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Contents:

A Consideration of Factors which Affect the Potassium Requirements of Various Crops

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1. Introduction

In 1762 the Englishman *Home* carried out an interesting experiment in growing barley on a sandy soil. In one treatment *Home* had added potassium sulphate to the soil and this resulted in increased vigour of growth of the barley, showing that potassium, or sulphate, had a beneficial effect on plant growth. In the following century the investigations and experiments of *Theodore de Saussure, Carl Sprengel* and *Justus von Liebig* showed clearly that K^+ is an essential plant nutrient. K^+ is indispensible for every plant species.

This qualitative aspect of the K^+ requirement of crops is interesting but, from an agronomic point of view, we need also to know how much K^+ the crop requires in order to produce a satisfactory yield of produce of good quality. The total K^+ requirement can be estimated from the total K taken up by a crop per unit area. Data of this kind have been published by many authors and they are of direct value to practical farming in suggesting what rates of potassium fertiliser should be applied. However, on their own they are insufficient as, in assessing fertiliser needs, it is also necessary to consider the *rate* at which this K^+ must be supplied to the plant. Thus both total requirement (quantity) and rate of supply (intensity) are equally important. The rate (intensity) requirement can conveniently be stated in terms of the amount of K^+ required by a crop per unit area and per day. K rate requirement has received only sporadic attention in the literature and for this reason it is a particular target of this paper and the following contributions to deal with this intensity aspect for the most important crop groups.

In further considering the quantity requirement, it will clearly depend upon the total amount of plant material produced per unit area but it also depends upon the kind of plant material, or type of plant organ, produced and harvested.

A final and most important point in assessing the requirement for K fertiliser is that crop requirement and fertiliser requirement are not identical; the latter will depend much on the K status and K dynamics of the soil, on the rooting pattern of the crop and also, probably, on root metabolism.

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2. Total K requirement

Total K requirement may be defined as the total amount of K (kg K/ha) needed to produce the highest possible economic yield under given conditions of growth. If this total requirement is correctly met, the various plant tissues should contain K in the optimum concentration; higher K concentrations than this mean that more K has been taken up than is really required, lower than optimum concentration may mean that too little K is taken up to satisfy the production potential of the plant. The total K in the plant includes the K of aerial parts and that of the roots and other organs (tubers) growing in the soil. Root K content is difficult to measure under field conditions and most estimates of total K uptake ignore the root content. However, in most cases, root K is only a small fraction of the total and the error thus involved may be tolerated.

The K content of organs low in dry matter is generally especially high, provided the K content is expressed on a dry weight basis. The difference in K content of tissues rich or poor in water is very small when it is expressed on a fresh weight basis. Thus, *Jungk [1970]* found that the K content of *Sinapis alba* was substantially constant throughout the growing season provided it was calculated on a fresh weight basis. The optimum K content found in this investigation ranged between 400 and 600 ppm K in fresh material.

The maintenance of cell turgor requires a certain K concentration in the water of cells and tissues. Considering that mesophyll tissues contain 85 to 90% water, of which about 90% is found in the vacuoles, 5% in the cytoplasm and 5% in the cell wall material, it is clear that the K content of leaf dry matter must be high. Most of this K is in the vacuoles where it contributes to cell turgor. According to *Mengel* and *Arneke* (unpublished results) K^+ is especially necessary for the turgor of young leaves and the general finding that younger leaves are richer in K^+ than older ones may be related to the higher physiological K demand of young leaves. Because K^+ is very mobile in the whole plant, much can be translocated from the younger to the older leaves *(Greenway* and *Pitman [1965])*. *Mengel* and *Arneke* found that insufficient K supply resulted in suboptimal turgor ($\psi_p < 6$ bar) in young leaves of *Phaseolus vulgaris*, which was associated with severe growth reduction, while the turgor of the older leaves was hardly affected by K deficiency. From these findings it is concluded that young growing tissues have an especially high K requirement for the maintenance of optimum turgor, which is needed for cell elongation and also, probably, for cell division. Because of the involvement of K^+ in various biochemical and biophysical reactions for which it is indispensible, the reaction which requires the highest K concentration controls the total K demand of the particular tissue. In young leaves this 'controlling reaction' is the osmotic function of K^+. In natrophilic species, Na^+ may partially substitute for K^+ in achieving optimum turgor as has been shown by *Marschner* and *Possingham [1975]* using leaf discs of sugar beet and spinach. In terms of practical crop production this means that, whenever the object is to produce young green plant material, much K is required per unit dry matter production.

Other than young leaves, non lignified stems, petioles and culms are generally rich in K. Much of these organs consists of phloem tissue and, as the most important inorganic ion in the phloem sap is K^+, this may explain why culms and stems often have higher K contents than leaves. In comparison with other inorganic ion species, the K^+

concentration in the phloem sap is high and, according to *Hall* and *Baker [1972]*, in the range 60 to 112 m molar. Thus, besides sugars and amino-acids, K^+ contributes substantially to the osmotic potential of the phloem sap. Turgor pressure is an important driving force for solute movement in the phloem tissue *(Geiger [1975])*. However, it seems doubtful if the beneficial effect of K^+ on phloem transport is mainly the result of its effect on the turgor in sieve tubes as, according to *Mengel* and *Haeder [1977]*, K^+ promotes phloem transport mainly by promoting phloem loading.

The phloem sap is the most important source of the material which is laid down in storage tissues such as tubers, roots, seeds and fruits and it is for this reason that, provided their water content is relatively high, these storage tissues are rich in K^+. Fleshy storage tissues like sugar beet roots, potato tubers, tomatoes, bananas, grapes and other fruits contain much K in proportion to their dry matter content and such crops generally have a high K requirement because much K is needed to fill these storage tissues properly with K^+. The most important function of K^+ in these tissues is probably that of maintaining optimum turgor. Much of the K^+ required by storage tissues and fleshy fruits comes from the K in the leaves and stems and will thus have been taken up by the plant before the major growth of storage tissues commenced. This is shown in Figure 1, based on data from a sand-solution experiment with sugar beet *(Mengel* and *Forster [1973])*. It appears that K uptake rates (mg K absorbed per plant per day) were highest during the period of vigorous leaf growth. At a later stage, however, during September and October when root growth and sugar storage were the major processes, the rate at which K was taken up was relatively low. Clearly

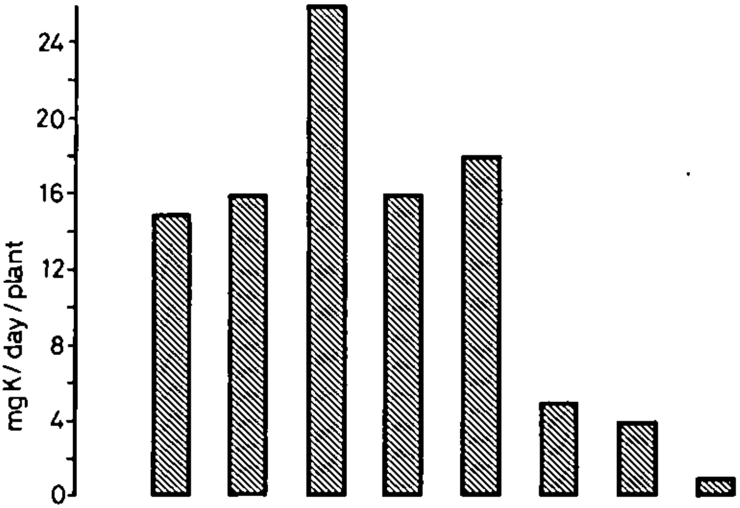

Fig. 1. Potassium uptake rates of sugar beet at different stages during the growing season *(Mengel* and *Forster [1973])*

at this stage substantial amounts of K^+ were translocated from the leaves along with photosynthates. It remains to be investigated whether this is also true for other crops. There is evidence that plants can take up K^+ at high rates during the vegetative stage of growth and this may be related to their phytohormone status *(Cram* and *Pitman [1972])*. It is thus supposed that only a minor part of the K^+ required by fruits and storage organs is taken up directly from the soil and that most of their K requirement is taken up during vegetative growth and translocated from the leaves to the storage organs and fruits. This question, which is relevant to the K rate requirement, needs further research. In the case of crops like cereals, oil seeds and cotton, their fruits are low in water and hence the K content of grain or seed, on a dry matter basis, is relatively low. As with the crops discussed above, the major part of the K requirement of grain crops is taken up during vegetative growth, as illustrated by results of *Mengel* and *Forster [1966]*, which showed that grain production by barley was not significantly affected by removing K^+ from the nutrient solution during grain filling. The physiological role of K^+ in grain and seed is probably related to the activation of starch synthetase and protein synthesising enzymes *[Evans* and *Wildes [1971], Hawker et al. [1974])*.

The total K requirement of a crop depends much on the growing conditions provided by soils and climate. When much organic matter can be produced, much K is also required. Total K requirement also clearly depends on genetic yield potential; for example, modern rice cultivars need two or three times as much K as local traditional varieties, as shown in Table 1 *(Kemmler [1973])*.

For many crops the total K content of the crop at maturity is lower than it is at an earlier stage of growth. Figure 2, showing a typical K uptake curve, reflects this behaviour (data of *Sturm* and *Jungk [1972])*. Total K taken up by the time of flowering was as much as 200 kg K/ha whereas at maturity, the above-ground portion of the crop contained only 125 kg K. The loss of K between flowering and maturity may be the result of the secretion of a substantial amount of K^+ from the roots into the soil during the period of grain formation. However, experiments by *Haeder [1971]* have shown that only one or two per cent of the total K content of the plant is secreted in this way and it is suggested this loss of K from maturing cereals is mainly due to leaf fall and the leaching of K^+ from the mature plant by rainfall.

