth of crops. High temperature is usually associated with high radiation. It increases respiration and reduces working ability. At high atmospheric temperature leaf temperature may remain 5-8 °C more. Stomata closes earlier, moisture stress sets in and leaves roll even if there remains ample moisture in the soil. The lag between moisture supply and atmospheric demand increases very fast. During summer high temperature usually associates with low soil moisture. Under such situations in rainfed areas, there remains no crop. In irrigated areas, summer rice shows wilting of leaves much before noon and recovers in the afternoon only after the effects of scorching sun is reduced. Leaves become turgid before sun set and drops of water trickle down from tips. In the day time transpiration remains very high and crop ET remains more than twice the pan evaporation. High temperature in general, reduces fertilization, increases sterility and affect fruit set.

High temperature adversely affects mineral nutrition, shoot growth and pollen development resulting in low yield.

High temperature with high humidity and low wind velocity is more harmful than that with high wind velocity. A high velocity wind takes away the harmful effects of high temperature and reduces respiration. But high wind velocity has harmful and destructive effects on crops. Like high temperature high wind velocity during flowering reduces pollination, increases sterility and decreases fruit set. It is necessary to have windbreaks and shelterbelts to reduce harmful effects of high temperature and high wind velocity. In the leeward side due to decreased wind velocity, yields of crops are usually more than in windward sides.

Low temperature stress

Low temperature affects several aspects of crop growth viz. survival, cell division, photosynthesis, water transport, growth and final yield. Low temperature stress occurs mainly due to frosts in high altitudes and latitudes.

Temperate crops like wheat and barley have high resistance to low temperature damage especially at a very early stage. When a 5 cm thick ice crust remained for 130 days, 60 cultivars survival among 520 winter wheat varieties collected all over the world.

Low temperature stress results in retardation of cell elongation than cell division. However, leaf growth is accelerated after cessation of low temperature. These reactions of the plant are similar to moisture stress conditions.

When C₄ plants like maize and sorghum are subjected to low temperature of 10°C, the activity of pyruvate dikinase is reduced, resulting in less photosynthesis. Crops are subjected to low temperature either due to cold waves or frosts. If there is sudden fall in temperature by more than 4°C, plants become chlorotic, roots become pale and less active. This type of behavior is seen in wheat and rice. This yellow syndrome on rice was observed over large areas in winter crop of rice even in the south India. Low temperature causes moisture stress. Entry of water into the plant is restricted due to low permeability of cells. The active transport of water from roots to the shoots is stopped at low temperature.

Temperate crops prefer low temperature during vegetative growth while tropical plants require high temperature. The optimum temperatures are different for different stages of crop growth. In temperate crops, the optimum temperatures are lower in the early stages and higher at later stages. The optimum temperature for vegetative, reproductive and grain development stages of wheat are 10, 18 and 20°C, respectively. In tropical crops, the optimum temperatures are more in the early stage and less in later stages. The optimum temperature for rice are 31, 30 and 20°C for tillering, flowering and ripening, respectively. In maize, seedling growth is reduced by 50% at 10°C.

Low temperature causes high spikelet sterility in rice. It ranges from 3.6 to 96.8% depending on variety. The critical temperature for spikelet sterility are 15-17°C. The main reasons for the failure of fertilization are: (1) Unripened pollen (2) indehiscence of anthers, and (3) abnormalities in microspores. The most sensitive stage for low temperature in rice is young microspore stage followed by early meiosis. A temperature of 12°C for even four days causes considerable spikelet sterility in rice. In a broad sense, booting stage is sensitive to temperature stress similar to moisture stress. As rice is a sink limited crop, whatever may be the cause for stress at sink developing stage, considerable reduction in yield occurs. Temperature and moisture stress at panicle

development stage is, therefore, more critical. Higher level of nitrogen application increases cool temperature susceptibility. However, application of P or FYM increases the tolerance of rice to low temperature induced sterility.

Less availability of surface irrigation

Water is more dynamic and essential constituent for every living being. It is the best gift of nature but is the costliest commodity. Its scarcity is felt everywhere in the ice caps, in plains and in oceans. It must to know the relation between water and soil, water and plant and soil-water-plant-atmosphere. Under limited availability it become more important to follow the cardinal principles such as when to irrigate, how much to irrigate and how to irrigate.

The crop is to be irrigated at soil moisture stress below which irreparable damage is caused to the crop and any subsequent manipulation does not help it. For most non rice crops, stress of 0.5 to 0.6 bar (depletion of 55 to 65% available moisture) is appropriate soil moisture stress for irrigation. For rice soil moisture should be retained at saturation from transplanting to panicle initiation followed by 3-5 cm standing water till 12-15 days after flowering. There is no necessity to maintain deeper standing water for longer time in the field.

Irrigation if available, must be applied at critical stage(s), when, unless irrigated the yield will reduce drastically. Depending upon availability of irrigation and importance of phase, number of irrigation is to be decided. At farmers level, the stage of the crop growth is the most deciding factor to select the time of irrigation.

Soil is the reservoir of water for crops, but it is leaky one. It can not hold much water than its field capacity. Hence, the field should be irrigated to bring the deficit to field capacity. Over irrigation leads to excess water use, reduction in WUE and increase in water logging.

Deficit of water after quantification can be applied through a suitable weir, flume or a water meter. Method of irrigation depends on topography, soil characteristics, type of crop and quantity of irrigation water available. Flood irrigation is most wasteful and drip irrigation the most efficient. Drip irrigation is successful in orchard and plantation crops and where water is scarce. Among water lifting devices use of pumps is the best. Under extreme irrigation water deficits, soil and water conservation practices, those recommended for rainfed agriculture may be followed.

Deficiency of nutrients under high moisture stress

Impeded drainage causes several chemical changes under reduced conditions. These situations cause deficiency or toxicity of certain elements. The disorders consider to be caused by submerged conditions are generally called physiological diseases. But some nutritional disorders may also occur even if the condition is not a submerge directly or indirectly created by weather/climate and many other factors. In Himachal Pradesh, deficiency of N,P, K, S, Zn and B in majority of soils is critical, whereas toxicity of Fe, Al, sulphide and organic acids have concern under waterlogged soils. Crop loss due to such disorders in general can be reduced by management of the ecosystem, drainage, water control, alternate wetting and drying and in few cases by supplementing deficient elements. In Himachal Pradesh, mixed farming is predominant and wherever FYM is used micronutrients deficiencies are seldom encountered. However, thorough decomposition, proper handling and application of FYM as well as other sources of organic manures need due focus. Every household in the rural establishments use fuel wood and plenty of ash rich in many nutrients is available. However, judicious use of it is important. Combining all the available organic sources present with the farmers may not fulfill nutrients need of crops especially of nitrogen.

Waterlogged soils wherever exists in the state have very poor physical conditions and difficult of be ploughed off in *kharif*. No bullock or tractor can enter into it. Only manual labour serve the purpose. These lands also suffer from Fe toxicity. The land remains almost fallow in *rabi*, though some of the farmers cultivate berseem in it. Putting these lands idle even in *kharif*

is also common. Drainage and potassium manuring can reclaim these lands. Growing non-tolerant varieties has a little benefit in these lands (Lenka and Jena, 2002). It is necessary to identify and delineate waterlogged and submerged area (both in rainfed and irrigated) and evolve strategy of management.

Basic concepts in Nutrient availability under moisture stress conditions

Most of the nutrients exist in mineral and organic matter and as such are insoluble or unavailable to plants. Nutrients become available through mineral weathering and organic matter decomposition. The nutrient availability process constitutes a sequence of reversible and irreversible reactions. These reactions depicting soil- plant- continuum are not so simple but are definitely governed by the principles of thermodynamics and rate kinetic. A part from these, other important factors including temperature, light, precipitation, irrigation, leaching and interactions of genotypic and phenotypic characteristics of individual plant species affect nutrient availability. Uptake of nutrients by plants occurs in the form of ions. The major processes which transport ions to the roots are root interception, mass flow and diffusion. The process of penetration of roots through the soil and thus coming in contact with soil colloids on which nutrients are held is termed as interception. Some of the nutrients are transported to the roots with water as it is absorbed by plants. This is called mass flow. As the nutrients absorbed by plant roots, concentration gradient occurs between the zone immediately around the root surface and the zone further away. As a result of this concentration gradient, diffusion of ions towards the root surface takes place.

In various soils, mass flow mechanism play an important role to supply Ca^{++} , Mg^{++} , NO_3^- , and SO_4^{2-} . However in some cases when the mass flow falls and nutrient supply is insufficient, diffusion becomes the important process as in the case of P and K. The extent of soil moisture plays an important role in determining the significance of mass flow and diffusion process. Diffusion, however, becomes progressively less important as the moisture content decreases.

Moisture stress v/s nutrient transformation

Moisture stress plays an important role in nutrient solubilization and precipitation reactions. As the moisture content in soil decreases the concentration of soluble salts in the soil solution increases. This leads to the enhancement of the osmotic potential of the soil solution and subsequently influences plant water relations. With the increase in the salt concentration some salts approach their solubility constants and they start precipitating. The soluble anions are HCO_3^- , SO_4^{2-} and Cl. One of the salts which precipitate first is gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$). Among the cations, if sodium (Na^+) is present in soil in significant quantity i.e. in excess of about 6% of CEC, it results in dispersion of soil aggregates and leads to decrease in hydraulic conductivity, increase in soil resistance and crust formation. Water availability up to certain extent may also affects dissolution (weathering) of soil minerals. This may keep feldspars and other potassium bearing minerals intact and these minerals serve as primary sources of plant available K. Moisture deficiency affects phosphorus availability. Drying of soil leads to precipitation of orthophosphate (PO_4) in various forms of calcium phosphate. In soils falling under temperate regions precipitated calcium phosphate exists mainly in the form of octacalcium phosphate, which is a less soluble source of plant available P. This compound remains in equilibrium not only with soluble PO_4 , but also with adsorbed P and other calcium phosphate minerals with the equilibrium concentration varying with moisture content of soil, salt concentration, pH and other associated factors. Often, P immobilized as octacalcium phosphate can eventually become available to plants. Solubility of nutrients is affected due to moisture stress by way of lowering down of root activity. If root system is highly active, a considerable amount of CO_2 is liberated into the soil solution which lowers down the pH of the solution and thereby altering the solubility of many minerals.

In Himachal Pradesh, fertilizer consumption is quite low and imbalanced (nearly 50 kg of NPK/ha) as against the recommended application of nutrients. Farmers are required to be educated for the balance application of nutrients. Even if some farmers apply fertilizers in sub-optimum quantities, they rush to Cooperative Societies only when demand is immediate. Many a times, the fertilizers are not available timely. Farmers, therefore, procure fertilizers at least a season ahead and store properly or they should place their demand in time, which is never in practice.

Insect-pest and disease epidemics

Insect-pests and diseases attack crops at different stages of growth. Yield losses due to pests (weeds, insects, diseases and others) is about 10.3%. Though insects and diseases do not compete for space and light, they do compete for nutrients, if not for moisture. Damage due to insects and diseases may be very severe even leading to complete damage of a crop over several thousand hectares. Weeds, wild rice and rice serve as perpetuating sources for insect survival and multiplication and infestation

from crop to crop in rice areas. Due to introduction of HYVs, responsive to high doses of N and spread of irrigation, many pests which were minor or unknown have become major or and their incidence has increased.

Among pesticides, consumption of insecticides is highest followed by herbicides and fungicides. Among crops, consumption of insecticides is highest for cotton (52%), rice (17%), vegetables (13%), plantation crops (7.8%), other cereals (6%), sugarcane (2%) and others (1%) (Lenka and Jena, 2002). Efficacy of insecticides depends on weather conditions. It is much less in wet season than in rabi/summer season. Pesticides are one of the potential sources of environmental pollution and cause health hazards to all animals, man, cattle, fishes. To safeguard against possible hazards from pesticides, it is pertinent to follow IPM. IPM comprises combination of cultural, mechanical, biological and chemical methods.

Prevention and control measures against diseases are also cultural, mechanical, biological and chemical. IPM or IDM is an environmentally sound alternative to the sole use of chemicals. IPM strives to optimize rather than maximize pest control efforts. To prevent entry of disease or pest infested materials from abroad, the GOI passed an act "Destructive Insect Pests Act of India 1994" and the act was enforced in 1925. Prior to this, there was no restriction on movement of seed/plant from abroad to the country. There are quarantine centers established at seaports, airports, railway heads and land frontiers in the country. There is also domestic quarantine to restrict spread of pathogen from one state to another.

Integrated farming systems, organic farming, resource conservation technology including modern concept of tillage; dry farming; determining the nutrient needs for yield potentiality of crop plants; precision agriculture

Integrated farming systems

To meet the multiple objectives of poverty reduction, food security, competitiveness and sustainability, several researchers have recommended the farming systems approach to research and development. A farming system is the result of complex interactions among a number of inter-dependent components, where an individual farmer allocates certain quantities and qualities of four factors of production, namely land, labour, capital and management to which he has access (Mahapatra, 1994). Farming systems research is considered a powerful tool for natural and human resource management in developing countries such as India. This is a multidisciplinary whole-farm approach and very effective in solving the problems of small and marginal farmers. The approach aims at increasing income and employment from small-holdings by integrating various farm enterprises and recycling crop residues and by-products within the farm itself (Behera and Mahapatra, 1999; Singh *et al.*, 2006).

The Indian economy is predominantly rural and agricultural, and the declining trend in size of land holding poses a serious challenge to the sustainability and profitability of farming. In view of the decline in per capita availability of land from 0.5 ha in 1950-51 to 0.15 ha by the turn of the century and a projected further decline to less than 0.1 ha by 2020, it is imperative to develop strategies and agricultural technologies that enable adequate employment and income generation, especially for small and marginal farmers who constitute more than 80% of the farming community. The crop and cropping system based perspective of research needs to make way for farming systems based research conducted in a holistic manner for the sound management of available resources by small farmers (Jha, 2003). Under the gradual shrinking of land holding, it is necessary to integrate land based enterprises like fishery, poultry, duckery, apiary, field and horticultural crops, etc. within the bio-physical and socio-economic environment of the farmers to make farming more profitable and dependable (Behera *et al.*, 2004). No single farm enterprise is likely to be able to sustain the small and marginal farmers without resorting to integrated farming systems (IFS) for the generation of adequate income and gainful employment year round (Mahapatra, 1992; 1994). Farming systems approach, therefore, is a valuable approach to addressing the problems of sustainable economic growth for farming communities in India.

The basic aim of IFS is to derive a set of resource development and utilization practices, which lead to substantial and sustained increase in agricultural production (Kumar and Jain, 2005). There exists a chain of interactions among the components within the farming systems and it becomes difficult to deal with such inter-linking complex systems. This is one of the reasons for slow and inadequate progress in the field of farming systems research in the country. This problem can be overcome by construction and application of suitable whole farm models (Dent, 1990). However, it should be mentioned that inadequacy of available data from the whole farm perspective currently constrains the development of whole farm models.

Integrated farming systems are often less risky, if managed efficiently, they benefit from synergisms among enterprises, diversity in produce, and environmental soundness (Lightfoot, 1990). On this basis, IFS models have been suggested by several workers for the development of small and marginal farms across the country (Rangaswamy *et al.*, 1996; Behera and Mahapatra, 1999; Singh *et al.*, 2006).

Conceptual Definition

“Farming System is a complex inter-related matrix of soil, plants, animals, implements, power, labour, capital and other inputs controlled in parts by farming families and influenced to varying degrees by political, economic, institutional and social forces that operate at many levels” (Mahapatra, 1992). The term “farming system” refers to a particular arrangement of farming enterprises that are managed in response to physical, biological and socio-economic environment and in accordance with farmer’s goals, preferences and resources (Shaner *et al.* 1982). “The household, its resources and the resource flows and interactions at the individual farm levels are together referred to as a farm system” (FAO, 2001)

“Systems” could be defined as an organised unitary whole composed of two or more inter dependant and interacting parts, components or subsystems delineated by identifiable boundary or its environmental super system (Singh, 2001). It is a set of interrelated elements each of which is associated directly or indirectly with other elements and no subset is under-related to any other subsets. In system approach, the whole farms rather than the individual crops/enterprises is considered before any decision relation to the choice of enterprise and or technology is made.

The farming systems can be described and understood as by its structure and functioning. The structure in its wider sense includes among others, the land use pattern, production relations, land tenures, size of holding and their distribution, irrigation, marketing including transport and storage, credit institutions and financial markets and research and education. Thus, the “farming system” is the result of a complex interaction among a number of interdependent components. To achieve it, the individual farmer allocates certain quantities and qualities of four factors of production: land, labour, capital and management, which has access the processes, like crop, livestock and off farm enterprises in a manner, which within the knowledge he possess will maximize the attainment of goal he is striving for.

The Farming System, as a concept, takes into account the components of soil, water, crops, livestock, labour, capital, energy

and other resources with the farm family at the centre managing agricultural and related activities. The farm family functions within the limitations of its capability and resources, the socio-cultural setting, and the interaction of these components with the physical, biological and economic factors.

Farming system focuses on:

- The interdependencies between components under the control of household and,
- How these components interact with the physical, biological and socio-economic factors, which is not under the control of household.
- Farm household is the basic unit of farming system and interdependent farming enterprises carried out on the farm.
- Farmers are subjected to many socio-economic, bio-physical, institutional, administrative and technological constraints.
- The operator of the farming system is farmer or the farming family.

The primary inter-relationships at the farming system level are illustrated in Figure 1. This highly simplified model puts the farmer the decision maker, at the center. Decisions are influenced by the priorities of the household, farmer's knowledge and experiences, and resource at his command. External factors - natural, economic and sociocultural, also plays significant roles.