The problem of total K requirement is still more complex in perennial crops than in annual crops. This is particularly true for fruit trees, vines and various plantation crops since they are able to store substantial amounts of K in the wood and bark. In deciduous trees and in vines K^+ is retranslocated from the leaves to the wood before the leaves are dropped. This K may be mobilised in the following spring when new leaves are developed. Net production of organic matter by these crops is

Table 1. Yield level and nutrient uptake of a conventional local rice cultivar and the modern high yielding rice cultivar 'TN 1' *(Kemmler [1972])*

Cultivar	Grain yield	Nutrient uptake, kg/ha		
	t/ha	N	P	K
Local	2.8	82	10	100
TN 1	8.0	152	37	270

Fig. 2. Quantity of K in the upper plant parts of winter wheat during the growing season (*Sturm* and *Jung [1972]*)

especially high during their juvenile development, and it is particularly over this period that an ample K supply is required. Thus *Frémond* and *Ouvrier [1971]* showed that the yield potential and also the precocity of fruiting of coconut palms depended much on the K supply of the young palms.

Quantitative data as to how much K is required per tree or per ha during the juvenile development of these crops until their full size is attained, how much K is mobilised in the wood and bark in spring and translocated to the newly-developing leaves and how much K is exported by the fruits are badly needed for a number of perennial tree crops.

3. Potassium rate requirements

The rate requirement may be defined as the K requirement per unit time, i.e. kg K per hectare of crop per day. A high rate requirement does not necessarily go hand-in-hand with a high total need for K, as exemplified by data of *Nelson [1968]* comparing K uptake by sugar beet and sugar cane. Both crops need about the same total amount of K (400 kg K/ha) but, while sugar beet reaches maturity in 120–150 days, the cycle of sugar cane is about three times as long, so that the former crop has an average K rate requirement about three times as high as that of the latter.

The K rate requirement differs between crops and, as it is closely related to the growth rate, climatic factors such as temperature, light intensity and water supply also come into play. For instance, the extremes represented by grassland in cool mountainous regions and the warm lowland conditions of the tropics impose very large differences in this respect. Tropical grass requires large amounts of K and needs a high K content of dry matter in order to achieve optimum production *(Gartner [1969])*; rate of growth is also high. The example demonstrates that the question of K rate must be considered in relation to the yield potential of a particular site.

It must be emphasised that the K rate requirement of a crop varies much throughout the growing season and the 'maximum K rate requirement' is particularly important in considering the ability of a soil to supply K to the growing crop in such a way as to impose no limit on growth. An approximate idea of this maximum rate requirement can be obtained from a K uptake curve which plots K quantity in the crop against period of growth. For practical purposes, as mentioned earlier, root K content may be neglected. Such a K uptake curve for maize is shown in Figure 3, after *Nelson [1968]*. The maximum rate requirement $\Delta K/\Delta$time can be obtained by drawing a tangent through the inversion point of this sigmoidly shaped curve. The maximum K rate requirement is found at the point where vegetative growth is at its maximum. High growth rates demand rapid K uptake and it is during such periods of rapid growth that plants are particularly susceptible to K deficiency.

The rate at which a crop can take up K is dependent upon the K intensity of the soil, high rates of uptake demanding high intensity and the reverse. The maximum K uptake rate of a crop should give a guide to the desirable level of K *intensity* of the soil while its total maximum K uptake is related to the *quantity* of K in the soil.

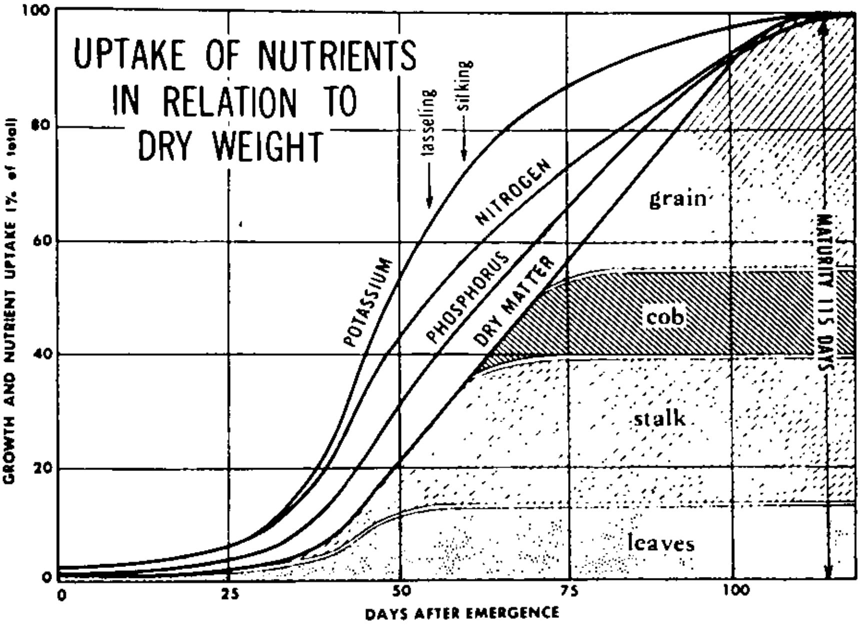

Fig. 3. Potassium, nitrogen and phosphorus uptake and dry matter production of maize during the growing season (Iowa State University, quoted by *Nelson [1968]*)

There has been much discussion of the concepts of intensity and quantity during the past ten years but there is, as yet, little agreement as to the parameters which best express these concepts. Conventionally, it is usual to state K quantity in terms of exchangeable K, but this simple measurement is not enough as, depending on soils and crops, soil K which is not exchangeable may make a considerable contribution to the K taken up by the plant *(Wiechens [1975])*.

From the point of view of plant nutrition, the K intensity may be defined as the rate at which K is supplied by the soil to the plant roots. This 'K supplying rate' is directly related to the K concentration of the soil solution which controls the rate of diffusion of K^+ in the soil. K diffusive flux and K uptake are positively related as shown for young maize plants in Figure 4 *(Mengel* and *von Braunschweig [1972])*. It seems, then, that the K concentration of the equilibrium soil solution is a reliable parameter for measuring K intensity in the soil.

The relationship between K quantity and K intensity differs considerably between various types of soil according to clay content and the type of clay minerals present *(Neméth et al. [1970])*. The slope of the curve showing the relationship between K quantity and intensity gives direct information on the K buffering capacity of a soil, a steep slope indicating high buffer capacity and *vice versa (Mengel* and *Kirkby [1978])*. Soils of high buffering capacity often have a high total K content even though the exchangeable K content may only be medium or low. In such soils non-exchange-

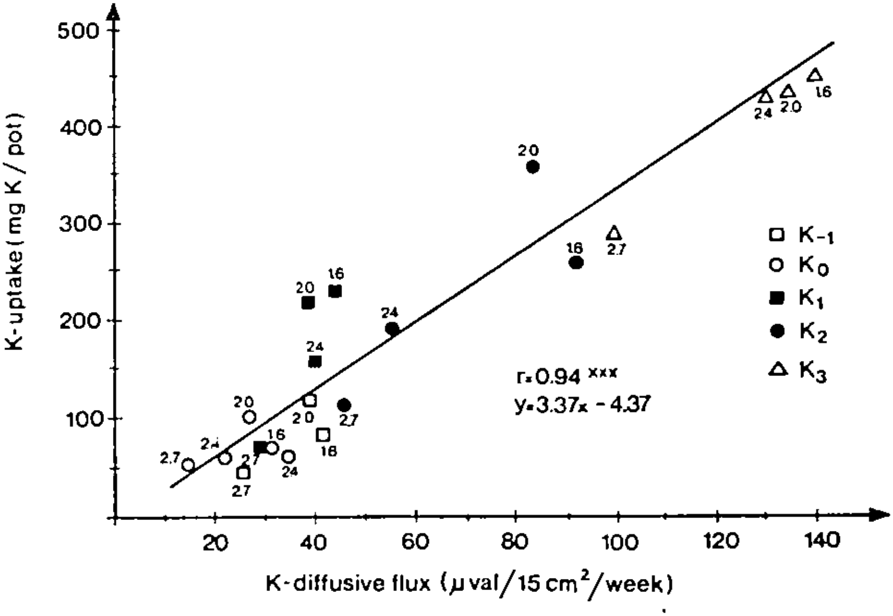

Fig. 4. Relationship between the K diffusion rate in the soil and K uptake by maize. The figures associated with the symbols denote the pF of the soil at which the particular diffusion rate and K uptake was obtained. The various symbols stand for different K fertilizer rates *(Mengel* and *von Braunschweig [1972])*

able K content may contribute considerably to buffering the K concentration of the soil solution. The quantities of non-exchangeable K can be very large and the fact that crops growing on such soils may suffer from K deficiency is not a consequence of too low a K quantity but because the K intensity is too low *(Neméth [1975])*. Clearly, when a crop has a high K rate requirement it will be liable to potassium deficiency if the soil K intensity is low even though the quantity of K in the soil is more than adequate.

The reverse problem may be encountered on sandy or organic soils which usually have a low K buffering capacity, insufficient to maintain soil solution K concentration at a sufficiently high level against removal of K by the crop. In such cases it is clearly the K quantity which is limiting and crop species having a high total K requirement may run into severe K deficiency.