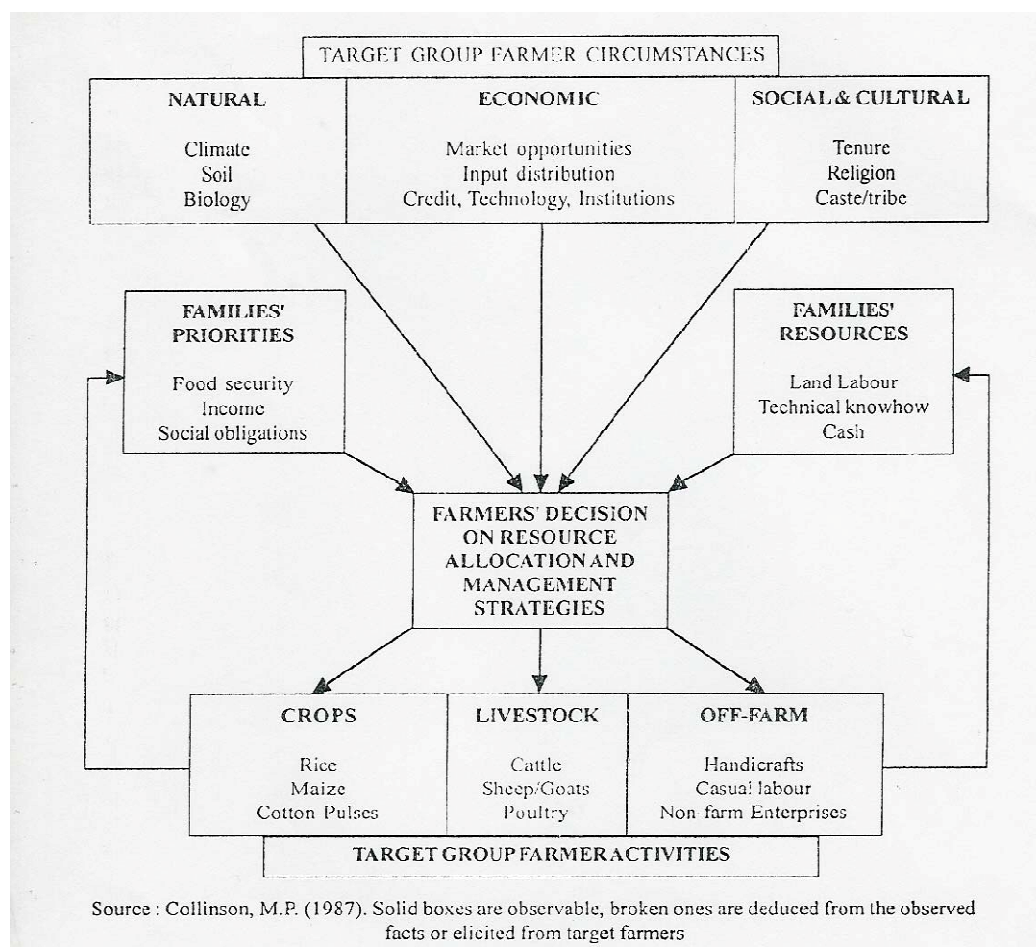


Fig.1: Farming System Model showing interrelationships at the farming system level

Determinants of Farming Systems

The key categories of determinants influencing farming system are as follows:

(i) **Natural Resources and Climate:** The interaction of natural resources, climate and population determines the physical basis for farming systems. The increased variability of climate, and thus agricultural productivity, substantially increases the risk faced by farmers, with the concomitant reduction in investment and input use. Certain soil and water

regimes are suitable only for given type of crops. Similarly, some of the physical and geographical features e.g. drainage characteristics, elevations and slopes as well as climatic factors e.g. total rainfall and its distribution, minimum and maximum temperature, humidity and intensity of sun light etc. are other factors which have to be taken in to considerations while making decision with respect to selection of enterprise for a farming systems.

(ii) Science and Technology: Investment in agricultural science and technology has expanded rapidly during the last four decades. During this period, major technical and institutional reforms occurred, which shaped the pattern of technology development and dissemination.

The research driven growth in developing countries has been green revolution, where it achieved considerable achievement in the field of food grain production and for this the policy and other aspects supported the farming system for such achievement. Research has been focused principally upon intensifying crop and livestock production. There has been for less research on integrated technologies for diversifying the livelihoods of small farmers in developing countries and increasing the sustainability of land use.

Despite these weaknesses, the natural and global research agenda is gradually moving from a focus on individual crop performance to a growing acceptance of the importance of increased system productivity. There has been emphasis in recent agriculture of targeting technologies towards women farmers and poorer households.

(iii) Trade Liberalization and Market Development: Markets have a critical role to play in agricultural development as they form the linkages between farm, rural and urban economics upon which the development processes depend. As a result of the reduction of impediments to international trade and investment, the process of trade liberalization is already generating changes in the structure of production at all levels-including small holder-farming systems in many developing countries. Not only the market development is accelerating, but patterns of production and natural resources usage are also changing profoundly in response to market forces.

The availability of new production, post harvest and transport technologies will also change demand patterns due to delivery of new products or established products in new forms to markets, where they have been previously unattainable.

(iv) Policies, Institutions and Public goods: The development of dynamic farming systems requires a conducive policy environment. Moreover, the establishment of the farm-rural-urban linkages requires effective demand. Policy makers have increasingly shifted their attention to the potential to increase the efficiency of service delivery through the restructuring of institutions. The production incentives have dramatic effect on farming systems. Policies on land ownership, water management and taxation reform etc have a great bearing on types of farming system in a region or area.

(v) Information and Human Capital: The evolution of farming systems based upon increasing specialization (e.g. large scale broiler units) or integrated intensification (e.g. rice-fish-ducks) has required extra knowledge on the part of farm operators. The need for better information and enhanced human capital has also increased, as production systems have become more integrated with regional, national and international market systems. Lack of education, information and training is frequently a key limiting factor to smallholder development. Many observers anticipated an information revolution i.e. bridge gap of knowledge between scientists and farmers will be very key factor for agricultural growth of these small farmers. Whilst in the past many development efforts failed women-because planners had a poor understanding of the role women play in farming and household food security-greater efforts are being made to take account of their actual situations. It is increasingly recognized and acknowledged by development workers that the empowerment of women is the key to raising levels of child and family nutrition, improving the production and distribution of food and agricultural products, and enhancing the living conditions of rural populations. It has been concluded that, if women in Africa received the same amount of education as men, farm yield would rise by between seven and 22 percent (FAO, 1990). Similarly, better access to credit, land and extension services would enable women to make an even greater contribution to eliminating rural hunger and poverty. As gender bias is progressively eliminated during coming years - often in the face of severe cultural and religious barriers productivity within many farming systems will be transformed.

(vi) Indigenous Technological Knowledge: Indigenous technical knowledge is the knowledge that people in a given community has developed over times, and continues to develop. It is based on experience, often tested over long period of use, adapted to local culture and environment, dynamic and changing, and lays emphasis on minimizing risks rather than maximizing profits. The ITK covers a wide spectrum – soil water and nutrient management; pasture and fodder management; crop cultivation; plant protection; farm equipment, farm power, post-harvest preservation and management; agro-forestry; bio- diversity conservation and also exploitation; animal rearing and health care; animal products preservation and management; fisheries and fish preservation; and ethnic foods and homestead management. Thus, the ITK of a farmer has a great influence in managing the farm and farming system.

Components of Farming Systems

The potential enterprises which are important in farming system in the way of making a significant impact of farm by

generating adequate income and employment and providing livelihood security are as follows:

1. Crop Production
2. Dairy Farming
3. Goat and Sheep Rearing
4. Piggery
5. Poultry
6. Duck Rearing
7. Apiculture
8. Fishery
9. Sericulture
10. Mushroom Cultivation
11. Agroforestry
12. Biogas

Interactions

Integrated Farming System (IFS), a component of farming systems introduces a change in the farming techniques for maximum production in the cropping pattern and takes care of optimal resource utilization. The farm wastes are better recycled for productive purposes in the integrated farming system. The inter-related, interdependent and interlinking nature of IFS, involves the utilization of primary produce and secondary produce of one system as basic input of the other system, thus, making them mutually integrated as one whole unit. This incidentally helps to reduce the dependence on procurement of inputs from open market, making thereby the IFS a self-supporting entity and sustainable system over time.

Unlike the specialized farming system (SFS), integrated farming systems activity is focused round a few selected, interdependent, interrelated and often interlinking production systems based on a few crops, animals and related subsidiary professions. The exploitation of possible complementarities or synergy among the various components or subsystems needs to be explored for improving resource use efficiency within the farming systems.

The on-station study involving enterprises such as crop, fishery, poultry, duckery, apiary and mushroom production revealed that there is chain of interactions among these enterprises. The byproduct of one enterprise may effectively utilize for the other enterprise, thus ensuring higher and efficient resource use efficiency.

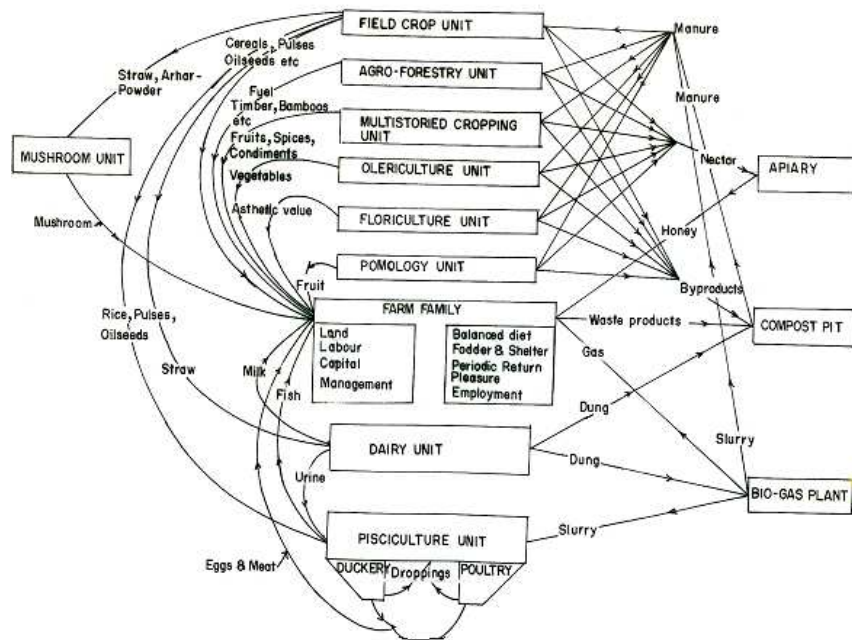


Figure 2: Interactions among different components of Farming Systems

A close examination of resource recycling (Fig.2) indicates the interdependence of the different components of the total farming system to make the farmer self sufficient in terms of ensuring the family members a balanced diet for leading healthy life and also making farm self sufficient through recycling of by products. The by-products of dairy i.e. cow dung forms a major raw materials for biogas plants. Digested slurry of bio-gas plant forms a major part of feed of pisciculture for increasing plankton growth as well as supplying valuable manure to raise the productivity of field crops/enrich the soil. The byproducts of field crops like paddy straw form a major by-product of mushroom cultivation. Straw after use in mushroom production is utilized as cattle-feed and compost preparation. Similarly, the poultry droppings form an important ingredient of pisciculture for increasing the plankton growth as well as increasing the fertility of land. Even apiary played a role of improvement in pollination, apart from giving a wholesome product like honey to farmers. Therefore, it is dangerous to deal separately in such linked agricultural system.

The entire philosophy of integrated farming system revolves round better utilization of time, money, resources and family labour of farm families. The farm family gets scope for gainful employment round the year, thereby ensuring good income and higher standard of living.

Farming System Approach to Research and Development

Farming system research has emerged as a major theme in international agricultural research and rural development. The farming system approach to research and rural development has two interrelated thrusts. One is to develop an understanding of the farm household, the environment in which it operates, and the constraints it faces, together with identifying and testing potential solutions to those constraints. The second thrusts involve the dissemination of the most promising solutions to other farm households facing similar problems. The central issue of the approach is that the analysis of farming systems within which the rural poor live and work can provide powerful insights in to strategic priorities for the reduction of the poverty and hunger now affecting so many of their lives.

Farming System Research (FSR)

Concept: The FSR concept was developed in 1970s in response to the observation that groups of small-scale farm families operating in harsh environment were not benefiting from the conventional agricultural research and extension strategies.

The farming system, as a concept, takes into account the components of soil, water, crops, livestock, labour, capital, energy and other resources with the farm family at the center managing agricultural and related activities. The farm family functions within the limitations of its capability and resources, socio-cultural setting and interaction of these components with physical, biological and economic factors. The term FSR in its broadest sense is any research that views the farm in a holistic manner and considers interactions (between components and of components with environment) in the system.

This type of research is most appropriately carried out by interdisciplinary teams of scientists, who, continuously interact with farmers in the identification of problems and in advising ways of solving them. It aims at generating and transferring technologies to increase the resource productivity for an identified group of farmers.

Objectives and Principles: The FSR advocates that: (i) development of relevant and viable technology for small farmers having the full knowledge of the existing farming system and (ii) that technology should be evaluated not solely in terms of its technical performance but in terms of its conformity to the goals, need and socio- economic circumstances of the targeted small farm system with special reference to profitability and employment generation.

FSR is based on the following basic principles:

- (a) Make the farm household self-sufficient and make the farm free being vulnerable from external forces.
- (b) Enterprise diversification to increase income, employment, risk minimization, improvement in natural resources, environment and diet of farm families.
- (c) The interactions between the components and the components with the environments

Core Characteristics: Many of the core activities of FSR/E can be operationalized in different ways. The approach is open to multiple interpretations. In spite of the variations in their perceptions about FSR/E among the practioners, the approach has certain distinctive core characters. These are:

- i) **It is problem solving:** As an applied problem solving approach, it emphasizes on developing and transferring

- appropriate technologies to overcome production constraints through diagnosis of biophysical, socio-economic and institutional constraints that influence technological solutions.
- ii) **It is holistic:** The whole farm is viewed as a system encompassing interacting sub-systems, and no potential enterprise is considered in isolation.
 - iii) **It acknowledges the location specificity of technological solutions:** Recognizing the location specific nature of agricultural production problems, it emphasizes on testing and adaptation of technological solutions based on agro-ecological and socio-economic specificities.
 - iv) **It defines specific client groups:** Emphasis is made on the identification of specific and relatively homogeneous groups of farmers with similar problems and circumstances for whom technology is to be developed as the specific client groups. On the basis of common environmental parameters, production patterns and management practices, relatively homogeneous recommendation domains need to be identified.
 - v) **It is farmer participatory:** It revolves round the basic principle that successful agricultural research and development efforts should start and end with the farmers (Rhoades and Booth,1982). Farmer participation is ensured at different stages of technology generation and transfer processes such as system description, problem diagnosis, design and implementation of on- farm trials, and providing feedback through monitoring and evaluation.
 - vi) **It gives weightage to ITK system:** The Indigenous Technical Knowledge (ITK), which is time tested at the farmer's level for sustainability through a dynamic process of integrating new innovations into the system as they arise, has to be properly understood by the scientists and utilized in their research activities.
 - vii) **It is concerned with 'Bottom-up' research strategy:** It begins with an understanding of existing farming system and the identification of key production constraints.
 - viii) **It is interdisciplinary:** It lays greater emphasis on interdisciplinary cooperation among the scientists from different areas of specialization to solve agricultural problems that are of concern to farmers.
 - ix) **It emphasizes extensive on-farm activities:** It involves problem analysis through diagnostic surveys, on-farm testing of the developed technologies, and providing feedback through evaluation to influence the research agenda of the experiment stations. It provides a structural framework for the farmers to express their preferences and apply their evaluation criteria for selecting technologies suiting to their circumstances.
 - x) **It is gender sensitive:** While explicitly acknowledging the gender-differentiated roles of farm family in agriculture, it emphasizes the critical review of farming systems in terms of activities analysis, access and control over resources and benefits and implication's in developing relevant research agenda.
 - xi) **It is iterative:** Instead of trying to know everything about a system at a time, it requires step- by-step analysis of only key functional relationships.
 - xii) **It is dynamic:** It involves recurrent analysis of the farming systems, permitting continuous learning and adaptations.
 - xiii) **It recognizes interdependencies among multiple clients:** The generation, dissemination and adoption of relevant technologies to improve the productivity and sustainability of agriculture require productive and interactive linkages among the policy planners, scientists, developmental agencies and farmers. The approach attaches more importance for this critical factor.
 - xiv) **It focuses on actual adoption:** It is to be judged by the extent to which it influences the production of socially desirable technologies that diffuse quickly amongst specified groups of farmer clients.
 - xv) **It focuses on sustainability:** It seeks to harness the strengths of the existing farming practices, and to ensure that productivity gains are environmentally acceptable. Towards preserving the natural resource base and strengthening the agricultural production base, it attempts to develop technologies that are environment friendly and economically viable.
 - xvi) **It complements experiment station research:** It only complements but does not substitute on station research. It has to draw upon the scientific knowledge and technologies generated at research stations. It has to be kept in mind that the approach is not being promoted as panacea for all maladies of local agricultural production systems.

Procedures and Methodologies: Generally farming system research is conducted by the following three possible ways:

- (a) FSR: On-farm Adaptive Research (OFAR)
- (b) FSR: On-station studies
- (c) FSR: Study of farming system by modeling, using suitable computer soft ware.

(a)On-farm research: On-farm research refers to the research which is conducted at farmers' field in relatively large plots compared to conventional on-station research with active participation of the farmers with the hope that technology generated through the combined efforts of researchers and farmers will be realistic to the socio-

economic environment of the resource poor group and the problematic situations that the farmers practically face during the process of farming.

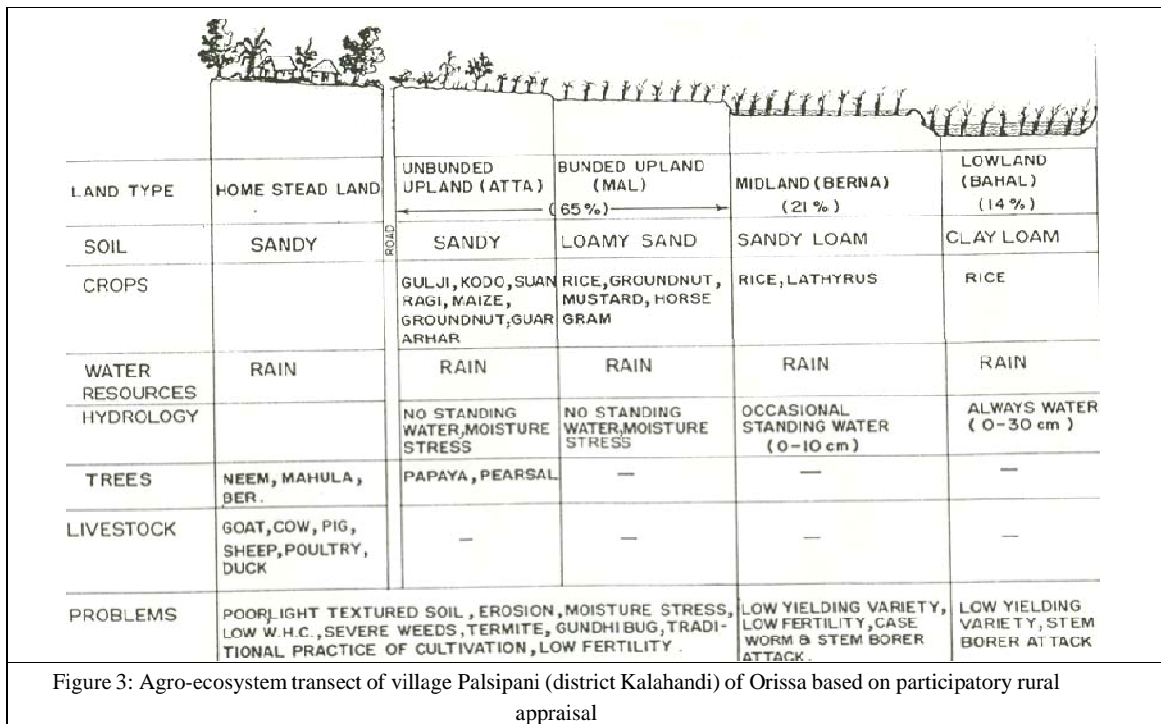
While conducting on-farm research in farming system perspective the following principles need to be considered.