4. The relationship between plant roots and K requirement

Satisfying the K needs of a crop is not just a matter of soil K quantity and intensity; rooting pattern, rooting depth and root metabolism are also involved in the complex of K uptake and K requirement. Unfortunately there are few available field data referring to this question and, for this reason, only a few major points will be discussed in this section.

Maertens [1971] showed, in an interesting investigation, that a small portion only of the total root system was capable of absorbing all the N, P and K required by the plant so long as the nutrient solution was high enough in N, P and K. Obviously, the optimum K concentration of the nutrient – or soil solution (K intensity) – which is required must depend upon the root surface area, since a large root surface area capable of taking up nutrient would require only a relatively low intensity and *vice versa*. *Jungk* and *Barber [1974]* showed that the total uptake of P by maize roots was related to root length. This finding also justified the conclusion that a plant with a relatively extended root system may better exploit the soil for nutrients than one with a low root/shoot ratio.

The critical period for the K requirement of a crop need not necessarily be at that time when the highest K uptake rate is found. *Mengel* and *Barber [1974]* have shown that the critical period for maize, during which the K demand of the vigorously growing shoot may not be met by the root uptake potential, may occur at a rather young stage. Table 2 shows calculated uptake rates of N, P and K per metre root length in relation to plant age and it appears that the requirement per unit root length is particularly high in the early stages of growth. More information is badly needed as to how root/shoot ratio and K requirement are related at different growth stages. This would give more precise information as to the particular stage of growth at which K supply by the soil might become critical.

Rooting pattern and depth of rooting differ between the various crops. Study of rooting patterns may indicate the extent to which soil K can be exploited by a crop. Even cultivars of the same species may differ in their ability to 'mine' the soil for K, as shown by a recent example for cotton *(Halevy [1977])*. Two cultivars, *Acala* 1517-C and *Acala* 4–42 were grown on the same soil, the former being the more susceptible to K deficiency while the latter had a larger root system and, in particular, more fine roots than *Acala* 1517-C.

Table 2. Effect of plant age on average nutrient flux into roots of maize grown under field conditions *(D.B.Mengel* and *Barber [1974])*

Plant age days	Calculated nutrient flux µmoles/m root length/day		
	N	P	K
20	227	11.3	53
30	32.4	0.90	12.4
40	18.5	0.86	8.0
50	11.2	0.66	4.8
60	5.7	0.37	1.6
70	1.2	0.17	0.15
80	0.46	0.08	0.06
90	2.0	0.10	0.37
100	4.2	0.23	0.16

Soils may vary in the depth of their rooting zones and it is suggested that a shallow soil needs a higher K intensity to satisfy the plant's needs while in a deeper soil the roots can exploit a relatively large volume of soil per unit surface area.

Root metabolism also has a crucial impact on 'mining' the soil for nutrients. Potassium uptake is closely associated with root respiration which, in turn, depends upon the translocation of carbohydrate from the above ground parts *(Pitman [1972])*. Sugar translocation is reduced when photosynthetic activity is low or when a high proportion of photosynthate is consumed in the upper plant parts.

Kaila [1967] suggested that the release of K^+ from K-bearing minerals is controlled by the K concentration of the adjacent soil solution, low concentrations favouring release of K^+. There is a dynamic equilibrium between K^+ in the soil solution and root K^+, the level of which is controlled by root metabolism. *Drews [1978]* has shown that plants exposed to reduced light intensity cannot deplete the K^+ of the soil solution to as low a level as plants in full light. This affected the release of K from clay minerals. The K concentration of the soil solution under stressed plants remained relatively high (40–50 µmolar K^+) and hardly any K^+ was released form interlayer positions. But, plants exposed to full light lowered the K concentration to about 10 µmolar K^+ and at this low level K^+ was released from the clay minerals so that, in effect, these plants were feeding from the interlayer K. From this point of view the results of *Malquori et al. [1975]* are interesting as they showed that wheat plants could feed from the interlayer K of biotite while lucerne could not. It may be worth investigating further whether differences between plant species in their ability to exploit interlayer K are related to differences in their abilities to lower soil solution K^+ concentration through plant uptake.

Legumes are not very effective in exploiting soil K, a statement which is supported by data published by *Schön et al. [1976]*. This field trial, continued for 20 years on a loess soil containing much non-exchangeable K, showed that *Vicia faba* and a grass-clover mixture responded most favourably to K fertiliser. K also markedly increased the yield of potatoes, whereas it only slightly increased the grain yield of cereals (see Table 3).

Grasses are very efficient in exploiting soil K but whether their high 'mining power' will suffice to produce continued high yields on soils rich in non-exchangeable K

Table 3. Response of various crops to K fertiliser application. Average yield data from an experiment lasting 20 years *(Schön et al. [1976])*

Crop	Yield, t/ha of tubers, grains, seeds or fresh matter		
	No.	NP	NPK
Winter wheat	3	4.21	4.55 (108)
Spring barley	5	2.84	3.21 (113)
Oats	3	3.54	3.80 (107)
Winter rye	2	3.08	3.15 (102)
Spring rye	1	2.26	2.49 (115)
Broad beans	2	1.27	2.46 (194)
Clover-grass	1	38.3	45.8 (120)
Potato	4	23.8	32.6 (137)

In parenthesis relative values as compared with the control (NP=100).

without the addition of K fertiliser is a question of great importance. There are numerous examples to show that the continued removal of K in cut grass will eventually reduce soil K to the point where growth is limited by deficiency. *Grimme [1974]* showed, in pot experiments, that there was a negative correlation between grain yield of oats and the proportion of K which was taken up from non-exchangeable sources in the soil. Similar results were obtained by *von Boguslawski* and *Lach [1971]*, also in pot experiments. Instances where, under field conditions, continued intensive cropping has led to K exhaustion are described by *von Boguslawski* and *Lach [ibid.]* for sugar beet and *De Datta* and *Gomez [1975]* for rice. The former work (Table 4) occupied 14 years on a soil derived from loess, which is generally rich in illite and thus has a high K supplying power. In the course of the 14 years, this particular soil released about 1600 kg K/ha, but as K depletion proceeded, the rate of release of K became insufficient to maintain crop yields at a satisfactory level. As shown in Table 4, K uptake by beet declined in a remarkable way and at the last two harvests (1960 and 1964) amounted to only about 25 or 30% of the total K needed for maximum sugar beet production under the climatic conditions of W. Germany. Needless to say, such a decline in K availability resulted in severe yield reduction.

Moisture promotes the release of interlayer K. *Wiechens [1975]* found that *Lolium perenne* could take up very large quantities of non-exchangeable K when soil moisture

Table 4. Dry matter production and K uptake of sugar beet grown without K fertiliser for 14 consecutive years *(von Boguslawski* and *Lach [1971])*

Year	Yield, kg DM (roots + tops)	K uptake kg K/ha/year
1954	1870	424
1956	1430	191
1960	1460	168
1964	980	118

was satisfactory but, under drier conditions, release of non-ecxhangeable K was very much restricted. This was shown in that, under moist soil conditions, only occasional responses to K fertiliser were recorded, whereas when conditions were dry, consistent K responses were obtained. This finding is of practical importance, showing that even plant species with a high 'K exploiting power' may be less able to extract soil K under dry conditions, in which case suboptimal K supply may result in very much reduced yield.

Continuous cropping without K fertiliser so exhausts soil K that even *Lolium perenne* known as a very potent soil K extractor, will also suffer badly from K deficiency under optimum soil moisture conditions. This has been recently shown by *Mengel* and *Wiechens [1979]* in pot experiments with rye-grass. During the first three cuts there was no significant difference in yield due to potassium. At the 4th cut the K_0 plants even produced a significantly higher yield than those receiving potassium. All the K taken up by the K_0 plants of the 4th cut originated from the non-exchangeable soil K fraction. Obviously these plants were able, under favourable weather and soil conditions, to extract the interlayer K of the clay minerals efficiently. Beginning at the 8th cut there were considerable yield depressions under the K_0 treatment and these became increasingly severe in the later cuts. At the last cut the yield was only 39% of that of the plants fertilised with K. By the 11th cut, the K_0 plants exhibited very marked K deficiency symptoms. These plants were so weakened that even their ability to exploit soil K was affected, as less than 50% of the K taken up originated from the non-exchangeable soil K fraction.

Pot experiments with barley and vetch on the same soil showed remarkable yield increases due to K fertiliser and they also showed a clear inverse relationship between the yield level and the proportion of K which originated from the non-exchangeable fraction (Table 5).

Table 5. Grain yield of spring barley and yield of aerial plant parts of vetch in relation to the percentage of K taken up from the non-exchangeable soil K fraction (data from pot experiment of *Wiechens [1975]*)

Content of exchangeable K at the beginning of the experiment, ppm K in dry soil	Grain yield g/pot	DM yield of vetch g/pot	% K from the non-exchangeable soil K fraction
K_0 500 (control)	77.8	31	60.2
K_1 800	85.5*	36*	23.3
K_2 1140	90.7**	41**	4.8

* $P<5\%$
** $P<0.1\%$ compared with the control treatment

5. Conclusion

Crops differ in their K requirements due to differences in the physiological roles in which K^+ is involved. Where the harvested produce consists of young green material the K requirement per unit dry matter produced is high, as in the case with young grasses. If the same crop is harvested at the fully mature stage, the K requirement per unit dry matter is substantially less. Crops producing fleshly fruits or storage organs contrast with cereals as they require much K for filling these tissues.