- (i) The whole farm viewed as a system - the research is conducted with recognition and emphasis on choice of priorities that reflect the whole farm.
- (ii) Avoid complex procedures that require scarce and highly qualified individuals to collect and analyse data.
- (iii) Maximise the returns by making results more widely applicable. This means defining target groups of farmers (recommendation domains) in broad terms. The extent to which improved systems can be transferred or extrapolated to other areas directly affects their efficiency.
- (iv) Be open to using second best solutions or the best of those readily available. Therefore, the emphasis in FSR has been on developing improved technologies that are better than most but not necessarily best for each environment.

On-farm research processes: After identification of target area and research area, the following 4 important operational stages in on-farm research process need to be followed (Zandstra *et al.*,1981):

(i) Descriptive or diagnostic stage: In this stage, target area is picked, the frame of farming families are divided into target groups or recommendation domains. Then efforts are made to determine the constraints farmers face in increasing the farm productivity, the circumstances in which farmers work, the weakness, strength, the opportunities and the threats with the farmers. The main aim is to understand the farming system; to prepare an inventory of farm resources, production constraints and support services. Talking to knowledgeable people, examining relevant secondary sources of information, surveys and technical monitoring are the chief strategies of this stage. In general, however, the methods used should be based on criterion of the lowest possible cost commensurate with the degree of understanding that is necessary. Extra accuracy takes resources and time. This information through diagnostic survey help in improving experimental (trial) planning in: bounding treatment levels; verifying evaluation criteria; identifying special locational characteristics to be observed in setting experiments and assessing current productivity levels. Other aspects important in this diagnostic or descriptive stage are: Participatory rural appraisal (PRA), agro-ecosystem analysis, establishing recommendation domains. Some of the information generated based on agroecosystem analysis and PRA are presented in figure 3.

(ii) Design or Planning stage: The priority for research is identified/recognized from the descriptive/diagnostic stage. Planning or design stage is recognized as crucial to the success of FSR in technology generation. On the whole, farmer's problems are readily identified. Range of strategies is identified that are thought to be relevant in dealing with constraints. The factors taken in to considerations are: technical feasibility, economic viability, social acceptability. In this stage suitable action plan for the selected farmers is formulated. The main variables included in designing and planning are: (i) potential for poverty reduction /income / employment generation; (ii) Potential for agricultural growth and (iii) Demographic or ecological or economic importance etc.



(iii) **Testing stage:** The objective of this stage is to evaluate the improved practices flowing from the design or planning stage to the farm. The evaluation criteria should be those found important to farmers in the descriptive/diagnostic stage. Usually the performance of the improved technology drops when it moves from the artificial conditions of the experimental station to the farm and drops even further when farmers manage and implement the final trials. In this stage most promising strategies identified at the design stage are evaluated under local farmers' conditions.

At the testing stage compromises have to be made in the experimental design, farm trials need to be less complex than those undertaken on experiment stations because of costs, worries about too much land being asked from farmers and the desirability of interaction between farmers and research workers. Researcher – farmer interaction is less likely when experiment become too complex. We place a lot of more emphasis on replication across farmers' fields rather than within farmers' fields at this stage of testing. The problem of experimental work is exposed to many additional sources of variation, including differences in management and non-treatment of variables by host farmers and often inability to explain differences between plots. During testing stage generally three types of trials are conducted with the participation of farmers, viz. Researcher designed and researcher managed trial (RDRM), Researcher designed and farmers managed trial (RDFM), Farmers designed and farmers managed trials (FDFM)

(iv) **Recommendation and Dissemination stage:** The acceptable new technology is promoted in collaboration with the line department of the state Govt. and NGO. Thus the technology is promoted. Once the technology or product is ready for extension, necessary supplies and support services must be ensured by the policy makers and planners and other involved such as extension workers and researchers.

After the technology has been demonstrated and promoted to all the farmers in the target group, it is important that their experiences with it are monitored. The improvement suggested may not always suit the farmers' situation, especially as circumstances may change over time. There may need to be a number of options rather than single recommendation. Feedback of the farmers' reaction to the technology will determine if technology is suitable and also when changes are needed. This review phase is vital since it emphasizes the continuous nature of needed improvements.

(b) **On-station FSR:** FSR is considered as highly farmers' participatory and conducted at the farmers' field by the interdisciplinary group of scientists. Farmer participation is ensured at different stages of technology generation and transfer processes such as system description, problem diagnosis, design and implementation of on-farm trials, and providing feedback through monitoring and evaluation (Rhoades and Booth, 1982). On-station experiments on farming system perspectives are also conducted at the research station by taking into consideration the farmers problems, resource availability with farmers such as land, labour, capital etc. and farm constraints (physical and bio-physical) into consideration (Rangaswamy *et al.*, 1996; Behera and Mahapatra, 1999).

Number of on-station studies on integration of different enterprises: lowland rice cum pisciculture farming system, rice-poultry-fish-mushroom integrated farming systems for low land, alternate system of land use through diversification of farming system etc. have been conducted in different parts of the country just by simulating the small and marginal farms situations (Rangasamy *et al.*, 1996; Rangaswamy *et al.* 1992; Mahapatra, 1994, Rath, 1989, Rautaray, 2004).

(c) F.S.R. through System Modeling: A model is a simplified abstraction of the real world. It simulates the behaviour of a real system. Modelling begins with the analysis of the systems, its circumstances and purposes. Defining the model gives insight into the working of the system. So far, the farming systems research has been rather inadequate or slow, particularly in less developed countries. Perhaps the only way by which improvement can be achieved is by the construction and application of suitable whole farm models (Dent, 1990). Recent computer software development may provide the basis for a start in modelling of whole farm systems even with incomplete conceptual understanding and data sets.

(i) Utility of FSR models: Farming system models are useful in the following ways:

- (a) To improve the understanding of farming systems, thereby helping in prioritization of enterprises, better planning and designing of FS experiments, and farm management and policy development.
- (b) To analyse and explain behaviour of a complex system and to determine the relative importance of different components/enterprises of the systems.
- (c) To examine the different scenarios resulting due to integration or mixing of different components or modifying different components in the systems.
- (d) To identify the areas where the knowledge of the system is fundamentally lacking.
- (e) Improvising the system for its wider application in varying situations i.e. under varying resource availability and resource constraints situations.
- (f) Models are cheaper than real life farming systems experiments. Experimentation in real world is expensive, time consuming and there are severe problems in controlling variables exogenous to the experiment. Thus, model saves energy, time and resources. The FSR studies are very complicated and time consuming and involve huge expenditure. With the help of suitable software, the results can be simulated for important decision-making. With the due perfection of the technique, a series of options can be chalked out and a few most important ones can be tested under actual field conditions.
- (g) Development of science. The FSR models help in integration of knowledge of various disciplines, better understanding of the process and their linkages with others and in identifying gaps in knowledge. This will help in re-orienting the research priorities of commodity and discipline based research institutes.

(ii) Enterprise mix by using Linear Programming (LP) Models: The purpose of constructing a LP farming system model is to identify which one of the new technologies are profitable at the farm level and on which type of farm they are likely to yield the best financial results. This model assesses the economic and production consequences of adoption of new technology at the farm levels (Yates, 2000). The linear programming models help in taking decisions for efficient allocation of the limited resources to optimize well-defined objective under a set of constraints. For example, a small farmer wishes to allocate his farm resources such as labour, land, capital and other resources between various potential agricultural enterprises in order to maximize gross margins.

Linear programming modelling is a mathematical technique and has been developed to overcome various shortcomings of planning techniques. Since its application started over a half century ago, it has been regarded as an established method for investigating resource allocation and enterprise combination problems (Dantzig, 1982). The application of linear programming to a certain problem involves different steps as: problem definition, matrix building, model solutions, results interpretations, model verification and validation, results stabilizing tests and action on results.

(iii) Concept of Linear Programming: The linear programming (LP) technique has been developed to handle complex situations and its practical use has been made possible only with the development of relevant computer software (LINDO, MPEXPRESS, MS EXCELL). Linear programming is a technique that is used to arrive at optimal combination of farm enterprises to maximise profit at the end of a specific time period such that all farm constraints are taken into account.

In general, the linear programming model can be written as follows:

$$\text{Max } Z = \sum_{j=1}^n C_j X_j \dots\dots\dots 1.0$$

Subject to

$$\sum_{j=1}^n a_{ij} X_j \leq b_i \quad i = 1 \text{ to } m \quad 1.1$$

And

$$X_j \geq 0 \quad j = 1 \text{ to } n \quad 1.2$$

Where,

Z = total gross margin

X_j = the level of the j^{th} activity

C_j = the gross margin of the j^{th} activity

a_{ij} = the quantity of the i^{th} resource required to produce a unit of j^{th} activity. b_i = the amount of the i^{th} resource available.

In general LP model, there are 'n' activities represented by the 'X' vector whose values are to be determined. The 'C' vector is known as the cost (return) vector and represents the cost (or margins) associated with each activity. The 'A' matrix represents the resources required for each activity unit, whilst the 'B' vector represents some predetermined limit of the available resources. The LP problems are usually solved using the simplex method developed by Dantzig (1982), although other algorithms are now also available (Karmakar, 1984).

Types of Farming Systems

Integrated Farming

Integrated farming is defined as biologically integrated system, which integrates natural resources in a regulation mechanisms into farming activities to achieve maximum replacement of off-farm inputs, secures sustainable production of high quality food and other products through ecologically preferred technologies, sustain farm income, eliminates or reduces sources of present environment pollutions generated by agriculture and sustains the multiple function of agriculture (IOBC, 1993). It emphasizes a holistic approach. Such an approach is essential because agriculture has a vital role to play that is much wider than the production of crops, including providing diverse, attractive landscapes and encouraging bio-diversity and conserving wild life. Sustainable development in agriculture must include integrated farming system with efficient soil, water crop and pest management practices, which are environmentally friendly and cost effective.

The future agricultural system should be reoriented from the single commodity system to food diversification approach for sustaining food production and income. Integrated farming systems, therefore, assume greater importance for sound management of farm resources to enhance farm productivity, which will reduce environment degradation and improve the quality of life of resource poor farmers and to maintain agricultural sustainability. The aims of the integrated farming system can be achieved by:

- (a) Efficient recycling of farm and animal wastes
- (b) Minimizing the nutrient losses and maximizing the nutrient use efficiency
- (c) Following efficient cropping systems and crop rotations and
- (d) Complementary combination of farm enterprises

The various enterprises that could be included in the farming system are crops, dairy, poultry, goat rearing, fishery, sericulture, agro-forestry, horticulture, mushroom cultivation etc. Thus it deals with whole farm approach to minimize risk and increase the production and profit with better utilization of wastes and residues. It may be possible to reach the same level of yield with proportionately less input in the integrated farming and the yield would be more sustainable because the waste of one enterprise becomes the output of another, leaving almost no waste to pollute the environment or to degrade the resource base. To put this concept into practice efficiently, it is necessary to study linkages and complementarities of different enterprises in various farming system. The knowledge of linkages and complementarities will help to develop farming system (integrated farming) in which the waste of one enterprise is more efficiently used as an input in another within the system.

Goals of Integrated Farming System: The four primary goals of IFS are:

- (a) Maximization of yield of all component enterprises to provide steady and stable income at higher levels
- (b) Rejuvenation/amelioration of system's productivity and achieve agro-ecological equilibrium.
- (c) Control the buildup of insect-pests, diseases and weed population through natural cropping system

management and keep them at low level of intensity.

- (d) Reducing the use of chemical fertilizers and other harmful agro-chemicals and pesticides to provide pollution free, healthy produce and environment to the society at large.

Farming systems in Rainfed areas: Agriculture in the rainfed areas and fragile ecosystems is inevitable for meeting the food, fibre and energy needs of the local inhabitants. The conservation of natural resources employing the modern concepts of integrated farming systems is essential for sustainable agricultural development and ensuring greater livelihood securities to the poor people of ecologically handicapped areas. Hence, integrated and holistic development of rainfed/fragile areas including hill, drylands and coastal areas need to be promoted by resource conservation techniques on watershed basis for improving productivity, profitability and thereby removing hunger and poverty. Integrated farming systems have emerged as a well-accepted, single window and sound strategy for harmonizing simultaneously joint management of land, water, vegetation, livestock and human resources. A number of such illustrations can be given emphasizing the greater advantage of integrated farming system in generating technologies aimed at combating land degradation (Solanki and Newaj, 1999). It is this approach that can lead to a quantum jump in the productivity on a sustainable basis and ensure better livelihood securities to the people in fragile ecosystems. Diversified cropping strategies such as mixed/intercropping, strip cropping, alley cropping and agri-horticultural systems are developed to retain maximum amount of rainfall *in situ* and ensure higher production and protection against erosion. Integrated farming systems have been developed for these areas, which reduce the risk of soil degradation, preserve the soil's productive potential, decrease the level of inputs required and sustain crop productivity.

Indigenous Farming Systems

(i) Shifting Cultivation: It refers to farming system in north-eastern areas in which land under natural vegetation (usually forests) is cleared by slash and burn method, cropped with common arable crops for a few years, and then left unattended when natural vegetation regenerates. Traditionally the fallow period is 10-20 years but in recent times it is reduced to 2-5 years in many areas. Due to the increasing population pressure, the fallow period is drastically reduced and system has degenerated causing serious soil erosion depleting soil fertility resulting to low productivity. In north-eastern India many annual and perennial crops with diverse growth habits are being grown.

(ii) Taungya Cultivation: The *Taungya* system is like an organized and scientifically managed shifting cultivation. The word is reported to have originated in Myanmar (Burma) and tauang means hill, *ya* means cultivation i.e. hill cultivation. It involves cultivation of crops in forests or forest trees in crop-fields and was introduced to Chittagong and Bengal areas in colonial India in 1890. Later it had spread throughout Asia, Africa and Latin America. Essentially, the system consists of growing annual arable crops along with the forestry species during early years of establishment of the forest plantation. The land belongs to forest department or their large scale leases, who allow the subsistence farmers to raise their crops and in turn protect tree saplings. It is not merely temporary use of a piece of land and a poverty level wage, but is a chance to participate equitably in a diversified and sustainable agroforestry economy.

(iii) Zabo Cultivation: Zabo is an indigenous farming system practiced in north eastern hill regions particularly in Nagaland. This system refers to combination of forest, agriculture, livestock and fisheries with well-founded soil and water conservation base. The rain water is collected from the catchment of protected hill tops of above 100% slopes in a pond with seepage control. Silt retention tanks are constructed at several points before the runoff water enters in the pond. The cultivation fully depends on the amount of water stored in the pond. The land is primarily utilized for rice. This system is generally practiced in high altitude hill areas, where it is not possible to construct terraces and or irrigation channels across the slope. This is a unique farming system for food production to make livelihood. Zabo means impounding of water. The place of origin of zabofarming system is thought to be the Kikruma village in Phek district of Nagaland.

Organic farming

The roots of organic agriculture developed from differing systems of thought, philosophies of life and agro-political motivations. One thing they all have in common is the desire to form a method of production capable of generating healthful foodstuffs, while limiting any damaging effects on the natural ecosystem. It has in the meantime been scientifically proven beyond doubt that organic farming systems are the most environmentally-friendly, and thus sustainable, agricultural methods. This method of production actively assists in preserving eco-systems and the variety of species, protecting the soil, keeping the water clean and reducing the impact of agriculture on the atmosphere.

Organic agriculture is concerned not only with leaving out technical production aids, such as pesticides or synthetically-produced chemical, mineral fertilizers, or simply replacing them with aids permitted in an organic farming system. But is rather more a holistic cultivation system whereby an agricultural site is viewed as an organism. This method of planting has little in common with the "Ancient's agricultural system", but has been developed from a process based on technical-biological progress. Organic agriculture consciously avoids trying to maximize the yield per cultivation area. The total productivity of a farm (including the ecological aspects), optimally adapted to the site conditions, is the most important aspect.

The following basic principles should be closely followed:

- Sustaining and improvement of the soil
- Realisation (near as possible) of nutrient re-cycling (farm, village, region)
- Intensive use of legumes/leguminous trees to provide nitrogen supply
- Biological plant protection through prevention
- Diversity of crop varieties and species grown
- Site and species appropriate animal husbandry
- Prohibition of Genetic Engineering and products thereof
- Maintenance of the surrounding natural landscape (sustainable eco-agro systems)
- Least possible consumption of non-renewable energy and resources
- Ban on synthetic, chemical fertilizers, plant protection, storage and ripening means as well as hormones and synthetic growth regulators (also harmful processing aids in food processing).

Each individual farmer, whether in the tropics or more temperate zones, must decide for himself exactly how he can practically apply these basic principles to his daily work. A variety of solutions can be developed, depending upon the specific site and farm conditions. Intensive levels of specialization (monocultures) within a farm (a village or region) should be avoided to the same degree as the destruction of an intact natural eco-system through agriculture (e.g. slash and burn method in tropical rainforests). Rather, sustainable eco-agro systems should be aspired to, which are integrated with the flora and fauna present at the site.

Finally, it should also be noted that a consensus exists within the International Federation of Organic Agriculture Movements (IFOAM), that organic agriculture must also take the socio-economical conditions of the people in a region, village or on a farm into consideration. The degree to which organic agricultural systems can thrive in a region depends to a large extent upon the opportunities the people who live there have to participate in them. In this respect, due to its inherent diversity, organic agriculture can be applied as an instrument with a range of uses in rural development strategies. By utilizing this instrument, developmental perspectives can be generated for a rural population.