The ability of a soil to supply a crop's K requirements is fairly well described by parameters of K quantity and K intensity. K intensity is particularly relevant to the K rate requirement, K quantity to the total K requirement. Root growth and root metabolism probably play a major role in determining K availability but the relationships between K requirement and root growth and metabolism are not yet fully understood.

The potassium requirement of a crop and the need for fertiliser K may differ widely according to soil and climatic conditions. Soils well buffered for K do not generally lose much K through leaching and when the soil K status is optimum the K fertiliser requirement can be based on the removal of K in harvested produce. On poorly buffered soils, especially on sandy soils under humid conditions, the K fertiliser policy must take into account the danger of loss through leaching. In this context it is also worth pointing out that the K in crop residues (straw, leaves and roots) can also be leached by winter rainfall or under monsoon conditions.

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Potassium Requirements of Cereals

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1. Introduction

Investigation of the effects of mineral nutrition on plant growth and crop yield has a long history and, recently, increasing attention has been paid to the ways in which the supply of mineral nutrients interacts with the other factors, such as light, water supply and temperature, which affect growth. Research workers have been concerned with the dynamics of nutrient uptake and the ways in which nutrients are partitioned within the plant and how these affect successive stages of development.

Growth and yield of cereals is determined by the apical meristems of the shoots which later in growth become reproductive meristems, by the meristems of the roots, of tillers and adventitious roots and the intercalary meristems of the leaves and internodes. There is competition between the meristems of shoots and leaves in the early stages of growth.

Most, if not all, of the grain dry matter is assimilated after flowering as has been demonstrated in wheat, barley, rice and maize. Thus, yield depends upon the level and duration of photosynthetic activity in those parts of the plant which remain green after anthesis.

2. Root system

Despite the fact that the root is one of the fundamental organs of the plant, its physiology has been less studied than that of the rest of the plant.

The root system of *gramineae* is made up from the seminal roots (3–5 in maize, 7–8 in wheat) and adventitious roots. The former have a much higher efficiency per unit weight than the latter. The roots grow over a long period, eventually reaching a length of one and a half to two metres; this applies to both principal and adventitious roots. Root growth depends upon carbohydrate supply which, in turn, depends on the development of the aerial part of the plant.

Gramineae generally have a well developed root system but there is much difference between species. Root growth is rapid during the vegetative stage and reduces when

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the plant goes over to the reproductive phase and there is sometimes even a reduction in root weight during grain ripening (Figure 1).

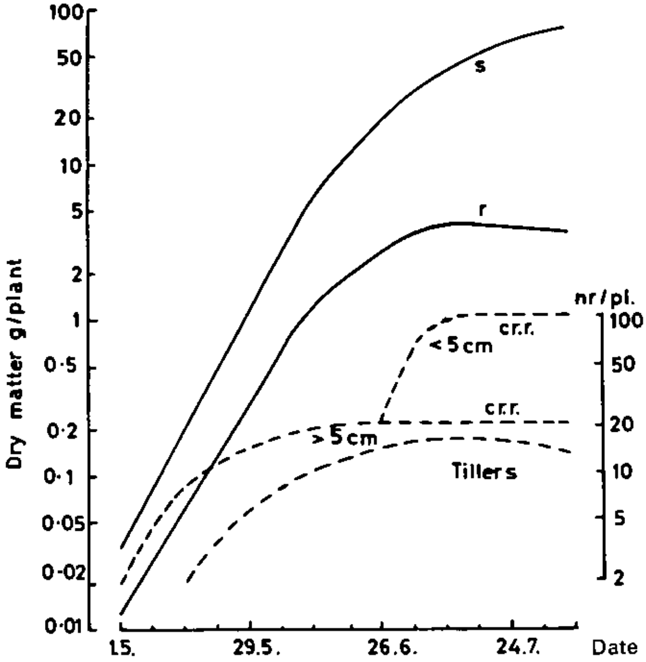


Fig.1. Full lines: dry weight of shoot (s) and root (r); dashed lines: number of crown roots (cr, r) and of tillers.

The seminal roots never comprise more than 5% of the total root mass, often only about 1%, but their efficiency is up to 50 times higher than that of the adventitious roots. Actually, comparatively little is known about the physiological difference between the two types of root.

Root/shoot ratio is usually fairly constant during vegetative growth but reduces rapidly later. Nitrogen supply greatly influences this ratio which increases when N supply is reduced. Potassium does not affect the root/shoot ratio.

Root growth of wheat is adversely affected by K deficiency which reduces rootlet number. The effect can be seen at the 6th day and is still more evident at day 10. K affects root length, both seminal and adventitious roots being affected in this way, the latter more so than the former (Figure 2). The seminal roots play the dominant role in the earliest stages of development, thus we find them to be more important in spring sown cultivars.

Soil type greatly influences root development and structure, root diameter being greater in heavier soils and this also holds for secondary and tertiary roots. Cultivation

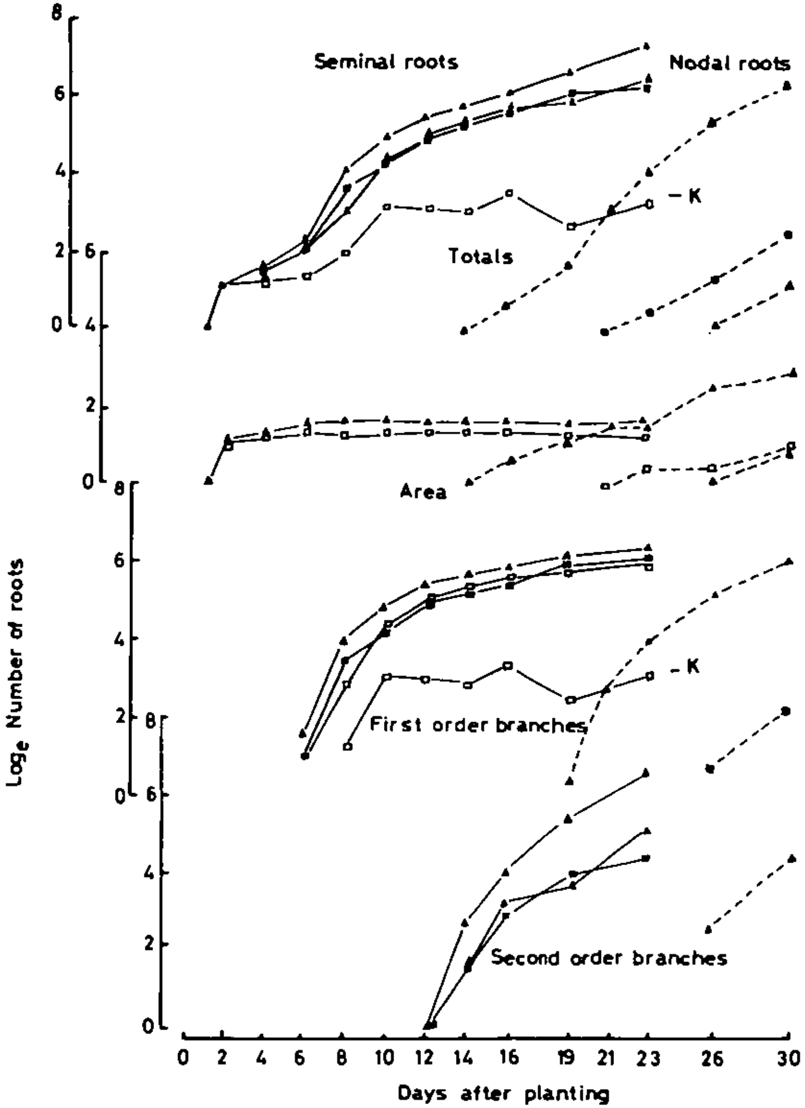


Fig. 2. Seminal and nodal root numbers (log$_e$) of wheat at 23 and 30 days after planting, respectively, in plants supplied with standard (▲), nil nitrogen (■), nil phosphorus (△) and nil potassium (□) nutrient solutions

improves apparent rooting density. A slight soil moisture deficit in the first weeks after sowing improves root penetration but a water deficit at tillering may reduce root growth. Too high temperature in the early stages of growth has an adverse effect. Poor soil aeration limits root growth. The roots reach a depth of 15–20 cm within a few days and then extend downwards. While most of the roots are found at 20–30 cm depth, at a density of 20–30 cm per cm^3, rooting density at 60–70 cm is reduced to between 0.1 and 1 cm/cm^3. It has been shown that the radius over which the root is effective is only up to 1 mm for P, while for N it exceeds 1 cm – K occupies an intermediate position. Thus, effective exploration for K requires 8 cm root per cm^3 while 1 cm/cm^3 suffices for N.

K uptake is not entirely confined to any particular zone though the root apex has always been thought to be most important, and uptake is better correlated with total root volume than with length or total area of root. The configuration of the root system is important when soil K availability is low. When the uptake rate is limited by low K concentration in the soil solution, total uptake will depend mainly upon the extent of the root system.

It has been shown that the absorption capacity of the root may change in response to the needs of the plant. While root growth and its capacity to take up K is much affected by local conditions, these are not the exclusive determinant factors and the plant's nutrient needs influence ion transport across the soil–root interface and the translocation of metabolites to that part of the root where growth is active.

3. Leaf area

The development of leaves on the shoot is closely connected with nutrient supply and this is especially so in relation to nitrogen shortage.

The total leaf area is determined by the number of living leaves and their individual areas. Both these parameters can be further subdivided. Leaf number is a result of the number of tillers, the number of leaves produced by each tiller and their longevity. Area per leaf is determined by expansion index and duration. The effect of the individual nutrients on each of these properties is not understood thoroughly but there is no doubt that all the nutrients and their interactions do affect leaf area. Though N has the largest effect, both P and K have positive effects at the higher levels of N. Experiments have demonstrated that both P and K increase area per leaf and that K improves longevity (Figure 3). The number of leaves per shoot varies little, so the

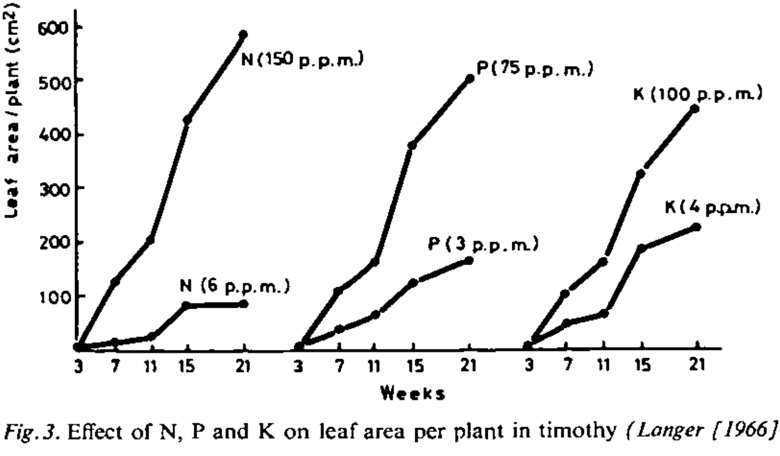


Fig. 3. Effect of N, P and K on leaf area per plant in timothy *(Langer [1966])*

influence of nutrients on total leaf number must be mainly through affecting the number of shoots.

4. Tillering

There is much experimental evidence to show that N deficiency in barley has the greatest effect in reducing tillering and that K only has an influence at real deficiency levels when the number of tillers is clearly reduced. Mineral nutrition also influences the duration of tillering which ceases at shooting. Low nutrient supply shortens the duration of tillering. The earliest formed tillers are the most important for yield, later tillers merely compete for nutrients without producing grain and it has been found that the removal of surplus tillers improves yield by removing competition. The apparent interruption in growth resulting from the loss of late tillers is not reflected in the growth of the main stem.

5. Stem elongation

At ear initiation, the stem begins to elongate by lengthening of the internodes through the production of new cells by the intercalary meristems and through cell elongation. Except in rice, where they grow earlier, the leaf sheaths grow at the same time as the stem, the lower internodes growing more strongly than the upper. The interval between germination and stem elongation varies greatly, very short for maize and up to 5 or 6 months for wheat. At this stage the plant is very sensitive to drought and there is severe competition for nutrients between the stem and ear, the leaves and the roots, in which the main stem has priority, leading to death of some of the lateral shoots.

6. Grain formation

Grain yield per unit area is the resultant of the following: ear number, number of grains per ear and weight per grain. Potassium has practically no effect on ear number since it does not affect tillering. The only reports of a positive effect of K on tillering are those of *Forster* and *Mengel [1975]* where K deficiency reduced yield of barley, spring wheat and oats by reducing tillering and, thus, ear number. There is, however, an effect of K on grain number per ear in that, while the number of flowers per ear is effectively constant, K deficiency reduces the proportion of flowers which are fertile. This effect is significant under adverse climatic conditions and there are many references to this in the literature.

It has been widely demonstrated that K increases weight per grain (1000 grain weight). K also increases apparent grain density by about 10% and, in certain cases, by up to 25% thus increasing flour yield. It appears that the main effect of K in winter wheat is on grain size, while the main effect in spring wheat is on grain number.

Potassium increases grain protein content of wheat thus improving quality. It also increases the oil content of maize grain.

It has been observed that K fertiliser increases the harvest index (grain:straw ratio) and grain :cob ratio in maize. It increases the C assimilation index during grain filling, increasing the carbohydrate content of ears and roots.

7. Carbon assimilation

Carbon assimilation depends on leaf area but also on the efficiency with which the leaves intercept the available light. The main effect of nutrients is on leaf area. Most of the grain carbohydrate in wheat (85%) is derived from that part of the shoot near the flag leaf; in barley the proportion is somewhat lower; in rice it is only about 70%. In maize, 50% comes from the 6 uppermost leaves, 35% from the next 5 and the remainder from the lowest 5 leaves. Winter wheats have a leaf area twice as great as that of spring wheats up to flowering but produce only about 15% more grain, probably because the total leaf area after flowering is only about 17% greater. There are similar differences between varieties. Most of the grain carbohydrate is synthesised after flowering, 80% of photosynthate produced at that time going to the grain with only a minor proportion translocated to other parts of the plant. It thus appears that grain yield depends mainly upon leaf area duration between flowering and ripening. It is well known that K deficiency reduces photosynthetic activity, probably mainly through its influence on the stomata but it also reduces leaf area. K has no influence on the number of leaves.

8. Uptake of potassium and its distribution

The influence of mineral nutrition on the plant is affected by its capacity to take up nutrient and the duration of active uptake. The young plant depends on the nutrient concentration in the soil solution surrounding the root. If this is low, the development of the root system will be the limiting factor. A more extended root system can compensate for low nutrient availability. Root development, in turn, is dependent on carbohydrate translocated from the shoot.

There are four phases in nutrient uptake: movement of ions from the solid phase into the solution, movement in the soil solution towards the root, penetration into the root and translocation from the root within the plant. Nutrients reach the root *via* three mechanisms: interception, mass flow and diffusion. Table 1 shows the extent to which these mechanisms are responsible for nutrients taken up by maize.

Table 1. The relative importance of interception, mass flow and diffusion in nutrient supply to maize from a fertile silt loam *(Arnon [1974]* after *Barber* and *Olson [1968])*

Nutrient	Required for 9.5 t/ha grain	kg/ha supplied by: Interception	Mass flow	Diffusion
N	187	2	185	–
P	38	1	2	30
K	192	4	38	150
Ca	38	66	165	–
Mg	44	16	110	–
S	22	1	21	–
Cu	0.1	0.01	0.4	–
Zn	0.3	0.1	0.1	0.1
B	0.2	0.02	0.7	–
Fe	1.9	0.2	1.0	0.7
Mn	0.3	0.1	0.4	–
Mo	0.01	0.001	0.02	–

The roots occupy only about 1% of the soil volume so the contribution of root interception to K supplies is small. The amount supplied by mass-flow depends on the rate of transpiration and would not exceed 20% of K requirement. The major contribution is by diffusion.

K uptake is rapid in the early stages of growth, the curve relating uptake to time being steeper than those for N and P and that representing growth (Figures 4 and 5). During the time of peak uptake rate, K is taken up at a rate of 2.0–3.3 kg/ha/day K

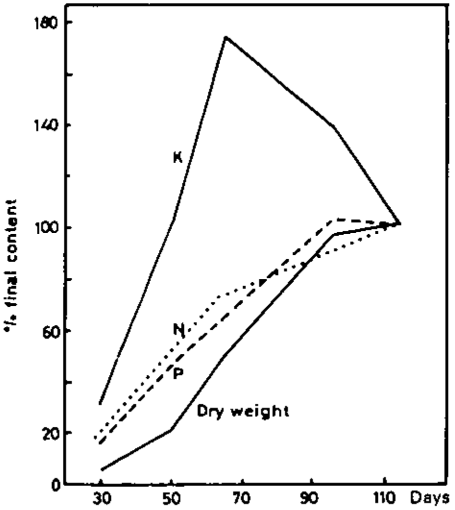


Fig.4. Effect of N, P and K on nutrient uptake and dry matter production of spring wheat (*Woodford* and *McCalla [1936]*)

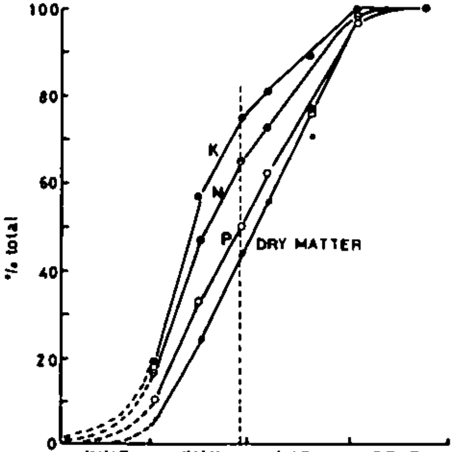


Fig.5. Relative rate of accumulation of dry matter, N, P and K in maize during the growing season with vertical dashed line showing date of silking (reproduced from *Hanway [1962]*)

by wheat and 3.1–6.0 kg/ha/day by maize. A sub-deficient level of K availability over this period can be decisive for final yield, wheat being more sensitive in this respect than barley or oats. Maximum K uptake is reached some time before maximum dry matter production and the K content decreases as the grain matures, though there is varietal and seasonal variation. Wheat takes up 70–75% of its K need by anthesis with 40–60% during tillering and ear initiation.

Maize takes up 75–90% of its K requirement by flowering with 60% by the time the 9th leaf emerges. In contrast, rice, because there is little translocation of K from the older leaves, takes up 48% of the total K after ear formation, so it is important to ensure good root development. It has been shown that for high yield in oats, 50% of the K should be taken up by flowering.