Soil fertility and nutrient cycles

Soil Performances

An important objective in organic farming systems is the achievement and sustenance of the soil's fertility. The fertility of a soil can be measured by the variety of species that grow in it. The soil is more than just a growth medium for plants. It is a decisive agricultural production factor which, when fertile, can fulfil a variety of purposes:

- Growth medium for plants
- Water storage and supply for plants
- Decomposition for organic material
- Anti-phytopathogenic potential (suppression of soil-borne diseases)

Nutrient reservoir and availability

The soil's capacities are not inexhaustible. False methods (wrong land usage systems, tillage, irrigation, etc.) are leading to a reduction of the soil's fertility on a global scale and not seldom to a irreversible soil destruction (soil degradation). Examples of this are the intensively developed coffee plantations in Costa Rica, cocoa plantations in Brazil near to Bahia and over-grazing in the Sahel. The people who often suffer the most from these methods are the small and marginal farmers living in the region, who invariably have no alternative sources of income.

Fertilization of the soil

In contrast to conventional agriculture, fertilizers and manures are used in organic farming systems to feed the soil and the organisms living within it. These have no need of mineral fertilizers, but for organic matter which they can turn gradually into plant available nutrients. Satisfying the edaphone (the sum of all soil organisms) thereby also provides the optimum requirements for a sufficient and continuous supply of nutrients to the crops. This is achieved through the maximum production (depending on site conditions) of biomass per unit area.

NOTICE: The most important requirement for the improvement and maintenance of soil fertility is a continuous supply of organic matter.

Regarding the nutrition of crops, the following questions are most relevant to the farmer:

A. How can I maximize the production of organic matter (surface or subterranean organic material)?

- In organic farming, not only the crops (cash crops/ self-consumption/ fodder) have to be grown on the available ground but also the organic matter required. A few measures are listed in this respect below:
- Strive to have a soil coverage in the growing area the whole year round (in annual and perennial crops).
- Incorporate annual and perennial green fallow periods into the crop rotation (plus planting of legumes), to regenerate the soil.
- Integrate annual and perennial forage cultivation (root biomass and manure) into the plantation system. Develop mixed cultivation systems (e.g. alfalfa rows in cotton, beans and maize, beans in young sugar-cane plantations).
- In permanent cropping, it is important to provide a sufficient number of leguminous trees and shrubs (agroforestry systems for bananas, coffee, cocoa, mango, tea etc.) as well as leguminous green manure plants covering the soil. Alley cropping, e.g. with *Leucaena* (usage of the pruning material to fertilize the crops growing between the rows of *Leucaena*).
- Leave single trees standing in the field, such as e.g. the legumes *Prosopis cineraria* and *Acacia tortilis* in arid regions.
- Hedgerows (one or more rows of trees/shrubs) with a wide range of functions, such as windbreaker, prevention of erosion, habitat for natural enemies of pests, timber for construction and fuel, fodder and pruning material for mulching and/or composting, protection against side-contamination with pesticides from conventional farms nearby etc.

B. How can I provide nutrients for my crops by supplying organic material?

B.1. Nitrogen:

The supply of nitrogen (N) in organic farming is usually provided by legumes. Through a symbiosis with nodule bacteria, these plants are capable of fixing atmospheric nitrogen and making it available to plants. There are other bacteria that can also fix nitrogen (Actinomycetes which are present in dead wood, soil-bound *Azotobacter* or *Beijerinckia* bacteria, which live in association with the tropical fodder-grass *Paspalum notatum* and other Gramineae). In paddy rice, the bacteria *Anabena azollae* is used, which forms a symbiosis with the water fern *Azolla*, and can, under tropical conditions, fix up to 400 kg N/ha and year,

and which is very often used as a green manure for rice crops.

As already mentioned, most important is the planting of site-appropriate legumes in crop rotation or agroforestry systems (there are over 12,000 types of legumes in the world). In crop rotation systems, at least 20% of the entire cultivated area should be planted with legumes.

B.2. Phosphorous

The phosphate content of the soil vary just as much as the availability of phosphates (P) for the plants (e.g. tropical soil with its high acid, iron and aluminium content has a very high rate of P fixation, thus applied P-fertilisers become unavailable for the plants). On organic farms emphasis is placed upon increasing the availability of the phosphate content of the soil for the plants. This is achieved by a biological conversion of insoluble to soluble P-compounds in the soil (enzymes and plant acids):

In fertile soils with sufficient organic matter the conversion to soluble P-compounds is most efficient: Fertile soils have a more intensive growth of roots and subsequently a more developed network of fine roots increasing the interaction between fine roots and phosphate compounds in the soil. Acids released by the fine roots than dissolve the fixed P-compounds and improves the availability for plants.

Fertile soils with a high organic substance content encourage the growth of VA- Mycorrhizza, a fungus that lives in a symbiosis with plants having a high capacity to dissolve fixed P-compounds.

Use of plants that are particularly capable to break up fixed P-compounds (e.g. onions in mixed crop systems with cotton, palms and vanilla in agroforestry systems).

Organic matter (mulching material, compost) increases the availability of phosphates

High pH values and poor phosphate availability can be alleviated by applying silicates.

Adding rock phosphates is still allowed on organic farms. If composting, then the compost can be directly prepared with the rock phosphate. With some crops (e.g. cotton) the seeds are infested with bacteria that can break up phosphate compounds, in order to ensure that the plants have enough supply during the important early stages of growth.

B.3. Potassium

Potassium (K) is easily leached out of sandy soils which contain little organic matter (humus compounds). The following strategies are important in organic farming to ensure a sufficient supply of K for the plants:

1. Regular applications of organic matter will improve the absorption of potassium in the upper soil layers, where it can be reached by the plants' roots.
2. Use of deep-rooting plants to mobilize K in lower soil layers.
3. Integration of plants with a high K-uptake in mixed cultivation systems (e.g. bananas on coffee plantations).
4. A permanent mulching layer, especially in the wet tropics in order to reduce leaching of K.
5. In arid regions with soils poor in K, it can be useful to mix pulverized rock containing mineral clay into the compost (e.g. as practised in Egypt, Israel).

In case of potassium deficiencies showed by soil analysis it is permitted to use certain potassium salts with a low chlorine content (Muriate of potash/ potassium chloride is not allowed). Wood ash from untreated wood is also allowed.

C. How can the resulting organic matter be best utilized?

One of the main objectives in organic farming is to minimize the loss of nutrients and to keep them recycling within the farm (and/or to use them).

The following criteria should be needed in this respect:

Burning of crop residues (e.g. common practice on sugarcane plantations) is not allowed in organic farming (exceptions may be permitted by the certification body, e.g. in cases of heavily infested crop residues). When crop residues are burnt, important nutrients and energy is lost.

Crop residues should be left on the soil's surface (agroforestry systems) or mulched into the

upper layer of the soil (arable farming). Alternatively, they can also be used as fodder or bedding for animals, or used directly as compost material.

Organic matter is created during the production and processing of several types of cash crops (coffee, bananas, sugar cane etc.). These residues should be returned into the cycle of nutrients on the farm. This is best achieved by mulching or composting, or by creating bio-gas with the resulting usage of any organic material left over.

Large amounts of pruning material are regularly given, especially in agroforestry systems, which are then also used as fuel. The nutrient rich ashes (minerals like e.g. potassium) should then be fed back into the nutrient cycle via compost. Farmers will need to decide just how much of the organic material created on their farm should be composted, depending on the site's requirements. Each form of composting will inevitably lead to a certain level of nutrient losses and will increase the working costs.

NOTE: One objective in organic farming systems is to realize nutrient cycles within a field or farm (or even in a local/ regional) system, closed as much as possible, and to reduce unnecessary losses of nutrients.

With the following examples, describing the situation in "arid climates" and "humid tropics", the above mentioned context can be illustrated:

Site	Basic principles of agriculture that protects the soil
Humid tropics	<p>Growth and decomposition processes are accelerated in these regions due to their high average temperatures with few fluctuations, high rainfall and humidity. Organic material in and on the ground is rapidly degraded and nutrients set free. In humid tropics, covering the ground with a thick layer of organic material and a humus-rich top soil are the most important sources of nutrients and water. It is therefore essential that this layer of soil is conserved, by leaving it continually covered (if possible) with organic material, by not carrying out any deep or involved tillage, and also, by implementing agroforestry systems to protect against erosion. In addition, planting, and if at all necessary, tillage on sloping sites should only take place along the hang-parallel (contour planting).</p> <p>Special arrangements for composting are usually unnecessary, as the organic material can be degraded "on site", i.e. where it falls. The aim is not to disturb the upper, fertile, humus-rich layer of soil through agricultural activities, which would lead to the humus being depleted and resulting loss of soil fertility and the additional danger of the soil drying out. Cattle-raising is not advisable in such areas. Clearing of land by burning organic material is not advisable (slash and burn) because enormous quantities of valuable nutrients/energy are then lost to the agro-eco system.</p>
Arid sites	<p>Growth conditions for plants are more often than not highly limiting in these areas due to high daily temperatures with large fluctuations, slight rainfall and often very dry winds. The careful use of water as the most important limiting growth factor under these conditions is the key to for the realization of a site-appropriate farming system.</p> <p>All possible measures to reduce the losses of water – especially through evaporation and transpiration – should be consequently realized, e.g. sufficient quantities of hedges to act as wind-breaks as well as good a permanent coverage and shading of the soil. In addition, the water- conserving capacity must be increased or at least maintained through the continual application of compost (humus compounds). Furthermore, it is worth noting that living plants are efficient fresh water savers, and can be effectively integrated into the system as a whole. The irrigation system used must also be capable of minimizing water losses and avoiding soil salinity.</p> <p>This system is also characterized by a partial utilization of the organic matter through animal husbandry and a respective arable fodder cropping system including legumes. Because of the limited biological activity of the soil, the organic matter cannot be degraded in the field (due to a lack of continual water supplies) but as a result of composting.</p>

With the contrary examples given, it becomes evident that in practice, the nearer a farm is to the continuously

humid tropics, and away from the changeable climates with their arid periods, the more the agricultural system chosen should adhere to the characteristics of an agroforestry system.

Soil management and protection against erosion

The soil is usually tilled in order to: prepare a seed bed (or plantation), work crop residues into the soil and for weeding.

In permanent cropping systems no tillage is needed, normally. Instead of this, a system should be introduced based on green manure plants (by e.g. local species of legumes) and mulching (green soil coverage and pruning material). In agroforestry systems in the tropics, soil tillage is also unnecessary. Soil cultivation is only carried out when the permanent cropping /agroforestry system is to be newly planted (either manually, using animals or machines, according to conditions).

In this respect, we need to take a critical look at the usual and traditional methods of slash and burn applied in the sub-tropical and tropical regions. Because these “technique” are one of the main reasons for the huge areas of primary and secondary forests which are constantly being destroyed in tropical regions (by setting fires and using the wrong form of soil management). Especially when the area is not then used as an agroforestry system. Slash and burn methods are not allowed in organic farming. Burning down of fallow land should be avoided, and is only permitted when an agroforestry systems is to be established (a detailed description can be found in the section “Organic cocoa cultivation”).

In the case of arable crops, deep and over-turning soil tillage (using a plough) should be avoided. Should a plough be used, then the lines must be parallel to the lines of elevation (across the slope) in order to reduce the risk of water erosion (contour planting). Simple mulching of the organic matter into the soil's upper layer is usually sufficient – crop residues should not be dug deep into the soil. (currying once or twice, rotary tillage etc.).

By carefully designing the crop rotation (which crop follows which) and encouraging the growth of soil organisms (e.g. earthworms) by continually applying organic matter, mechanical tillage of the soil can be largely replaced by biological measures. Crop rotation will also help to suppress the unwanted growth of weeds. In this way, the soil texture is protected, whilst soil tillage procedures, which are costly in both energy and man-hour terms, can be reduced.

Note: In order to protect the soil against climatic conditions (sun, wind, rain), all cultivation methods should be aimed to realize a constant coverage of the ground (green coverage and/or mulching layer).

Sites which are susceptible to heavy soil erosion require special additional measures to ensure that the fertile upper layers of the soil are not depleted (wind and water erosion). If these measures are not carried out, sometimes even outside of the farm itself, whole regions can become endangered by irreversible soil degradation (desertification). Quite often, for this reason, the measures required are performed together by the population of a village or region as the only possibility to protect the own farm.

In practice, both mechanical and biological measures are put to use:

Examples of erosion protection measures	
Mechanical measures	Stone walls erected along the lines of elevation of a site to slow down the water flow.
	Stone barriers in water channels to slow down the outflow of water.
	The building of stone terraces on steep slopes (wood should not be used in the tropics because it rots too quickly)
Biological measures	Planting of hedges (e.g. in the Sahel, several species are planted alongside stone walls, such as <i>Cajanus cajan</i> , <i>Euphorbia balsamifera</i> or <i>Jatropha curcas</i> (flax nuts), which are resistant against animal bites; in Egypt, rows of <i>Casuarina equisetifolia</i> help to protect against the extreme desert winds)
	The cultivating of rows of plants running across the main slope direction of the site, (mix of grass & legumes suited to the site)
	The reforestation/planting of the edges of extremely steep slopes (e.g. in Darjeeling, with elephant grass and a variety of shrubs/trees)
	Large scale reforestation including protective methods against harming animals and uncontrolled use of wood for fuel

Because mechanical methods of providing protection against erosion are work-intensive (e.g. construction

of terraces), it is worth considering whether the same effect could be achieved with biological methods (e.g. green fences).

Experience shows that problems with erosion are caused by a variety of factors – including socio-economical ones. This becomes evident when using the Sahel as an example:

Heavy and intense localized rainfall,

Those soil characteristics that promote erosion,

Growing population, with accompanying increase in demand for food and fuel, Change in soil tillage methods (mechanization with animals instead of manual tillage),

Shortening of the fallow land period and/or abandonment of fallow land, Intensification of cash crop production for export with the result that food production for domestic consumption more and more takes place in remote and marginalized areas,

Not appropriate number of livestock.

It has been proven that protection measures against erosion can only be successfully implemented when the local population is included in the development of the regional strategies, and that their requirements are also sufficiently met.

Livestock and animal husbandry

The integration of animal husbandry in organic farms in the temperate and arid zones is one of the basic principles behind organic farming. It is of less importance in the tropics. In these regions, micro-organisms (and rapid decomposition rates) take over the ecological function played by the larger animals.

Animal husbandry enables the recycling of organic matter to be further optimized in agro-eco systems, e.g. through the use of crop residues as fodder for the animals, and by using animal dung for the crops. It is not absolutely necessary that each individual farm keeps its own animals. It is just as practical for neighbouring farms with and without animal husbandry to co-operate.

The number of livestock kept on a particular farm or region is therefore dependent upon the amount of fodder available, or the size of crop area used to grow fodder on the site itself.

Planting fodder crops (especially legumes) is of particular help in improving the fertility of the soil, and in diversifying the crop rotation. Hedges can be useful not only as windbreaks and as protection against erosion, they can also act as constant source of forage for cattle.

Industrialized large-scale livestock farming (many animals – not enough land) are not permitted in organic farming systems, because an optimal synergistic effect between the plants, soil and animals cannot be achieved with them. Strategies will always have to be adapted according to the prevailing site and regional conditions, and these also include the way that animals are kept. For example, it is important to take care that over-grazing or damage through bites do not occur, as these could cause problems with erosion (see the Sahel as an example). If animals are to be introduced into a functioning farm unit, then care must be taken not only to choose the correct race of animal suited to local conditions, but also to make sure that the species itself can be adapted to the existing eco-system without causing any damage. For example, the introduction of sheep and goats into the Andean regions has had serious consequences for the soils and vegetation. The expansion of cattle-rearing in the tropics has had a similar effect.

Cattle-rearing is a special case (they have no direct natural competition for food because they eat plants that are not consumed by humans; they produce protein in form of milk and meat, and also leather and wool; they can be used for transport purposes; they produce dung). Cattle-rearing has a long tradition in many regions worldwide, and it should be remembered that large areas are required (stables, outdoor runs and forage area e.g. pasture or arable forage cultivation). Pigs can be easily adapted to a small farm structure, as they will feed on crop residues and organic waste products. Nevertheless, stalls must be provided with plenty of space for them to roam outside, to protect the environment – especially delicate eco- systems – against the animal's natural tendency to root around. Animal husbandry in organic farming rejects in principle the concept of maximising a short-term performance of the animals. Instead, an attempt is made to achieve an optimum life performance of the animal.

Productive livestock must be kept according to their behavioural needs. Animals kept in ways which disregard their behavioural needs adversely affects them, makes them more susceptible to illness, and also reduces their overall efficiency (e.g. production of milk or meat). For these reasons, in organic farming, care is taken to ensure that the animals have sufficient free movement, fresh air, natural daylight, suitable food and access to fresh water.

It is also important only to keep animals suited to the region who will be able to cope with the local climatic conditions, and are capable of withstanding the potential presence of diseases. Medication used in a preventive manner is forbidden in organic farming (with the exception of vaccinations).

Composting

Throughout the previous chapters, it has often been mentioned that it is largely dependent on the specific site and farm conditions whether composting makes sense as a strategy or not. A farmer should need the following aspects before making his decision:

- a) Nutrients will also be lost even when composting is optimally organized (e.g. potassium in drainage water, or loss of gaseous nitrogen and carbon).
- b) Successful composting generally goes hand in hand with keeping livestock.
- c) Workload caused by composting (production, application).

Selecting composting materials

The most basic requirement for every type of composting method is the correct choice and preparation of the used compost materials. Factors that are important include the ratio between carbon and nitrogen (C : N ratio), the humidity and ventilation. Decomposition will only take place to produce nutrient-rich compost when all of these factors are correct. The ratio between carbon and nitrogen in the materials chosen should ideally be 25-30 : 1, this may be a little higher at warm, humid sites.

A selection of C: N ratios in materials usually used for composting:

Material	C : N- ratio
Saw dust	Up to 400
Maize stalks	50 – 150
Straw	50
Green material from legumes	20 – 30
Dung including bedding	20 – 25
Straw from legumes	15
Farm Yard Manure	15
Top soil	10 – 12

In practice, the necessary C : N ratio for each of the materials used can only be reached when a sufficient quantity of manure is added (ca. 50%).

Rock phosphate (phosphorous compounds which have not been broken up, and are thus not readily available to plants) can be used by mixing it directly into the compost. During the composting process, and especially in an acidic milieu, the rock phosphate is turned in part into forms that the plants can access. Furthermore, Mycorrhiza fungi can also dissolve phosphates in a compost.

The following points should be cleared up before organic material is used from sources other than the farm itself:

The origin of all organic material must be ascertained. Manure is only acceptable if it originates from organic or at least extensive animal husbandry and/or organic material if it is not polluted with pesticide residues or other contaminating substances.

The importation (bought-in) of organic material into the farm system is limited, with the main proportion being produced on site.

Every instance of organic material purchase (both type and amount must be approved beforehand by the certification body).

Selection of a compost site

In principle, every compost heap must be protected against heavy sunlight (drying out) and too heavy rainfall (leaching). A suitable site would therefore be in the shade, under trees. In extreme regions, such as e.g., the Sahel, the dung needs to be protected in compost pits against drying out too quickly.

In addition, the location of the compost site has to be chosen carefully for different technical reasons. By necessity, this includes both the method of transporting the organic material to the heap, and also the distribution of the finished compost within the farm.

Construction of a compost heap

The construction of compost heaps which measure ca. 1.5 m high, 2 m wide and are as long as desired have proven themselves in practice, because they produce a roof-type of structure, that helps to drain off any rainwater and thus prevent water-logging – especially in wet climates. In extremely dry regions, it can make sense to dig compost pits.

The following basic rules should be needed:

- a) The organic material needs to be mixed by chopping it up (into small pieces, yet not too small) or layered alternately.
- b) Plant remains that are very woody need to be chopped to aid decomposition.
- c) The foundation needs to be well drained. If the ground tends towards water-logging, then the first layer should consist of loose material (e.g. branches).
- d) The compost heap should be protected from drying out and/or leaching by covering it with natural materials (e.g. straw or banana leaves) or with perforated foil (the perforations allow gases to escape and prevent internal sweating).

Regulating the rate of decomposition

Compost worms and other micro organisms are necessary for the efficient decomposition of the compost material. The process can be accelerated by adding bits of old compost heaps. Special compost preparations can also be added which will support the process. The time required for the material to decompose depends upon:

- the temperature of the air
- the composition of the composting material
- the moisture content composting material the ventilation

Disease carriers and weed seeds are killed off by the high temperatures inside the heap. The insides can attain a temperature of up to 80°C, which can then lead to a loss of N, and is therefore not desirable. The temperature should therefore not exceed 60°C. The inner temperature can quite easily be established, yet so-called compost thermometer are also sometimes used. If the temperature exceeds 60°C, then steps must be taken to lower it again (e.g., removing the covering, watering the heap or even turning it over to ventilate it). The factors ventilation and moisture can be counteracted by manually turning the heap, uncovering it or watering. A compost heap should be turned over around 3 times during its 3-6 month decomposition cycle. A basic rule states that the longer the decomposition takes, the more nutrients are also lost. Losses are caused by the gassing out of nitrogen or carbon compounds or by leaching of nutrient-rich draining water (e.g. potassium).

Uses for compost

Finished compost has a crumbly structure. It smells pleasantly of earth, and contains only traces of rotting material. Large residual pieces can eventually be sieved out. Now the compost can be spread over the fields or beds (or tree trunks) and lightly worked in (being careful not to damage any roots) or covered over with mulching material to prevent premature drying out on the soil's surface.

The time that compost is added is most important. This depends upon the growing period of the crop and its respective nutrient requirements. It should be noted that nutrients stemming from compost are released slower than those from mineral fertilisers.

The following weights of contents gives a general indication of how to integrate dosing of compost material into the total nutrient cycle:

Substance	Percentage weight in dry matter
Organic substance	60
Carbon	35
Nitrogen (as pure N)	2,8
Phosphorous (as P ₂ O ₅)	2,2
Potassium (as K ₂ O)	2,6
Calcium (as CaO)	3,1
Ash	40

Biological plant protection in organic agriculture

In organic farms, preventive measures have absolute priority. The whole point is not how to eradicate a pest or disease, but how to prevent them appearing. When a plant becomes diseased or is overcome with pests, the farmer needs to ask himself how it is that the plant is too weak to thrive in the actual eco-system without significant damage occurring. The central question therefore remains what the underlying causes are. Possible causes include:

- a) The variety used is unsuited to the site: In such cases, it is advisable to try out different varieties on-site. Yet in addition to its suitability to the conditions on-site, a variety must also meet market demands (quality requirements).
- b) The cultivation system is unsuitable: This can have many causes. Soil-borne diseases (root-rot, nematodes) are often the cause behind a poor crop rotation, or failing secondary vegetation. Certain fungus types thrive when the plants are set too close together, or in agro forestry systems that are too poorly ventilated. Pests can appear in large numbers when there are no habitats for their natural enemies (useful insects) to grow. Existing hedges or trees on the farm or near to the crops can offer pests hibernation possibilities or hosts during certain of their life-cycle stages.
- c) Reduced soil fertility: Healthy growth can only come from healthy soil. Poor soil fertility, compression of the soil, water-logging or a too high salinity can all be stress factors for the crops. Stress in plants always results in a higher susceptibility to diseases and pests.

A precise analysis of the actual situation and an alleviation of the causes will lead in both the middle and long term to the most success. This is also because treating the causes will keep the farm largely independent of the use of biological plant protection materials, and thus cut running costs.

NOTE: The main method to protect plants in organic farming is treat the causes.

In order to help combat pests/diseases that turn up on certain occasions, a multitude of traditional methods exist throughout the world. For example, the manufacture of watery extracts from neem seeds, bitter ginseng extracts, chilli extracts, stinging nettle mixtures etc. These plant protection products can be manufactured on the farm without much effort (time and cost).

Above a certain limit, the appearance of pests or disease in plantation crops calls for measures to protect the harvest. The products for pest and disease control allowed in organic agriculture are listed in the regulation for organic agriculture (EEC) No. 2092/91 as well as the IFOAM Basic standards. It needs to be stressed, that plant protection products, including those allowed on organic plantations, can only have a limited effect and are not capable of combating the actual root causes.

Diversification strategies

A diversification of the agroecosystem is one of the basic requirements in organic agriculture:

It is not unusual for a farmer's income to be entirely dependent on the sale of harvest from one single

crop (especially on small farms). When prices then fall, this will inevitably lead to very serious problems. Diversified agro eco-systems consisting of a variety of crops that can either be sold (local market, export) or are for own-use (food, fodder, building material and fuel) have a far better crisis-resistant structure. Yet such diversified systems require an efficient planning and organization of the available workforce. In general, there are two forms of diversification:

Horizontal diversification

Vertical diversification

Horizontal diversification: A new crop is to be introduced into a farm. During the planning stage it is necessary to satisfy the requirements for success within the farm. In addition to the first, basic question of whether the crop in question can be planted at the site or not, the following must also be ascertained:

Are the technical requirements for post-harvest treatment (e.g., drying, storage etc.) present, in order to fulfil market demands for quality?

That the parallel cultivation of different crops does not place too much strain on the available man-power (e.g. if different crops should need to be harvested at the same time).

An example of this would be if vanilla or pepper were to be integrated into tea plantations (growth on the shade trees).

Vertical diversification: When a farmer decides not only to sell his crops in a raw state, but to process them himself. This would be a way to increase his income, or to achieve a higher net profit. This strategy is of particular interest to smallholder farm co-operatives or groups of producers (larger amounts of harvested produce), who then either invest in their own processing plant or use the service of a sub-contracted and qualified processor.

One example of this would be when smallholder coffee farmers were to have instant coffee produced for their domestic market or for export.

Whether and in which framework diversification opportunities have a chance of success must be decided by each individual farmer themselves. But what basically needs to be established, is whether sufficient capacity to successfully expand exists on site, or whether this can be easily achieved. This is especially true for products with high market quality requirements.

Standards and Certification Requirements

There are international valid standards for organic agriculture including inspection and certification. Compliance with these standards/regulations is the pre-requisite for certification and access to the organic market.

Standards for Organic Agriculture

The organic agriculture (cultivation as well as processing) is regulated by a complex set of standards in the meantime. At international level the basic standards for organic agriculture defined by IFOAM (International Federation Of Organic Agriculture Movements) are most relevant.

These basic standards are defining not only the principle requirements for the production of organic foodstuff but also minimal requirements for the inspection and certification of organic producers. Furthermore, the basic standards of IFOAM are the obligatory basis for detailed production standards set by private certification bodies, who are evaluated on behalf of IFOAM within the frame of the IFOAM Accreditation Programme. Actually, about 16 private certification bodies are accredited by IFOAM worldwide.

Out of the IFOAM Basic Standards also official regulations for the organic industry were developed in different countries for instance in the European Union (EEC- regulation for organic agriculture (EEC) 2092/91), in Turkey, in Argentina and in Japan. Furthermore, the Codex Alimentarius also took the IFOAM Basic standards for defining minimal requirements for the organic plant cultivation (animal husbandry will follow).

Finally decisive for producers are to follow the legal requirements for organic agriculture as far as they are existing in the country of production and/or in the country of importation.

Inspection and Certification

Every producer, processor and exporter who intends to produce and sell organic products shall fulfil all requirements laid down in the internationally valid standards for organic agriculture as well as in existing regulations in the country of importation. Therefore, the precondition to enter the organic market is to follow the inspection and certification procedure of an internationally accredited certification body for organic agriculture. At least once per year all production units have to be inspected by the certification.

Conversion Plan

Prior to the conversion of a farm or a processing plant it is of utmost importance to acquire sufficient information about all certification requirements. This can be done best by selecting a qualified certification body with the objective to develop a conversion plan for the operation. Furthermore, prior to the first inspection it has to be clarified which information is needed by the certification body and/or which records have to be taken constantly (e.g. Bought-in of raw materials and production means, sales documentation etc.).

Farm operations

In the above mentioned context the producer must be aware of the conversion requirements (beside all detailed standards for production) at first. For example the EEC-regulation for organic agriculture (EEC) 2092/91 requires a conversion period for all permanent crops of 36 months and for all annual crops a conversion period of 24 months (products can be sold as „organic in conversion“ after 12 months of organic production, however, for most of the products it is very difficult or nearly impossible to sell „products in conversion“). This conversion requirement is therefore very important for the short- and midterm planning of any farm operation. In this context it is also important to know that the EEC-regulation for organic agriculture do count the conversion period from the date of the first external inspection on. That means that in case the history of the farm cultivation was in line with the requirements of the EEC-regulation this normally cannot be taken into consideration when calculating the conversion time.

Processors and Exporters

To get processed foodstuff certified as organic it is not sufficient to use only organic ingredients of agricultural origin. Beside the used agricultural ingredients a couple of other aspects have to be taken into account. In this context the use of ingredients of non-agricultural origin (e.g. food additives, carriers, flavourings, water and salt, micro-organisms preparations, minerals and vitamins), the use of processing aids (e.g. tannic acid, silicon dioxide gel, gelatine), the use of disinfectants as well as the application of specific processing methods (e.g. ionising radiation is prohibited) is regulated in a very restrictive manner. As already said for the farmers also processors interested in the processing of organic foodstuff are recommended to contact an accredited certification body in time, to develop a conversion plan.

Resource conservation technology including modern concept of tillage

At present mainly in the rice-wheat cropping system biological research is focusing on issues related to **natural resource management (NRM)**. Its most notable success to-date has been the recent development of several **resource conservation technologies (RCTs)** due to the efforts championed by rice and wheat coordinating (RWC) units with its NARS (National Agricultural Research System) partners, including the private-sector machinery manufacturers. There is evidence of a significant change in the tillage and crop establishment methods being used by farmers in the wheat-based system of the northwest IGP. This impact is a major achievement for the RWC of regional significance and contributes to the global application of RCTs into a new ecosystem. However, the success of the tillage practices raises a number of concerns as well as opportunities. The chief of these is the lack of farm-level impact studies that can guide the process of adaptation to other zones, and identify emerging issues that need to be addressed by the RWC partners. Although, some monitoring studies were launched a few years ago, e.g., on soil health, there is need for more holistic monitoring of long-term impacts on the productivity and sustainability of the RWSs in the context of RCTs. The scope, coverage and locations of such long-term work should be debated amongst members to develop a work plan with clearly agreed responsibilities of the national and international partners.

Resource Conservation Equipment & Technology

•Laser land leveller	•30-50% saving in water
•Rotavator	•50% fuel saving & better quality seed bed
•Zero till drill/minimum till drill/ multipurpose tool bar/ raised bed planter	•5-10% increase in yield and saving of Rs. 2000-3000/ha.
•Pressurized irrigation	•20-30% saving in water
•Rotary power weeder	•20-30% saving in time and labour
•Vertical conveyor reaper/ combine	•Timely harvesting, more yield
•Multi-crop thresher	•50% saving in labour and time and 54% saving in cost of threshing
•Straw combine	•Recovers 50% straw and also 70-100 kg grain/ha resulting into an average saving of Rs. 1250/ha.
•Straw baler	•Makes bales and checks environmental pollution
•Straw cutter-cum-spreader	•Cuts and spreads the straw evenly and helps in sowing by zero till drill.
•Improved manual harvester for mango & kinnow	•No damage to fruit and higher capacity

The focus on RCTs is important for reasons other than efficiency and sustainability per se. The new RCTs provide a novel 'platform' for land and water management approaches and to introduce new crops and varieties into the systems, which may also help to re-establish better ecological balance. However, the work to foster greater diversification of the RW systems lacks a comprehensive strategy, including policy and market analysis, to guide the research and development efforts in the region. Agreement on an overall strategy would help to set more appropriate priorities for fostering systems diversification suited to needs of different transects of the IGP.

The biophysical and socio-economic heterogeneity in different IGP transects must be borne in mind in planning future programs. In the west, traditionally a wheat-based production system, introduction of intensive rice cultivation has raised concern about environmental sustainability due to antagonism between the current soil-water production requirements of the two crops. The challenge for RWC is to undertake research to determine what possibilities exist to grow rice in different ways to the benefit of the RWSs in terms of productivity, diversity and sustainability (particularly of water use) and determine under what circumstances (including national policies) such changes are appropriate. The RWC can make significant contributions both by improving water use efficiencies at farm-level through new RCTs, including laser land leveling and bed planting, and by joining with the CGIAR's Challenge Program on Water and Food. In the east, where the production systems are traditionally rice-based, intensification and diversification in the winter (non-monsoon) season will need to be focused on enhancing economic viability, learning from farm-level experiences with diversification in Bangladesh.

The RWC has facilitated a change towards a systems approach and use of farmer participatory methods for location-specific multidisciplinary research. It has successfully linked NRM with production systems research. While these processes have been adopted in some institutes, especially in the context of RWS research, much greater effort is needed through the national research establishments to mainstream these processes as a regular feature of program planning and implementation. RWC can play a bigger role towards this goal by influencing national research policy, disseminating benefits and continued efforts to build capacity of the national partners.

There are opportunities for greater contributions from IARCs/ARIs in support of RWC's need for attention to policy analysis work and new knowledge about the system processes impacting on its long-term resilience and profitability in the context of full exploitation of RCTs and distinctly different needs of the western and the eastern transects of the IGP. These include strategic research themes of regional and global significance related to land, nutrient, water and crop component management and safeguarding the environment (global warming gas emissions and carbon balance). IARCs are well placed to assist by developing/introducing new tools and techniques and establishing new theme-based partnerships for pioneering research. Planning of future research should be backed up with a formal analysis of research priorities, and development of a Medium-Term Plan (MTP). It is not about tradeoffs, but about better targeting of limited resources available for research to both the national and the international partners of the RWC.

The needs for expansion of successful RCTs, for system diversification and for water management research present an attractive window of opportunity for adoption of such a strategy and for exploring different options for securing medium-term funding. At the same time, the RWC members should also examine a move towards a more equitable cost sharing arrangement in line with their size, degree of involvement and capacity to bridge the gap in sustainable funding for the CU.

Types of tillage

Clean tillage / conventional tillage/ traditional tillage: is one wherein 100 per cent of the top soil is mixed or inverted.

Conventional tillage has been defined as combined primary and secondary tillage operations performed in preparing the seed bed. With clean tillage all the plant residues are removed and buried. The growth of weeds is prevented.

Suitability

- Adopted in Class I lands

Advantages

- Weeds are efficiently controlled
- Crop residues are thoroughly incorporated
- Better microbial activity

Disadvantages:

- More energy requirement
- Greater loss of soil moisture
- Formation of hard pan
- Surface soil is more prone to erosion

Modern concepts of tillage

- Minimum tillage:
- Zero tillage
- Conservation tillage
- Stubble mulch tillage
- Blind tillage

Minimum tillage may be defined as a group of soil preparation methods for planting in which the number of tillage operations over the field is less than conventional tillage. This can be achieved by omitting the tillage operations which do not give much benefit when compared to the cost. For example combining seeding and fertilizer application, row zone tillage, plough plant tillage, wheel track planting

Suitability

- Medium textured soils

Advantages

- Reduced soil compaction
- Better soil conservation
- Energy requirement is less
- Reduced labour and machinery
- Time saving

Disadvantages

- Low seed germination and establishment. Difficulty in sowing
- Nodulation is adversely affected
- Use of herbicides is indispensable
- Decomposition of organic matter is slow
- Perennial weeds may become dominant

Zero tillage is an extreme form of minimum tillage. Primary tillage is completely avoided and the secondary tillage is restricted to seedbed preparation in the row zone only. Planting is done in previously unprepared soil by opening a narrow slot or trench or band only of required width and depth for sowing and covering the seed or seedling.

Weeds are taken care by using broad spectrum nonselective and non-persistent herbicide before sowing subsequent to sowing by using selective and persistent herbicides.

Till planting is one of the zero tillage method in which heavy machineries are used to clean a narrow strip over the crop row. Then a narrow band of soil is opened. Seeds are placed and covered.

Advantages

- Saving in energy, labour and time
- Reduced compaction
- Increased earthworm activity and soil organic matter
- Disadvantages
- Difficult establish optimum crop stand
- Mineralization of soil organic matter is slow
- Nitrogen requirement of crops is high
- Build up of perennial weeds and pests

Conservation tillage is the tillage operation performed to reduce soil erosion and to conserve soil moisture is referred as conservation tillage. This is achieved by covering the soil at least by 30 per cent of the surface by the crop residue. Conservation tillage operations include reduced tillage operations like minimum tillage, no tillage, mulch tillage.

Stubble mulch tillage is method of tillage in which a mulch crop grown during the fallow period or the stubbles of the previous crop are uprooted and brought to the surface and spread during tillage operation. The main objective is to protect the soil from erosion.