Most of the K taken up by maize in the period of maximum absorption accumulates in the leaves, where K deficiency first becomes apparent. K is translocated to the grain from all parts of the plant except the stem and, at harvest, 40% of the K is found in the stem, 20% in leaves, 15% in sap and 20–25% in grain (Figure 6).

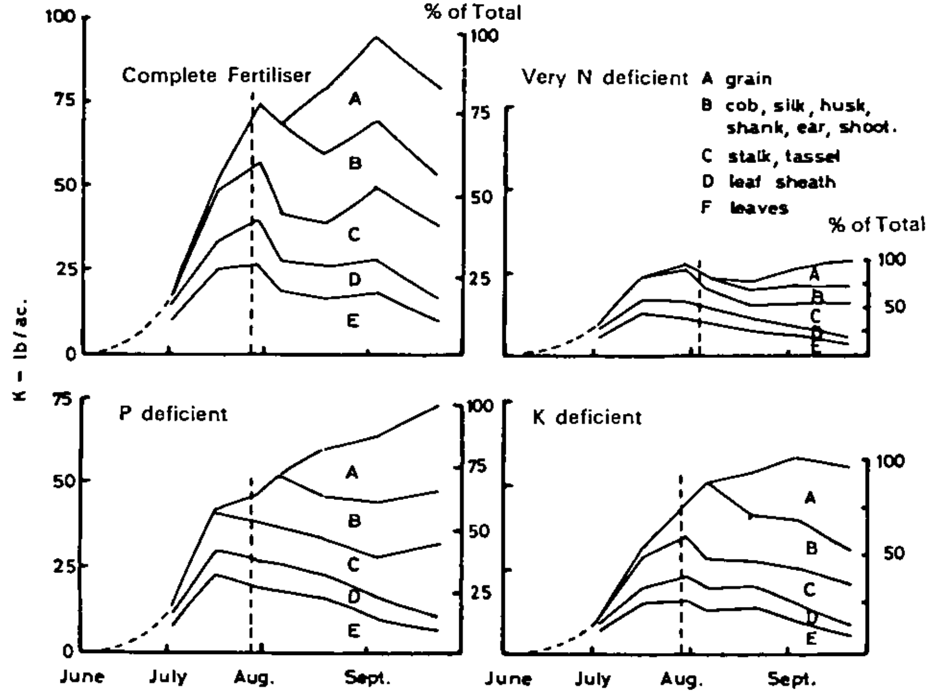


Fig. 6. Total K contents, in pounds/acre and in percent of total, of different parts of the maize plant taken from four plots on seven dates with the date of silking shown by the vertical dashed line (reproduced from *Hanway [1962]*)

K uptake by sorghum follows a pattern similar to that in other cereals, except that uptake is generally speaking rather slower (Figure 7). K uptake is rapid in early growth, less so between flowering and the onset of grain formation, during which it speeds up. After this, K is lost from the plant as in other cereal crops.

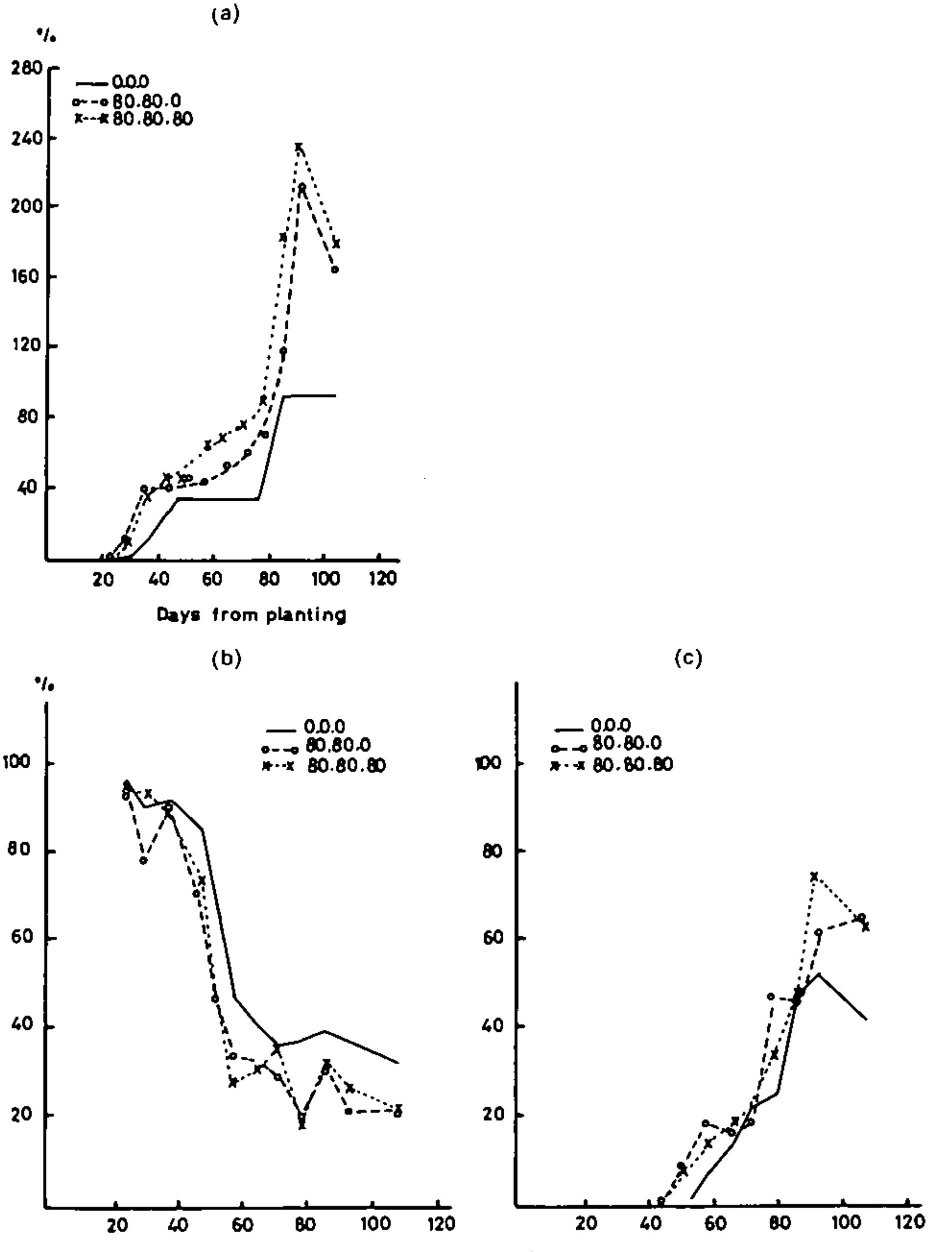


Fig. 7. Uptake of K by sorghum *(Lane* and *Walker [1961])* (a) K content of whole plant as % of maximum; (b) leaf K content as % of total K in whole plant; (c) K in head as % of total K in whole plant

Varieties and species differ considerably in their ability to take up nutrients; probably the result of adaptation to different soils and to the effects of competition. It has been shown that the exchange capacity of roots is negatively correlated with K uptake. Figure 8 illustrates varietal differences in K uptake in maize; generally speaking the newer hybrids are more K demanding than the older varieties.

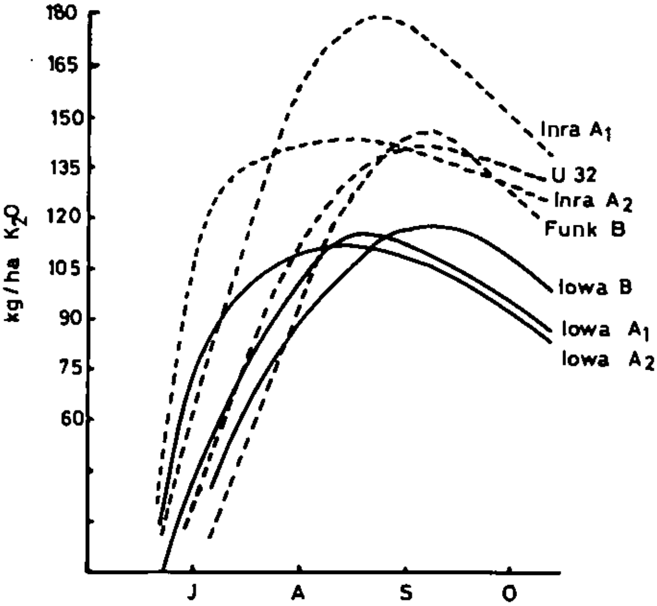


Fig.8. Uptake of K (kg/ha K_2O) by various maize *cvs* at 40 000 plants/ha *(Loué [1963])*

9. Resistance to disease and adverse conditions

Application of P and K to barley grown in Oregon reduced the effects of yellow dwarf virus even when the soils were high in P and K. K reduces rust in winter cereals and reduces the effects of other fungal diseases, particularly *Erysiphe graminis, Septoria avenae* and *S. tritici.* On the other hand, net blotch *(Pyrenophora teres)* in barley is reduced when K supply is lowered. K deficiency increases the visible symptoms of *Ophiobolus* spp. It reduces stem and root rots in maize. With the exception of blast, the common rice diseases are reduced by K as has been shown for *Helminthosporium oryzae, Leptosphaeria salvinii, Thanatopherus cucumeris* and *Rhizoctonia solani.*

K has often been observed to have a beneficial effect on frost resistance. K also has a favourable effect on drought resistance by increasing osmotic pressure in the cells, improving the transpiration coefficient and root development.