Suitable in sloppy areas and drylands

Advantages

- Reduced loss of soil and water
- Improved organic matter content

Disadvantages

- Less effective weed control
- Stubbles interfere in sowing operation

Blind tillage is the tillage of the soil after sowing a crop either before the crop plants emerges or while they are in early stages of growth. It is extensively employed in sorghum and drilled paddy where emergence of crop seedlings is hindered by soil crust formation on receipt of rain or by irrigation immediately after sowing. Shallow harrowing with entire blade harrow without disturbing the emerging crop seedlings will loosen the soil crust and help in emergence of seedlings. Generally weed seedlings emerge within two to three days after sowing while many cereals take 7 to 8 days for seedling emergence. By blind tillage weeds are killed at their early stages.

Conservation agricultural (CA) practices have been widely adopted in tropics/subtropics and temperate regions of the world for rainfed and irrigated systems. Acreage of CA is increasing steadily world-wide to cover about 108 m ha (Derpsch and Friedrich 2009) globally (7% of the world arable land area). Thus CA is an innovation process of developing appropriate CA implements, crop cultivars etc for iterative guidance and fine-tuning to modify crop production technologies. Recent estimates revealed that CS based RCTs are being practiced over nearly 3.9 m ha of South Asia (Gupta 2010).

In conservation tillage, crops are grown with minimal cultivation of the soil. When the amount of tillage is reduced, the stubble or plant residues are not completely incorporated, and most or all remain on top of the soil rather than being plowed or disked into the soil. The new crop is planted into this stubble or small strips of tilled soil. Weeds are controlled with cover crops or herbicides rather than by cultivation. Fertilizer and lime are either incorporated earlier in the production cycle or placed on top of the soil at planting. Because of this increased dependence on herbicides for weed control and to kill the previous crop, the inclusion of conservation tillage as a "sustainable" practice could be questioned. It is included in this book for two reasons. First, on highly erodible soils, protecting the soil may be an overriding consideration. Second, growers and researchers are working on less herbicide-dependent modifications of conservation tillage practices, some of which are described here.

Methods described as no-till, minimum till, incomplete tillage, reduced tillage, or conservation tillage differ from each other mainly in the degree to which the soil is disturbed prior to planting. Even in 'no-till systems, the soil is opened by coulters, row cleaners, disc openers, in-row chisels or roto-tillers prior to planting the seed. By definition, conservation tillage leaves at least 30 percent of the soil covered by crop residues.

In another variation of reduced tillage, narrow strips are tilled and then planted with standard equipment. Where soils are compacted but subject to erosion, strip tillage is a good compromise because crops can be planted efficiently and grow well in the loosened soil of the tilled strips while the untilled portions of the field conserve soil and water and control weeds.

Advantages and Disadvantages

Reduced tillage practices in agronomic crops such as corn, soybeans, cotton, sorghum and cereal grains were introduced over 50 years ago to conserve soil and water. Crops grown without tillage use water more efficiently, the water-holding capacity of the soil increases, and water losses from runoff and evaporation are reduced. For crops grown without irrigation in drought-prone soils, this more efficient water use can translate into higher yields.

In addition, soil organic matter and populations of beneficial insects are maintained, soil and nutrients are less likely to be lost from the field and less time and labor is required to prepare the field for planting. In general, the greatest advantages of reduced tillage are realized on soils prone to erosion and drought, but significant advantages were seen in a 12-year study of Wisconsin silt-loams which were excellent agricultural soil. This study found improvements of many soil quality factors compared to chisel or plow treatments. These included greater water-stability of surface soil aggregates, higher microbial activity and earthworm populations and higher total carbon. Soil loss was less from sprinkler irrigation than in the plow treatment.

There are also disadvantages of conservation tillage. Potential problems are compaction, flooding or poor drainage, delays in planting because fields are too wet or too cold, and carryover of diseases or pests in crop residue. Additional problems from residues may be caused by allelopathy and high C:N ratios. Allelopathic effects are most often seen when small-seeded vegetables, such as lettuce, are planted directly into rye residues. When the residues are incorporated, as in strip tillage, allelopathic substances break down relatively quickly and are usually not a problem. (See [Weed Management](#) for a discussion of allelopathic effects on weed seed germination.)

In vegetable crops, the difficulty of controlling weeds and the need for custom-built equipment have slowed the acceptance of reduced tillage practices. Commercial seeders which plant well into stubble have been developed for most agronomic crops, but are only now becoming available for vegetable crops. A subsurface tiller transplanter has recently been developed at Virginia Polytechnic Institute and State University that should, when it becomes commercially available, greatly increase the ability of vegetable growers to transplant their crops into stubble.

Other relative disadvantages of reduced tillage in vegetables relate to the intensive nature of vegetable production. Since inputs are high in terms of seeds or transplants, fertilizers, pesticides and harvest expenses compared to agronomic crops such as corn and soybeans, the economic return must also be high.

For example, one no-till tomato grower in Pennsylvania estimated he saved \$70/acre by skipping moldboard plowing, three diskings, and two cultivations. For most growers, this represents a small percentage of total costs.

In general, vegetable growers want to harvest as soon as possible in the spring in order to get a high price and recover production costs. Without spring tillage, some no-till fields are too compacted and poorly drained for the crop to get a good start. Soil temperatures under the stubble are cooler in the spring, potentially delaying maturity of warm-season vegetables such as sweet corn, snap beans and squash. In addition, if the transplanter does not work well in stubble, the crop may be delayed and mature less uniformly.

Variable maturity is a costly problem in commercially grown vegetables especially those like cabbage where each plant is harvested once. It may not be cost-effective to bring crews in to harvest more than once or twice so late or early-maturing plants may not be harvested at all.

Another consideration in no-till production is an increased possibility of soil compaction in no-till compared to conventionally tilled soil. During one year of a four-year study, severe compaction and crusting prevented the transplanter shoe from penetrating the soil, resulting in cabbage yields 65 percent lower than conventional tillage. Planting also had to be delayed a month because the site was too wet to plant.

A further consideration is that as no-till is generally practiced in agronomic crops, the field is prepared for planting by killing the previous crop with herbicidal desiccants such as glyphosate (e.g. Roundup) or gramoxynil (e.g. Paraquat). The no-till seeders available for agronomic crops were designed to plant into these dried residues. Recently, agronomists have been developing no-till systems where cover crops are planted for weed control then killed with flail or other types of mechanical cutters instead of herbicides. No-till seeders must be modified to work on these tougher residues, but residues control weeds legumes contribute extra nitrogen. (See [Cover Crops](#) for information on cover crop cutting schedules.) Similar systems are under development for vegetable growers who want to reduce tillage operations without using herbicides.

With experience, and with the increasing sophistication and availability of no-till equipment for planting vegetables, no-till growers should be able to reach yields at least as high as with conventional tillage practices. If soil water-holding capacity improves, no-till systems may even produce higher yields. Assuming weeds can be controlled and appropriate planters found, most vegetable crops could probably be grown with reduced tillage. Asparagus, snap beans, lima beans, beets, cabbage, carrots, dry bulb onions, peas, potatoes, spinach, popcorn, sweet corn, sweet-potatoes, and tomatoes have been successfully produced in conservation tillage systems. The feasibility of using these systems without herbicides has also been demonstrated, but, as with any new technology, growers will need to experiment to develop a cover crop/vegetable crop system that works well for them.

Dryland farming

Indian agriculture is predominantly a rainfed agriculture under which both dry farming and dry land agriculture is included. Dry farming was the earlier concept for which amount of rainfall (less than 500 mm annually) remained the deciding factor for more than 50 years. In modern concept, dry land areas are those where the balance of moisture is always on the deficit side. In other words, annual evapotranspiration exceeds precipitation. In dry land agriculture, there is no consideration of amount of rainfall. It may appear quiet strange to a layman that even those areas which receive 1100 mm or more rainfall annually fall in the category of dry land agriculture under this concept. To be more specific, the average annual rainfall of Varanasi is around 1100 mm and the annual potential evapotranspiration is 1500 mm. Thus the average moisture deficit so created comes to 400 mm. This deficit in moisture is bound to affect the crop production under dry land situation ultimately resulting into total or partial failure of the crops. Accordingly the production is either low or extremely uncertain and unstable which are the real problems of dry land in India.

The success of crop production in these areas depends on the amount and distribution of rainfall, as these influences the stored soil moisture and moisture used by crops. The amount of water used by the crop and stored in the soil is governed by the water balance equation: $ET = P - (R + S)$. When the balance of the equation shifts towards right, precipitation (P) is higher than ET, so that there may be water logging or it may even lead to run off (R) and flooding. On the other hand, if the balance shifts to the left, ET becomes higher than the precipitation, resulting in drought in the various severity. Taking the country as a whole, as per meteorological report, severe drought as large area is experienced once in 50 years and partial drought in five years while folds are expected every year in one part of the country or the other, especially during rainy season. In fact the balance of the equation is controlled by the weather, season, crops and cropping pattern.

Status

Out of 14.2 million ha of net sown area in the country, rainfed agriculture is practiced in 95 million ha (67%). Nearly 67 m ha of rainfed area falls in the mean annual precipitation range of 500-1500 mm.

The average annual rainfall of the country is 1200 mm amounting to 400 million ha-m of rain water over the country's geographical area (329 m ha). However, the distribution across the country varies from less than 100 mm in extreme arid areas of western Rajasthan to greater than 3600 mm in NE states and 1100 mm from east coast 2500-3000 mm in the west coast. The broad area of the summer monsoon activity extends between 30° N to 30° S and from 30° W to 16.5° E. the detail information on rain fall and monsoonal pattern in India has been summarized in the following table:

Rainfall pattern in fall

Season/Period	m ha m	%
Winter (Jan-Feb)	12	3
Pre-monsoon (Mar-May)	52	13
South-west monsoon (Jun-Sept)	296	74
North-east monsoon (Oct-Dec)	40	10
Total for the year	400	100

Rainfed farming comprises about 91% area of coarse cereals (sorghum, pearl millet, maize and finger millet), 91% pulses (chickpea and pigeon pea), 80% of oilseeds (groundnut, rape seed, mustard and soybean), and 65% of cotton. Also, about 50% area under rice and 19% area under wheat is rainfed.

During the past 25 years there occurred significant changes in the area and yield of important crops of rainfed farming areas. The area under coarse cereals decreased by about 10.7 million ha and most of this was under sorghum. The area under oilseeds increased by 9.2 million ha and most of this increase was due to irrigated rapeseed and mustard and soybean. The total area under pulses and cotton remained constant but more of cotton became irrigated and shifts in the area occurred from one agro-ecological region to others. Area under chickpea in the northern belt decreased but increase in the central belt. This change occurred due to increase in area under rice-wheat cropping system which displaced chickpea and also pearl millet to a great extent and maize to a small extent.

According to the present concept, there are 128 districts in the country which face the problems of dry land. Of these 25 districts covering 18 m ha of net area sown with 10% irrigation receive 375-750 mm rainfall annually spread over Central Rajasthan, Saurashtra region of Gujarat and rain shadow region of Western Ghats in Maharashtra and Karnataka. Twelve districts have irrigation covering 30-50% of the cropped area and do not pose serious problems. The remaining 91 districts covering mainly *Madhya Pradesh, Gujarat, Maharashtra, Andhra Pradesh, Karnataka, Uttar Pradesh, parts of Haryana, Tamil Nadu* etc., represent typical dry land area. The total net sown area in these districts is estimated to be 42 million hectares of which 5 m ha are irrigated. Rainfall in these districts varies from 375 to 1125 mm. Therefore, more and more efforts are to be made for enhanced and stable production in these areas so that the recurring droughts do not stand in the way of meeting the growing food demands.

It is not that no attention has been paid in the country towards the development of dryland farming. Efforts were made right from 1923 to improve crop yields with the establishment of a research projects at Manjari in Maharashtra and later at Solapur, Bijapur, Raichur and Hagari in Deccan and Rohtak (Haryana) in the north. An All India Coordinated Research Project for Dry land Agriculture was launched by ICAR in 1970 in collaboration with Government of Canada. Later Central Research Institute for Dryland Agriculture (CRIDA) was established in 1985 at Hyderabad. These projects generated technology, which, if followed, can bring marked improvement in cropping intensity, productivity and stability in production.

Problems

In dry land agriculture, scarcity of water is the main problem. Apart from the low and erratic behavior of rainfall, high evaporative demand and limited water holding capacity of the soil constitute the principle constraint in the crop production in dry land area. Yield fluctuations are high mainly due to vagaries of weather, often much behind the risk bearing capacity of the farmers. It is surprising to a layman that even humid areas with 2000 mm of annual rainfall not only suffer from moisture stress, but also face drinking water scarcity. Monsoon starts in the month of June and ends in last week of September or sometimes in the first week of October. Most of the rainfall is received during this period. With undulating topography and low moisture retention capacity of the soil, major portion of the rain water is lost through runoff, causing erosion and adding to the water logging of low lying areas. After the rain stops, very little moisture is left in the profile to support plant growth and grain production.

In dry land area deficiency and uncertainty in rainfall of high intensity causes excessive loss of soil through erosion which leaves the soil infertile. Owing to erratic behaviour and improper distribution of rainfall, agriculture is risky, farmers lack resources, tools become inefficient and ultimately productivity is low.

Vertisoles have high clay content and high moisture retention capacity. Owing to its swelling and shrinking characteristics, permeability is low and hence the rate of infiltration of water is minimum. This causes more surface and high soil loss from the top layer owing to surface erosion. It is estimated that 68.5 tones/ha per year soil is lost from *vertisoles*. Due to high clay content it develops cracks during Rabi season at flowering stage of crops.

Alfisols are, by and large, light textured soils which have low moisture holding capacity but high water intake. The rain water falling in such areas gets soaked up and saturates the profile. The soil water percolation is more and therefore, is lost for crop use. Owing to faster intake of water in the profile the surface runoff is limited and soil loss from erosion is low (3.05 t/ha/year). Soil crusting is a common problem in low rainfall areas.

Entisols are generally loamy sand or sandy loam. Depth in these soils is not a constraint. These soils have very low clay content and hold water up to 200 mm per meter of soil profile. Its nutrient holding capacity is poor. In low rainfall areas monsoon cropping is practiced and in high rainfall areas double cropping is possible.

Submontane soils are medium in texture and depth is medium to deep as well as moderate in clay content. Moisture retention capacity is high (300 mm/m. profile). These soils are poor in nitrogen but in other nutrients. Phosphorous may be limiting in high production system. Due to high rainfall double cropping is possible in these soils.

Sierozems are extremely light soils, effectively depth being influenced by the CaCO_3 concentration in soil profile. Its moisture holding capacity is low (150 mm water.m). Sierozemic soils are low in nitrogen and sometimes inadequate in phosphorous. Subsoil salinity is common. These soils are mostly monsoon cropped, except in deep sandy loams where post-monsoon cropping is also possible. Crusting is very frequent.

Improved Dryland Technology

The improved techniques and practices, which have so far been generated and recommended for achieving the objective of increased and stable crop production in dryland areas, have been summarized in following lines.

Crop Planning

The farmers of the dry land areas, prior to the development of dry land techniques, were growing a crop either on rainwater in kharif or on conserved soil moisture during the winter. The crop varieties are grown when moisture is sufficiently available. Such varieties have low genetic potential for yield. Selecting suitable crops and varieties capable of maturing within actual rainfall periods will not only help in enhancing production of a single crop but in intensifying the cropping intensity. Many criteria have been laid out for selecting a crop variety for drylands. The capacity to produce a fairly good yield under limited soil moisture conditions is the most desirable criteria. The duration of kharif crops/varieties should not normally exceed the number of rainy days. In other words, crop varieties for dryland areas should be of short duration, through resistant tolerant and high yielding which can be harvested with in rainfall periods and have sufficient residual moisture in soil profile for post-monsoon cropping.

Under dry land agriculture determination of length of growing period (LPG) i.e., moisture availability of a given soil type, provides better index than total rainfall based crop planning. LPG is defined as the period when the moisture and temperature regimes are suitable for crop growth and the period is determined by the FAO method (1983). The LPG is computed as the sum of the period when P is more than 0.5 PET plus time taken to utilize stored soil moisture (assured 100 mm) after P falls short of PET. For example 'Nagpur' and Ratnagiri in Maharashtra receive mean annual rainfall of 1120 mm and 2500 mm, respectively but LPG determination indicates that both the places have LPG of 210 days in deep black soils. Therefore, both the places are suitable for single long duration on a short duration crop with a relay rabi crop.

Planning for aberrant weather

Dryland agriculture is subject to high variability in areas sown, yields and output. These variations are the results of aberrations in weather conditions, especially rainfall. Delay in normal monsoonal pattern causes problems of timing and the organization of preparatory tillage and other initial activities for commencing cultivation processes for the season. Such monsoonal delays have repercussions on the programme of activities for the entire agricultural year. Even after the onset of monsoon and the commencement of planting, there may be monsoonal withdrawal causing moisture stress on plants and creating difficulties in the adoption and timing of approval cultural practices ultimately causing reactions in yields and outputs. Some crops are highly susceptible to such mid-season variations in moisture availability such as at the flowering stage in rice. Major crops like rice and maize get seriously affected if monsoonal rains cease early.

The need for modifying and introducing and introducing new technology for increasing and sustaining yield in dry land areas can hardly be overemphasized. Equally urgent is the need to decelerate and ultimately eliminate the process of damage to agricultural assets which are proceeding unabated in dry land areas. Erratic rainfall results in fluctuating production. This in turn leads to frequent scarcities, like the ones experienced in Indonesia and Vietnam in 1977 which created severe food shortages. Droughts in China in 1972, 1974 and 1985 brought depression of food grain production by up to about 25 million t. Frequent droughts in India during 1966, 1968, 1972, 1974, 1979, 1982 and 1987 seriously affected the food and fodder production in the country. Hence, it is necessary to understand the distribution of South-West monsoon within the season to determine the extent to which the crop productions are likely to be affected by the vagaries of monsoon.

Several attempts have been made to understand the behavior of South-West monsoon rainfall in different agro-climatic regions on the basis of historical rainfall records. These studies (Singh, 1987, Ramanna Rao, 1988) have brought out that (i) there is large variation in dates of commencement of South-West monsoon from year to year in different parts of the country, (ii) the monsoon rainfall is of sequential nature with long dry spells or breaks extends sometimes to the period of even one month or more, (iii) there is large year to year variation in dates of withdrawal of South-West monsoon, (iv) there is variation in quantum of rainfall received from year to year and (v) high intensity rainfall occurs in association with movement of cyclones or depression resulting in sizeable loss of rainwater through run-off and deep drainage. Thus, crop production in dry lands fluctuates widely from year to year due to vagaries of weather. An aberrant weather can be

categorized under three heads i.e. (i) delayed onset of monsoon, (ii) long gaps or breaks in rainfall, and (iii) early stoppage of rains towards the end of monsoon season. Therefore, to mitigate such weather situations, farmers should make some changes in normal cropping schedule for getting some production in place of total crop failure.

Crop Substitution

Alternate crop strategies have been worked out for important regions of the country for *vertisols*, *alfisols*, *entisols*, *submontane* and *sierozemic* soils. Strategy has also been evolved for normal onset of rains, breaks in rains, early withdrawal, its uneven distribution; through selection of crops/varieties which efficiently utilize the soil moisture, responsive to production input and potential producers. Appropriate crops, suiting varying rainfall situations, have been identified for most of the dry land regions of India (Table below).

Crops which do better under normal rainfall years may not do so under abnormal years. Studies conducted in agro climatic conditions of Varanasi (eastern U.P.) revealed that under normal monsoon crops like short duration upland rice, maize, pearl millet, blackgram, greengram, sesame, pigeon pea etc. should be taken up on the basis of needs. These crops should be followed by chickpea, lentil, barley, mustard, safflower, linseed etc. on residual moisture during winter season.

If monsoon sets in as late as second week of July, short duration upland rice (variety - NDR-97 and NDR-118) may be included in place of Akashi and Cauvery. If the rains are delayed beyond the period but start somewhere in last week of July or first week of August and growing season is reduced to 60-70 days, then cultivation of hybrid pearl millet (NHB 3-4, B.J. 104), blackgram (Type 9), greengram (var-Jagriti and Jyoti) may be included in place of T-44 and K-851 etc. Yet another alternative could be to harvest a fodder of either pearl millet, maize, sorghum or a mixture of cowpea, blackgram and one of the above fodder crops.

In case monsoon rains stop early towards the end of season, normal sowing of short duration upland rice, black gram and sesame may be taken up. If the rain stops very early, i.e. by the end of August or first week of September, only fodder crops or grain legumes could be harvested. Depending upon the soil moisture condition, relay sowing of crops like chickpea, lentil, mustard, linseed and barley could be done in rabi season.

Table: Traditional and Alternate Efficient crops in Different Dryland Regions of India

SN	Region	Traditional crop	Alternate efficient crop
1.	Deccan Rabi season	Cotton, wheat	Safflower
2.	Malwa Plateau	wheat	Safflower, Chick pea
3.	Uplands of Bihar Plateau and Orissa	Rice	Ragi, Black gram, Groundnut
4.	South-easy Rajasthan	Maize	Sorghum
5.	North Madhya Pradesh	Maize	Soybean
6.	Eastern UP	Kalitur	Chick pea
7.	Sierozems of North-west India	Wheat	Mustard, Taramira (Eruca sativa)

During the recent drought, it was found that farmers in Karnataka, Andhra Pradesh and Maharashtra who went in for sunflower cultivation were in gainers. Sunflower succeeded where other crops failed. In other dry land regions, alternative efficient crops can profitably substitute the traditional ones (Table below).

Table: Relative Yield of Traditional and Efficient Crops in Dryland Areas

Region	Traditional	Yield (q/ha)	Efficient crops	Yield (q/ha)
Bellary	Cotton	2.0	Sorghum	26.7
Varanasi	Wheat	8.6	Chickpea	28.5
Ranchi	Upland Rice	28.8	Maize	33.6
Indore	Green gram, Wheat	11.8	Soybean	33.3
			Safflower	24.2
Agra	Wheat	10.3	Mustard	20.4
Hisar	Wheat	3.0	Taramira	16.0
Udaipur	Maize	18.0	Hybrid sorghum	29.0

Dry land research has remained confined to important traditional crops such as sorghum, millet, pulse and oilseeds and has not explored the possibility of growing non-traditional crops such as dye-providing crops (e.g. Henna (*Lawsonia inermis*: mehadi) and jaffra (*Bixa ovellana*) species (e.g. cumin), and medicinal value crops (e.g. citronella, lemon grass, senna and isabgol)}. These crops need to find an important place in research agenda of dry land farming.

Time has come for the relevant researchers to plan a joint integrated research programme for maximizing the profitability, productivity and sustainability of learning systems of rainfed areas. Sericulture offers great promise in rainfed farming strategy, particularly of the watershed approach in peninsular India.

Efficient Cropping System

Besides putting various measures to increase the productivity levels of dry land crops, efforts would also be needed to increase the cropping intensity in dry land areas which was generally 100%, implying that a single crop was taken during the year. Cropping intensities of these areas could be increased by practice of inter cropping and multi cropping (sequential) by way of more efficient utilization of resources. The cropping intensity would depend on the length of growing season which in turn depends on rainfall pattern and the soil moisture storage capacity of the soil. For example in Indore region, receiving 1000 mm annual rainfall, only single crop can be taken on shallow soils, inter cropping in medium depth soils and double cropping on deep soils. Similar crop combinations have been identified for different regions of the country. In dry land of Varanasi region upland rice-chickpea/lentil sequence can be practices with advantage.

Inter cropping of vegetables with grain crops was pursued vigorously in some centers such as Varanasi and Phulbani. At both the places long duration pigeon pea was inter cropped with vegetables such as okra, radish and chilli. Such inter cropping systems would be very useful to get maximum returns from rainfall agriculture. Even at Solapur, leafy vegetables and some short duration beans were grown as intercrops during the rainy season.

Fertilizer Use

Soils of dry lands in the country are not only thirsty but hungry also because these soils are severely eroded horizontally as well as vertically. Whenever efforts are made towards bunding and levelling of the fields in dry land areas, it is the surface soil which is removed. The resultant effect is that the fields are rendered shallow in depth and completely deprived of plant nutrients, particularly nitrogen, phosphorus and potassium. It is, therefore, necessary to apply all the three major nutrients in adequate amounts. Since soil moisture is limiting in dry lands, the availability of nutrients becomes limited, attempt should always be made to apply fertilizers in furrows below the seed. If seed-cum-fertilizer drills drawn by bullocks or tractors are available, this very objective can be fulfilled. There has been belief among the farmers of dry land areas that use of fertilizer increases the chances of crop failure but recent findings have shown that the use of fertilizer is not only helpful in providing nutrients to crop but also helpful in efficient use of profile soil moisture (Table below). If dry land farmers are shown such results, they will be convinced to use more and more fertilizers.

Table. Effect of N on Yield and Moisture Use Efficiency (MUE) of Barley and Wheat (Varanasi)

Nitrogen levels (kg/ha)	Grain yield (q/ha)	Total moisture use (mm)	MUE (kg/mm)
Barley			
0	14.05	133.7	10.5
30	20.45	136.3	15.0
60	30.00	142.3	21.0
90	37.20	141.6	26.3
Wheat			
0	9.55	145.5	6.6
30	13.55	144.4	9.3
60	18.35	153.6	11.9
90	24.15	155.1	13.6

Studies on the management of legumes in crop sequences for their residual effect indicated that in alluvial soils an advantage of 25-30 kg N/ha could be obtained in barley or mustard grown after black gram or green gram. Another possibility for

nitrogen management in cropping system is to use legumes as green manures either at flowering stage or after one picking. Studies conducted at Varanasi clearly showed that general yield levels of barley and mustard were greater when legumes raised in the previous season was incorporated I soil after first picking as compared to that harvested at normal maturity (Table below).

In dry land areas, a proper mixing of organic and inorganic would be desirable. Organics have low nutrient content, but help to improve the moisture holding capacity of soils. In addition to yield advantage, nutrients like potassium help to increase drought tolerance by affecting plant-soil relationship. Transpiration losses are reduced and productivity per unit water increases.

Table. Nitrogen Economy to Legume-Cereal System (4 years average)

Nitrogen (kg/ha)	Crop yield (q/ha)	
	Green gram Incorporated	Unincorporated
Mustard	1.89	2.23
Barley		
0	16.98	13.65
30	21.30	18.64
60	24.43	21.84
90	27.27	25.20

Rain water management

Efficient management of rain water can boost agricultural production from dry lands. The broad bed and furrow system of the **International Crop Research Institute for the Semi Arid Tropics (ICRISAT)** for managing rain water in vertisols made it possible to increase crop yields four to five times as compared to normal practice. However, this method could not be adopted widely by the farmers in India because it is costly and labour intensive. The vertical mulching developed at Bellary centres increases the infiltration of water in soil profiles and improves in situ moisture conservation. The scope for managing profile moisture is limited in alfisols but the surface run off in such soils can be reduced by ridge-and-furrow technique. Alternatively, application of compost and farm yard manure as well as raising legumes will add the organic matter to the soil and increase the water holding capacity.

The winter rain which is not retained by the soil flows out as surface runoff. The run-off-recycling holds immense prospects in deep black soils where the seepage losses are very much less. This runoff water, if not permitted to drain out safely, causes erosion. Therefore, safe disposal of excess water from the field drains to the disposal system should be planned properly. This excess runoff water can also be harvested in storing dug out ponds and recycled to donor area in the event of severe moisture stress during rainy season or for raising crops during the winter.

Water-shed Approach for Resource Improvement and Utilization

Watershed management is a holistic approach arrived at optimizing the use of land, water and vegetation in an area and thus, providing solution to alleviate drought, moderate floods, prevent soil erosion, improve water availability and increase fuel, fodder and agricultural production on a sustained basis. On the basis of the experiences of ICAR Operational Research Projects, which attracted the attention of our farmers, State departments, administrators and scientists, 47 model watersheds were established during the year 1983 for development, jointly by the Ministry of Agriculture, ICAR and various State Government Department and Agricultural Universities, in 16 states and then the Department of Agriculture and Co-operation launched the National Watershed Development Project for Rainfall Areas (NWDPA) covering almost the same states. Out of these 47 model watersheds, the Central Research Institute for dryland Agriculture (CRIDA), Hyderabad has been entrusted with 30 watersheds. These activities were in micro and mini-watersheds covering 500-2000 ha. Major components in these model watersheds are: (i) Improvement of water resources, (ii) In situ soil and water conservation: rain water harvesting for safe disposal of surface runoff, (iii) increase in cropping intensity and (iv) alternate land use system for efficient use of lands as per land capability to provide stability in productivity.

The model watersheds in operation have provided a fruitful experience of how development can lead to all round improvement in food and fodder production, economic condition of the farmers. Sakho-majori model, where creation of

eater source worked as a catalyst and triggered the development process can be repeated under similar situations. Similar experiences have been gained at Tejpura (Jhansi), Ariel (Bareilly District) and Tejpura watersheds which have been awarded the First and Second Prizes respectively by the President of India on 14-11-1988 based on the recommendation of National Productivity Council.

Alternate land use system

All dry lands are not suitable for crop production. Some lands may be suitable for range/pasture management, while others for tree farming, lay farming, dry land horticulture, agro-forestry systems including alley cropping. All these systems which are alternatives to crop production are called as alternate land use systems. This system not only helps in generating much needed off-season employment in mono crop dry land but also minimizes risk, utilizes off season rains which may otherwise go waste as runoff, prevents degradation of soils and restores balance in the ecosystem.

Crop production may be disastrous in the years of drought, whereas drought resistant grasses and trees could be remunerative. Scientists of dry land have developed many alternate land use systems which may suit different agro ecological situations. These are alley cropping, agri-horticultural system and silvi-pastoral systems which utilize the resources in better way for increased and stabilized production from dry lands.

Alley Cropping: For imparting stability and providing sustainability to the farming system, a tree-cum-crop system will be one most appropriate for such situations. One such system called 'alley cropping' - a version of agro-forestry system, could meet the multiple requirements of food, fodder, fuel, fertilizer etc. Alley cropping is a system in which food crops are grown in alleys formed by hedge rows of trees or shrubs. The essential feature of the system is that hedge rows are cut back at planting and kept pruned during cropping to prevent shading and to reduce competition with food crops.

For example, fast growing leguminous trees such as *Leucaena leucocephala* or *Gliricidia spp.* are planted in rows. During the cropping season, trees are lopped at about 0.5 m height. These loppings are used as mulch to reduce moisture loss and improve the nutrient status of soil. Arable crops like maize, rice, pearl millet, legumes, oilseeds etc. are planted in the alleys formed by the two rows of trees. This is also known as agri-silvi culture. Alley cropping is also a form of conservation farming which enhances soil fertility and prevents erosion.

One very strong argument in favour of alley cropping is its ability to produce usable material even in years of severe drought. At Rajkot in 1985, rainfall received during the season was only 30% of the normal. There was total failure of grain production of the three legume crops tried in the system. In sole crop plots production was limited to 5.0 q/ha to 17.0 q/ha of green fodder. However, in alley cropped plots, *Leucaena* hedge-rows produced over 50.0 q/ha of green fodder.

Agri-horticultural system: Agri-horticultural system plays an important role in dry land areas, especially in semi-arid regions where production of annual crops is not only low but also highly unstable. Fruit trees if suitably integrated in dryland farming system could add significantly to overall agricultural production including food, fuel and fodder, conservation of soil and water and stability in production and income. Dry land fruit trees being deep rooted and hardy, can better tolerated monsoonal aberrations than short duration seasonal crops. Hence, in drought year when annual crops usually fail or their production is highly depressed, fruit trees species yield considerable food, fodder and fuel.

A suitable example of agri-horti-system is growing of cow pea/green gram/horse gram in inter space of *ber* (*Zizyphus mauritiana*) at 6 x 6 m spacing at Hyderabad. Phalsa (*Grewia asiatica*) may be planted in between two ber plants in a row with a view to intensify the system. A well managed dry land orchard of ber should give 50 kg fruits per tree/year. There should be 250 plants/ha for optimized production. The gross income would touch around Rs. 50,000/ha (250 x 50 x 4), assuming that one kg *ber* fetches Rs. 4. One could get an additional income of Rs. 800-Rs. 1000 from green gram/cow pea (2.5-3.0 q/ha).

Silvi-Pastoral System: This system is suited to marginal dry lands and is most preferable where the fodder shortages are experienced frequently. The system essentially consists of a top feed tree species carrying grasses on legumes (preferable perennial) as understorey crops. Dry land farmers having larger holdings and keeping a land fallow for a longer period for one reason or the other, should go in for this system which could provide both fodder and fuel. In a survey carried out in Andhra Pradesh, Karnataka and Maharashtra by CRIDA scientists, it was revealed that after food it is the fodder which is of paramount importance for sustaining animal wealth in rural areas. In years to come, fuel will assume greater importance.

In August, 1981 *Leucaena leucocephala* was planted in contour trenches 7.5 m apart, the plant to plant spacing being maintained at 2.0 m at CRIDA. Four strips at upper reaches of plot (2% slope) were put under *Cenchrus ciliaris*, while lower four strips were seeded with *Stylosanthes hamata*. The system has come up very well.

Efficient Implements

In order to take full advantage of annual precipitation in dry land agriculture, higher doses of energy input is essential. Farmers in dry lands have been using traditional and outdated farm equipments which not only perform poorly but also demand a lot of energy and time and post-harvest operations. Farm implements can help to conserve as much rain water in situ as possible and to harvest rain water. Shallow off season tillage with pre-monsoon showers ensures better moisture conservation and lesser weed intensity. It has resulted in 20% yield increase in sorghum in Andhra Pradesh. Deep tillage helps in increasing water in soils having textural profiles and hard pan. This has resulted in 10% yield increase in sorghum and 9% yield increase in case of castor. For in-situ moisture conservation, land has to be opened so that it can cause hurdle to flow of rain water. Tillage machines of appropriate size and type matching the power sources need to be used. Location specific seeders have been developed for dry land areas and these have shown good prospects and promise. A feature of these machines is that the seeds and fertilizers are placed in the moist zone of the soil resulting in a high percentage of seed germination and good crop vigour. In deciding farm mechanization in dry land areas, where farmers are generally poor, and their socio-economic condition should always be kept in mind.

The foregoing discussions show that technology of crop production in dry land areas have been generated to a great extent. What is important now is to view it in socio-economic context of the farmers. Once the technology is adopted by the farmers, the contribution of dry land areas to the total production can be sizably improved and the living standards of the farmers of these areas can be improved. This has been clearly shown in selected watershed areas and what is needed is to have more watersheds identified, proper technology to be developed and implemented.

Determining the nutrient needs for yield potentiality of crop plants

There are thirteen essential nutrients which plants get from soil. The six that the plants need the most of are called Macronutrients. They are N, P and K, Ca, Mg and S. The other nutrients, which are needed only in trace amounts, are called Micronutrients. They are Fe, Mn, Zn, Cu, B, Mo and Cl.

N encourages leaf growth. P encourages roots and flowers. K encourages general vigor. If one of these nutrients isn't available, then plant growth will be slower or stunted, and leaves will be discolored. For example, lack of N causes the old leaves to turn yellow. Lack of Fe causes the new leaves to be yellow. Nutrient deficiencies will form patterns on the leaves that follow the vein patterns: sometimes along the veins, sometimes between the veins. Disease symptoms don't follow the veins.

Soil laboratories will test soils for nutrients as well as pH and organic matter. However, a general recommendation is: All soils are short on N; shallow rooted plants such as lawns and flowers need extra P and K; Fe and S are often deficient, especially around acid loving plants. Usually, the soil contains enough of the other nutrients, although some may be deficient in certain parts of the country.

Organic fertilizers and specially treated synthetic fertilizers are slow release so they won't burn and the nitrogen won't wash away in the rain before plants can use it.

To achieve their potential yield, **crop** nutrient requirements cannot be met by soil supply alone. Yield potential of crop plants therefore, can be achieved by external supply of nutrients through organic and inorganic fertilizers. The nutrients are identical whether they come from organic or synthetic sources, but the source will affect how fast the nutrients are available to plants. The soil contribution is estimated by soil tests. Although soil testing is generally accepted as a workable practice, there are some differences in interpreting the tests. This results in radically different fertilizer recommendations to the farmers. There are three major concepts for making fertilizer recommendations: maintenance, cation saturation ratio and sufficiency level.

Maintenance concept implies that whatever may be the soil supplying capacity, a quantity of nutrient has to be applied to replace that amount removed by the crop. Even though the soil supplying capacity of a given nutrient is adequate for top yields, still fertilizers are recommended based on the maintenance concept.