10. Resistance to lodging

For high yields, a cereal must be able to tolerate high N dressings without lodging, which may be due to insufficient mechanical strength, to disease or pests or to combinations of these and other factors. Rice, like many other crops, responds to K fertiliser by resisting lodging because K speeds up lignification of the schlerenchyma cells and increases cell wall thickness, especially at the base.

In maize, K deficiency reduces root development especially of adventitious roots, rendering the plant more liable to lodging. At cob formation, assimilates are translocated in great quantities from the root and stem to the cob. If total carbohydrate production is reduced through K deficiency, these losses are the more important and the effects are seen in the lower leaves where the parenchyma disintegrates. This is a normal phenomenon as maize matures but is accelerated by K deficiency making the stem liable to breaking (Figure 9). There is much variation between genotypes in this behaviour.

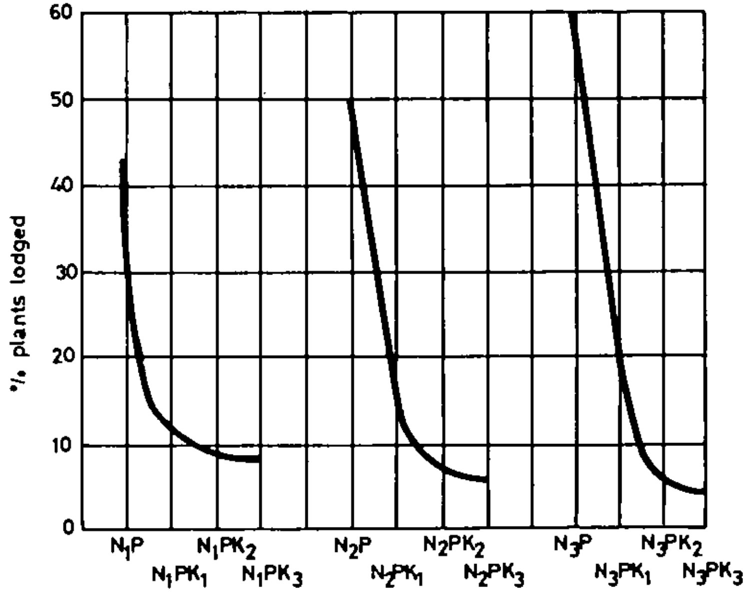


Fig. 9. Effect of N and K treatments on lodging in maize (Rhodesian double hybrid) *(Burkersroda [1965])*

11. K deficiency symptoms

Because of the mobility of K in the plant, deficiency symptoms appear first on the older leaves. The first sign of deficiency in maize is a reduction in size and vigour of seedlings and young plants. Then the first formed leaves turn yellow, the edges and tips become yellow and, finally, the whole leaf withers. In less extreme deficiency, growth is retarded but symptoms only appear when the plant is fully developed. Early deficiency can be corrected by inter-row application of K fertiliser. Leaf symptoms in mature leaves are the same: the leaves turn yellow-green, the edges turn brown and die – necrosis of the leaf margin is a characteristic symptom. In acute deficiency damage to leaves is obvious and growth is reduced so that the internodes do not elongate, the cobs are small and the grain not filled.

The leaves of K deficient winter cereals may appear bluish green, through the characteristic symptoms are the same as in maize – scorching of the leaf margin and tip. Barley may also show purplish spots on the leaves.

12. Potassium needs

Though cereals are often thought to have only a moderate K requirement as indicated by the quantities of K removed by the mature crop, like all graminae their requirements at the peak of growth are very high. This aspect has been discussed in paragraph 8 above where it was shown that there is considerable loss of K from the plant as it matures. In deciding on a K fertiliser policy therefore there are two distinct aspects which have to be considered:

a) Soil fertility

Fertiliser K must replace K removed in crop or soil fertility will decline. The amount of K fertiliser needed for this purpose will depend on whether or not the straw is removed from the field. In general the straw contains at least twice as much K as the grain alone. There is a good deal of variation in published figures for K removal by the mature crop, but the values given below may be taken as typical (kg/ha K per tonne grain).

	Wheat	Barley	Oats	Rye	Rice	Maize	Sorghum
Grain	5	6	6	5	5	7	3.5
Straw	10	12	14	10	20	13	17

b) The needs of the crop at the period of maximum growth and K uptake

If growth and yield are not to be restricted by limitation of the K supply, it is clear from the discussion above (paragraph 8) that soil K supply plus fertiliser K must be much larger than the amount removed in the mature crop. Thus in the case of wheat, for example, while applying 15 kg/ha K per tonne of grain produced might maintain the *status quo* as regards soil K, larger amounts should be applied if soil K availability is low or only moderate.

It must also be realised that the nutrient demands of the modern high yielding cultivars and hybrids are much higher than those of the traditional varieties and it is suggested that fertiliser recommendations should, in appropriate cases, allow for some build up in soil nutrient levels to ensure that the needs of future, higher yielding, crops can be met. The following figures for K removal in mature crops (grain + straw) for low and high yield levels will illustrate this discussion:

Wheat: Germany, yield 2.8 t/ha 73 kg K; yield 5.0 t/ha 100–125 kg; India, yield 2.2 t/ha 67 kg K; yield 6.0 t/ha 126–175 kg K *(Kemmler [1974]).*
Rice: Improved indica 2.7 t/ha 50–60 kg/ha K; high yield varieties 7.4 t/ha 250 kg K *(von Uexküll [1970]).*

13. Critical levels

Figure 10 serves to indicate how response by cereals to applied fertiliser K varies with the level of available soil K. It is not possible to lay down a critical value for soil K above which response would not be expected as this would vary with soil type, climate and, of course, variety. It might appear from Figure 10 that the critical value for maize is somewhere between 0.10 and 0.20 meq%.

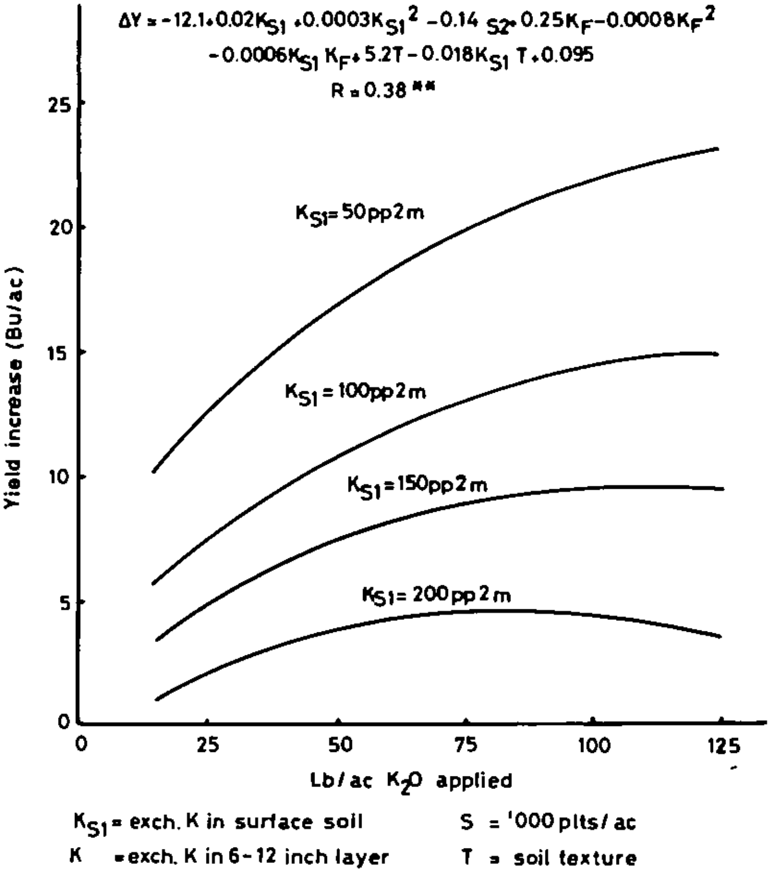


Fig. 10. Effect of soil K level on K response in maize *(Hanway et al. [1962])*

Plant analysis may be expected to give more consistent results. For instance the critical level for barley is said to be 0.92% K in the flag leaf at ear emergence and 1.01% in the stem. In rice 1% K at earing is considered critical and 2% optimum At the same stage 1.12% is thought critical for oats and the corresponding figure for rye is 0.95%. Maize has been more thoroughly investigated and the results are variable; in summary it appears that the critical leaf level lies between 1.3 and 1.8% K, hybrids usually requiring higher levels (Figure 11). There is little published information on sorghum but it may be taken that critical values are similar to those for maize. The following values for stems and leaves in maize are quoted from *Loué [1963]*.

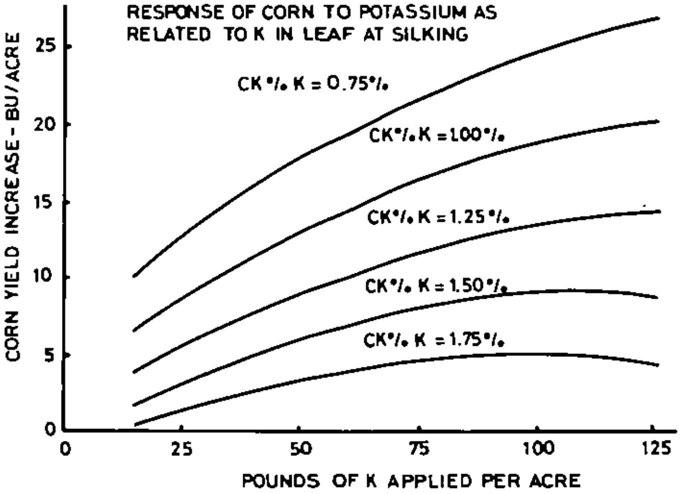


Fig. 11. Predicted yield increase in maize in response to applied K at various levels of % K in leaves at silking *(Hanway et al. [1962])*

Acute deficiency	0.25–0.41% K
Severe deficiency	0.41–0.62% K
Deficiency without symptoms	0.62–0.91% K
Normal	0.91–1.3 % K
Generous	1.3 –2.1 % K

Several authors report close correlation between leaf K and available soil K and it appears that, when N and P are adequate, K content of the whole plant or of the 6th leaf is better correlated with yield than is soil K.