As per the cation ratio concept, a soil is considered as an ideal one with the following distribution of exchangeable cations: 65 per cent Ca, 10 per cent Mg, 5 per cent K and 20 per cent H so as to have ratios of Ca: Mg as 6.5: 1; Ca: K as 13: 1, and Mg: K as 2 : 1. Fertilizers are recommended to maintain this ratio. However, wide variations in these ratios have no adverse effect. In sufficiency level concept, crop response to applied nutrients is considered. This concept is followed in most of the fertilizer recommending approaches.

Several approaches are followed for recommending fertilizers and each approach has advantages and disadvantages.

Blanket recommendation

Based on the fertilizer experiments conducted in different regions with improved varieties, fertilizer dose is recommended for each environment. This approach does not consider soil contribution. However, it is suitable for recommendation of nitrogen since residual effect of fertilizer N applied to previous crop is negligible and soils are generally low in N content.

Soil test based fertilizer recommendations

The soil samples analyzed for available N, P and K are categorized into low, medium and high fertility classes with respect to each nutrient. These fertility classes for available N, P and K are given in Table 1 for the soils of Himachal Pradesh. The state level fertilizer recommendations for a particular crop as given in the package of practices for kharif and rabi crops are meant for medium soil fertility class. If the test shows a particular nutrient in low fertility class then the state level fertilizer dose with respect to that particular nutrient has to be increased by 25%. If the soil test fall in high class, then the state level fertilizer dose has to be decreased by 25%.

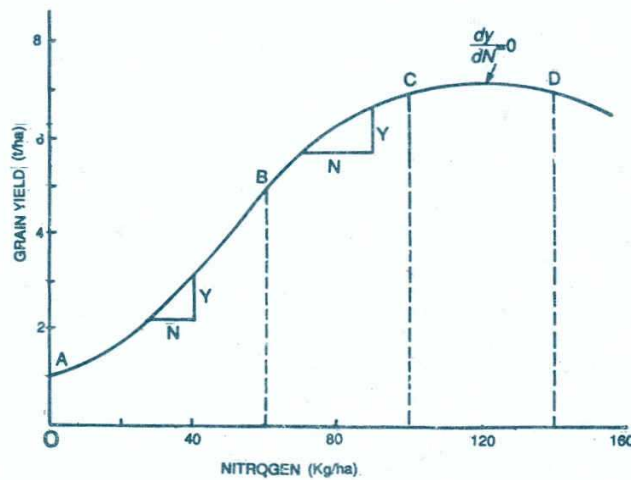
Nutrient (kg/ha)	Fertility class		
	Low	Medium	High
N	<280	280-560	>560
P	<10	10-25	>25
K	<118	118-280	>280
OC%	<0.50	0.50-1.00	>1.00

The rating limits for classifying the soils are very wide and without considering this fact same fertilizer dose is recommended over a wide range of available nutrient. This means that there are too many discrepancies in the interpretation and fertilizer recommendations on the basis of soil test rating. Moreover, these rating limits are of general nature and do not

take into account either crop/variety, soil type or climatic conditions existing in a particular area. The crop variety differ greatly in its requirement for each nutrient and efficiency of each soil available as well as added fertilizer nutrient is a function of soil type and climatic conditions. Therefore, the above method of fertilizer recommendation on the basis of soil test rating may not give the precise dose of fertilizer nutrient. Because of this type of soil test interpretation and fertilizer recommendation, two type of situations arise. In the first case, fertilizer nutrients are applied beyond the requirement of the crop which leads to mere wastage of costly inputs like fertilizers. In the second case, fertilizer nutrient are applied much less than the actual requirement of the crop which in turn, is responsible for not harvesting the full potential of the crop.

Response equations

Field experiments are conducted with different levels of fertilizers. The yield responses to different levels of fertilizers are fitted into a mathematical equation based on the shape of the curve. From the equation, economic optimum dose is calculated and recommended to the farmer.



Response of rice to nitrogen

Curve Fitting. Generally, the response to fertilizers is quadratic i.e. yield increases at increasing rate with increase in fertilizer dose upto a certain level and at a decreasing rate with subsequent doses of fertilizers. At a particular level, yield approaches a plateau and further increase in fertilizer dose decreases the yield.

From Fig. above, it can be seen that even with no fertilizer application, one t/ha of grain yield can be obtained due to inherent soil fertility. There is linear increase in yield upto 60 kg N/ha (from A to B). Subsequently, the response line is curvilinear (from B to C) i.e. for every increase in fertilizer dose, the yield increased at a decreasing rate. Beyond 100 kg N/ha, the grain yield does not increase with increase in fertilizers which is called as plateau (C to D). Further increase in fertilizer dose beyond 140 kg N/ha, yield decreases and is considered as toxic level.

This curve can be expressed as a mathematical equation.

$$Y = a + bN + cN^2$$

Where Y is grain yield (kg/ha), N, nitrogen dose (kg/ha) and a, b and c are constants. Constant a is known as intercept which indicates the yield level without fertilizers. Constant b, otherwise known as slope, provides the response rate (kg grain obtained per kg N applied). Constant c represents the curvature of the response line which indirectly indicates the adverse effect of excess dose of nitrogen. Generally, constant c has a negative sign.

The drawbacks in the responses equation approach are: (1) soil contribution is not considered, (2) the level of production, which is low with the farmer, is not taken into account, and (3) response equations have to be different for each variety tested.

Soil Test Crop Response (STCR) Approach

This approach takes into account the soil contribution and yield level for recommending fertilizer dose for a particular crop. This approach is also called as rationalized fertilizer prescription or prescription based fertilizer recommendations. It is specific to a given type of soil, crop and climatic situation. The requirement of nutrients is different for different crops. The efficiency of soil available nutrients and those added through fertilizers is also different for different type of soils under a particular set of climatic conditions. Therefore, following three basic parameters are worked out for the specific crop and area for the development of prescription based fertilizer recommendations:

1. Nutrient requirement (kg/q) = $\frac{\text{Total uptake of nutrient (kg/ha)}}{\text{Grain yield (q/ha)}}$
2. Efficiency of available nutrient (CS%) = $\frac{\text{Uptake in control plot (kg/ha)}}{\text{Soil test value (STV) of nutrient (kg/ha) in control plots}} \times 100$
3. Efficiency of fertilizer nutrient (CF%) = $\frac{\text{Nutrient uptake fertilized plots} - (\text{STV fertilized plot} \times \text{CS})}{\text{Nutrient applied through fertilizer (kg/ha)}} \times 100$

After calculating these three basic parameters from the yield and uptake data from the well conducted test crop experiment, these basic parameters, in turn, are transformed into workable fertilizer adjust equations as below,

Fertilizer nutrient dose (kg/ha)	=	$\frac{\text{NR}}{\text{CF\%}}$	x 100 x T	-	$\frac{\text{CS\%}}{\text{CF\%}}$	x	STV
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Thus equations for nitrogen, phosphorus and potassium are of the type

$$FN = X T - Y SN$$

$$F P_2O_5 = X_i T - Y_i SP$$

$$F K_2O = X_j T - Y_j SK$$

Where SN is soil nitrogen (N kg/ha); SP soil phosphorus (P kg/ha); SK soil potassium (K kg/ha); FN fertilizer N to be applied (N kg/ha); FP fertilizer P₂O₅ to be applied (P₂O₅ kg/ha); K₂O fertilizer K₂O to be applied (K₂O kg/ha) and T is targeted yield (q/ha).

Based on this approach, fertilizer recommendations are developed for different regions. One such equation developed to recommend N, P, K fertilizers for rice is given below:

$$FN = 4.39 T - 0.6723 SN$$

$$F P_2O_5 = 2.83 T - 6.110 SP$$

$$F K_2O = 1.41 T - 0.329 SK$$

It is to be remembered that in the equations, soil phosphorus and potassium are considered in elemental form while fertilizer phosphorus and potassium are in oxidized form (P₂O₅ and K₂O).

The prescription based fertilizer recommendations method avoid wide variation in soil rating limits used in the previous method as it substitutes the exact values for soil available N, P and K. This method ensures the balanced nutrition of crops besides the maintenance of soil fertility.

The drawbacks of STCR approach are that these equations are not available for different crops and regions and development of these involves cost and time. These equations are suitable when available N P and K are estimated by potassium permanganate, Olson and ammonium acetate methods, respectively.

DRIS Approach

Recently Diagnosis and Recommendation Integration System (DRIS) approach is suggested for fertilizer recommendation. In this approach, plant samples are analyzed for nutrient content and they are expressed as ratios of nutrients with others. Suitable ratios of nutrients are established for higher yields from experiments and plant samples collected from farmer's fields. The nutrients whose ratios are not optimum for high yields are supplemented by top dressing. This approach is generally suitable for long duration crops, but it is being tested for short duration crops like soybean, wheat etc.

Modeling Approach

This approach is particularly suitable for recommendation of nitrogenous fertilizers where soils are rich in organic matter as in temperate regions. The soil contribution is estimated based on the fact that mineralization depends on soil temperature.

$$Y = K [(T - 15) \times D]^n$$

Where Y is amount of mineralized nitrogen; T soil temperature (°C); K coefficient related to the potential of mineralized nitrogen; n constant relating to the pattern of nitrogen mineralization, 15 threshold temperature and D is incubation period.

The N use efficiency for applied fertilizers ranges from 30 to 40 per cent depending on the nature of the fertilizers, source and management practices. Based on the mineralizable N during the crop period, the balance amount of nitrogen is supplied through fertilizer after considering nitrogen use efficiency.

Precision agriculture

Precision farming is a method of crop management by which areas of land within a field may be managed with different levels of inputs depending upon the yield potential of the crop in that particular area of land. The benefits of so doing are twofold:

- the cost of producing the crop in that area can be reduced;
- the risk of environmental pollution from agrochemicals applied at levels greater than those required by the crop can be reduced.

Precision farming is an integrated agricultural management system incorporating several technologies. The technological tools often include the global positioning system GPS, geographical information system GIS, remote sensing, yield monitor and variable rate technology.

The Need for Precision Farming

The 'Green revolution' of 1960's has made our country self sufficient in food production. The food grain production shot up from 51 million tonnes (mt) from 97 m ha (1950-51) to a record of 241 mt from 123 m ha (2010-11). This showed a growth rate of 360 per cent with a meagre 24 per cent increase in gross cultivated area. All this has been possible due to high input application, like increase in fertilization, irrigation, pesticides, higher use of HYV's, increase in cropping intensity and increase in mechanization of agriculture.

i) Fatigue of Green Revolution

Green revolution of course contributed a lot. However, even with the spectacular growth in the agriculture, the productivity levels of many major crops are far below than expectation. We have not achieved even the lowest level of potential productivity of Indian high yielding varieties, whereas the world's highest productive country have crop yield levels significantly higher than the upper limit of the potential of Indian HYV's. Even the crop yields of India's agriculturally rich state like Punjab is far below than the average yield of many high productive countries (Ray *et al.*, 2001).

ii) Natural Resource Degradation

The green revolution is also associated with negative ecological/environmental consequences. The status of Indian environment shows that, in India, about 182 m ha of the country's total geographical area of 328.7 m ha is affected by land degradation of this 141.33 m ha are due to water erosion, 11.50 m ha due to wind erosion and 12.63 and 13.24 m ha are due to water logging and chemical deterioration (salinisation and loss of nutrients), respectively. On the other end, India shares 17% of world's population, 1% of gross world product, 4% of world carbon emission, 3.6% of CO₂ emission intensity and 2% of world forest area. One of the major reasons for this status of environment is the population growth of 2.2% in 1970 – 2000. The Indian status on environment is, though not alarming when compared to developed countries, gives an early warning.

In this context, there is a need to convert this green revolution into an evergreen revolution, which will be triggered by farming systems approach that can help to produce more from the available land, water and labour resources, without either ecological or social harm (Swaminathan, 2002). Since precision farming, proposes to prescribe tailor made management practices, it can help to serve this purpose.

The Basic Components of Precision Farming

Precision farming basically depends on measurement and understanding of variability, the main components of precision farming system must address the variability. Precision farming technology enabled, information based and decision focused, the components include, (the enabling technologies) Remote Sensing (RS), Geographical Information System (GIS), Global Positioning System (GPS), Soil Testing, Yield Monitors and Variable Rate Technology.

Precision farming requires the acquisition, management, analysis and output of large amount of spatial and temporal data. Mobile computing systems were needed to function on the go in farming operations because desktop systems in the farm office were not sufficient. Because precision farming is concerned with spatial and temporal variability and it is information based and decision focused. It is the spatial analysis capabilities of GIS that enable precision agriculture. GPS, DGPS has greatly enabled precision farming and of great importance to precision farming, particularly for guidance and digital evaluation modelling position accuracies at the centimetre level are possible in DGPS receivers. Accurate guidance and navigation systems will allow for farming operations at height and under unfavorable weather conditions even.

In India, we have all these technologies available and they can be implemented through agricultural training centres by giving training to agriculture officers in these technologies.

Basic Steps in Precision Farming

The basic steps in precision farming are,

- i) Assessing variation
- ii) Managing variation and
- iii) Evaluation

The available technologies enable us in understanding the variability and by giving site specific agronomic recommendations we can manage the variability that make precision agriculture viable. And finally evaluation must be an integral part of any precision farming system.

i). Assessing variability

Assessing variability is the critical first step in precision farming. Since it is clear that one cannot manage what one does not know. Factors and the processes that regulate or control the crop performance in terms of yield vary in space and time. Quantifying the variability of these factors and processes and determining when and where different combinations are responsible for the spatial and temporal variation in crop yield is the challenge for precision agriculture.

Techniques for assessing spatial variability are readily available and have been applied extensively in precision agriculture. The major part of precision agriculture lies in assessing to spatial variability. Techniques for assessing temporal variability also exist but the simultaneous reporting a spatial and temporal variation is rare. We need both the spatial and temporal statistics. We can observe the variability in yield of a crop in space but we cannot predict the reasons for the variability. It needs the observations at crop growth and development over the growing season, which is nothing but the temporal variation. Hence, we need both the space and time statistics to apply the precision farming techniques. But this is not common to all the variability/factor that dictate crop yield. Some variables are more produced in space rather with time, making them more conducive to current forms of precision management.

ii). Managing variability

Once variation is adequately assessed, farmers must match agronomic inputs to known conditions employing management recommendations. Those are site specific and use accurate applications control equipment.

We can use the technology most effectively. In site-specific variability management, we can use GPS instrument, so that the site specificity is pronounced and management will be easy and economical. While taking the soil/plant samples, we have to note the sample site coordinates and further we can use the same for management. This results in effective use of inputs and avoids any wastage and this is what we are looking for.

The potential for improved precision in soil fertility management combined with increased precision in application control make precise soil fertility management as attractive, but largely unproven alternative to uniform field management. For successful implementation, the concept of precision soil fertility management requires that within-field variability exists and is accurately identified and reliably interpreted, that variability influences crop yield, crop quality and for the environment. Therefore, inputs can be applied accurately.

The higher the spatial dependence of a manageable soil property, the higher the potential for precision management and the greater its potential value. The degree of difficulty, however, increases as the temporal component of spatial variability increases.

Applying this hypothesis to soil fertility would support that Phosphorus and Potassium fertility are very conducive to precision management because temporal variability is low. For N, the temporal component of variability can be larger than its spatial component, making precision N management much more difficult in some cases.

iii). Evaluation

There are three important issues regarding precision agriculture evaluation.

- Economics
- Environment and

□□□Technology transfer

The most important fact regarding the analysis of profitability of precision agriculture is that the value comes from the application of the data and not from the use of the technology.

Potential improvements in environmental quality are often cited as a reason for using precision agriculture. Reduced agrochemical use, higher nutrient use efficiencies, increased efficiency of managed inputs and increased production of soils from degradation are frequently cited as potential benefits to the environment. Enabling technologies can make precision agriculture feasible, agronomic principles and decision rules can make it applicable and enhanced production efficiency or other forms of value can make it profitable.

The term technology transfer could imply that precision agriculture occurs when individuals or firms simply acquire and use the enabling technologies. While precision agriculture does involve the application of enabling technologies and agronomic principles to manage spatial and temporal variability, the key term is manage. Much of the attention in what is called technology transfer has focused on how to communicate with the farmer.

These issues associated with the managerial capability of the operator, the spatial distribution of infrastructure and the compatibility of technology to individual farms will change radically as precision agriculture continues to develop (Pierce and Peter, 1999).

Technology Transition

Precision agriculture is dependent on the existence of variability in either or both product quantity and quality. If this variability does not exist then a uniform management system is both the cheapest and most effective management strategy and precision farming is redundant. Thus, in precision farming, “Variability of production and quality equals opportunity”. Having said this, the nature of the variation is also important in determining the potential for PA in a system. For example the magnitude of the variability may be too small to be economically feasible to manage. Alternatively the variability may be highly randomized across the production system making it impossible to manage with current technology. Finally the variability may be due to a constraint that is not manageable. Thus the implementation of precision farming is limited by the ability of current variable rate technology (VRT machinery/technology that allows for differential management of a production system) to cope with the highly variable sites and the economic inability to produce returns from sites with low variability using precision farming (VRT).

Due to these constraints PA is at present operating on a zonal rather than a completely site-specific basis. As VRT improves and the capital cost of entering PA decreases, the minimum size of management zone needed to effectively implement PA will decrease till eventually a truly site-specific management regime is possible. Until this occurs there is need to be able to quantify both the variability of a production system and the size of the minimum manageable zone (MMZ). If the variability in the production system dictates management zones smaller than the MMZ, then PA is not relevant to the system. At the present time (but may be in future). It will be interesting to see how the concept of the management zone develops and to see how it compares with the concept of terror.

Present Scenario

Though precision farming is very much talked about in developed countries, it is still at a very nascent stage in developing countries, including India. Space Application Center, ISRO, in collaboration with CPRI, Shimla, has initiated a study on exploring the role of remote sensing for precision farming. The study on precision agriculture has already been initiated in India, in many research institutes. Space Application Center (ISRO), Ahmedabad has started experiment in the Central Potato Research Station farm at Jalahandhar, Punjab to study the role of remote sensing in mapping the variability with respect to space and time. M S Swaminathan Research Foundation, Chennai, in collaboration with NABARD, has adopted a village in Dindigul district of Tamil Nadu for variable rate input application. IARI, New Delhi has drawn up a plan to do precision farming experiments in the institutes'. PDFSR, Modipuram and Meerut (UP) in collaboration with Central Institute of Agricultural Engineering (CIAE), Bhopal also initiated variable rate input application in different cropping systems. In coming few years precision farming may help the Indian farmers to harvest the fruits of frontier technologies without compromising the quality of land.