14. The influence of other factors on K nutrition

Cultural methods, climate, supply of other nutrients are all concerned here. Poor soil aeration, to which K is more susceptible than other nutrients, reduces K uptake and when soil aeration is poor differences in soil temperature affect K content of the grain.

Long term field trials at *Purdue University* underline the importance of K supply in relation to water availability. Under normal conditions of soil moisture, sufficient soil K was mobilised to produce satisfactory yields and K fertiliser seldom gave any response, but the response to K fertiliser under dry or excessively wet conditions was a yield increase up to 50%. The role of K in controlling stomatal opening is well known – plants well supplied with K utilise soil moisture more efficiently and wasteful transpiration loss is prevented. Soil moisture content greatly influences K uptake and drying out of the rooting zone limits the rate of diffusion of K in the soil and mass-flow is non-existent. Deficiency of soil moisture adversely affects the K content of young maize plants.

The effect of K on carbon assimilation and yield of spring wheat grown at varying light intensity was that increased K availability increased yield only under full lighting, while when plants were shaded, though it increased vegetative growth, yield was somewhat reduced.

Timing of K fertiliser application seems generally to have little effect and there is no advantage in applying potassium at other times than in the seedbed. But, cases have been reported where there is advantage in giving divided dressings to rice. This applied in warm climates on light soils of low exchange capacity or at high N levels on poorly drained sites when the first application should be at tillering and the second 4 to 6 weeks before ear emergence.

K uptake is much affected by N level; the effect of P level is more variable. In most cases, K is the more effective the higher the level of N fertiliser and this applies especially to modern high-yielding varieties of rice, wheat and barley (Figure 12 and Table 2).

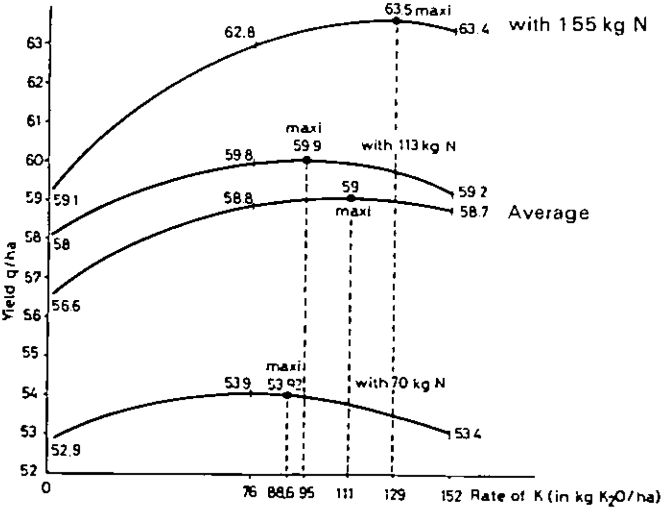


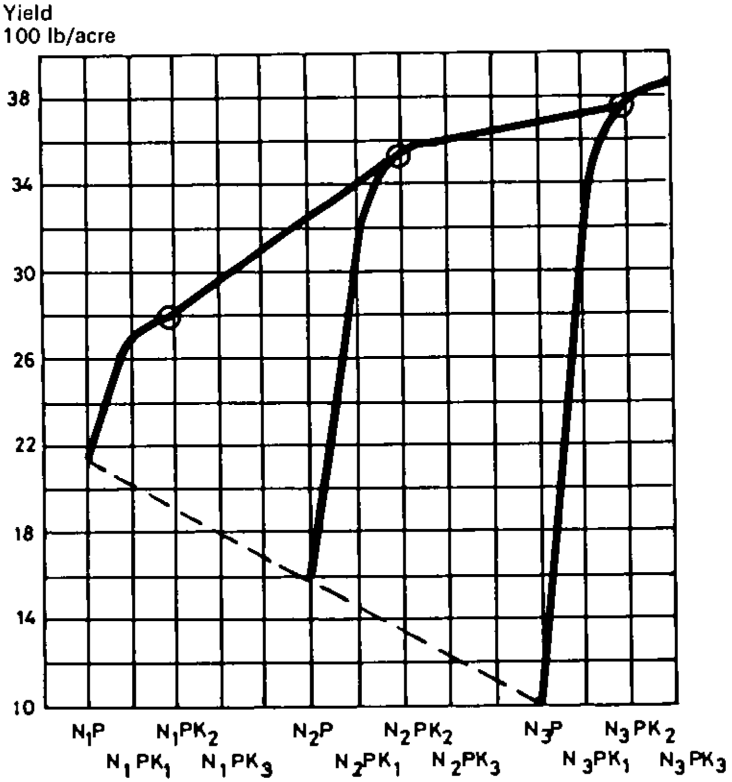
Fig. 12. Effect of K fertiliser at different levels of N applied to wheat *(Loué [1977])*

Table 2. Effect of potassium on rice yield at three levels of N fertiliser (average of 6 years). After *Singh* and *Singh [1978]*

Grain yield (tonne/ha)

N applied (kg/ha)	K applied (kg/ha K) 0	42	62	83	125	166	187	250
100	4.14	4.38		4.54	4.81			
150	4.14		4.84		4.91		5.24	
200	4.14			5.15		5.16		5.53

A striking example of this N × K interaction is illustrated in Figure 13 which shows that increasing N reduced maize yield in the absence of K fertiliser and increased it when K was applied. K increases dry matter production and grain yield and reduces the number of unproductive tillers and improves translocation of N to the grain.



N_1 = 40 lb/ac N K_1 = 30 lb/ac K_2O 60 lb/ac P_2O_5 overall
N_2 = 80 lb/ac N K_2 = 60 lb/ac K_2O
N_3 = 120 lb/ac N K_3 = 120 lb/ac K_2O

Fig. 13. Effect of N and K treatment on maize yield *(Burkersroda [1965])*

15. Response to K fertiliser

In introducing this section it is appropriate to point out that the preceding sections have shown that K supply affects several yield components. That the relative importance of these varies between cultivars is illustrated in Figure 14 showing how yield is built up in 4 *cvs* of spring wheat at varying K levels.

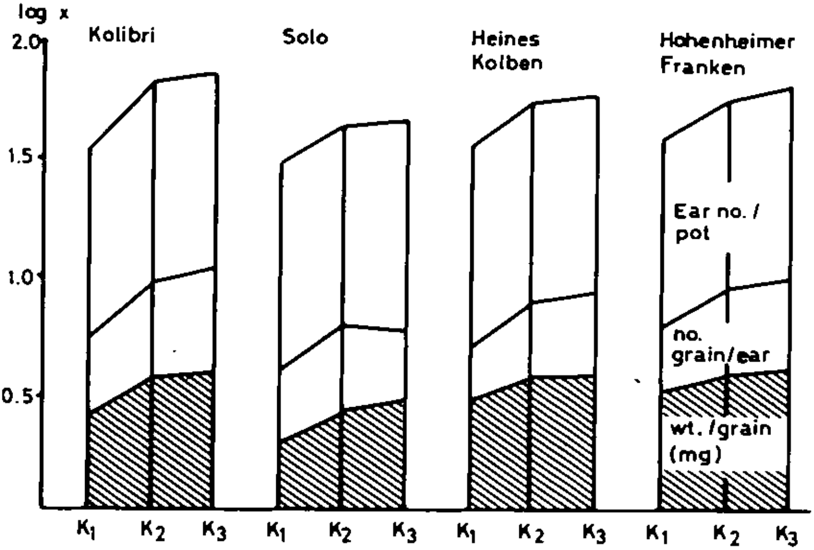


Fig. 14. Grain yield components of 4 *cvs* spring wheat as affected by K supply *(Forster* and *Mengel [1974])*

As has been pointed out above, response by cereals to K fertiliser varies greatly with soil type, soil K level, the availability of water and plant population. The variation in response to K fertiliser between species and varieties grown on the same site is illustrated in Figure 15.

The results of plant breeding and improved cultural methods in the rice crop are shown in that ten or twelve years ago, potash responses, when they were recorded at all, amounted to about 2 kg grain per kg K_2O applied, while now, with a variety like IR 8 the corresponding figure is 7–13 kg grain. There are major differences in responsiveness between the modern cultivars of rice, IR 8, IR 26 and IR 30 responding better to K fertiliser than IR 20 and IR 22. Response by rice appears variable in other respects, some trials having shown better K response on high than on low K soils. Rice growing is normally a long-term project and, particularly when high yielding cultivars are used, continued cropping without K fertiliser leads to soil depletion and declining yield (Figure 16).

Response by wheat can also be very variable though response would always be expected with a soil K level below 0.10 meq%. In long-term experiments, the responses increase with time and can reach as high as 7–8 kg grain per kg K_2O applied, though

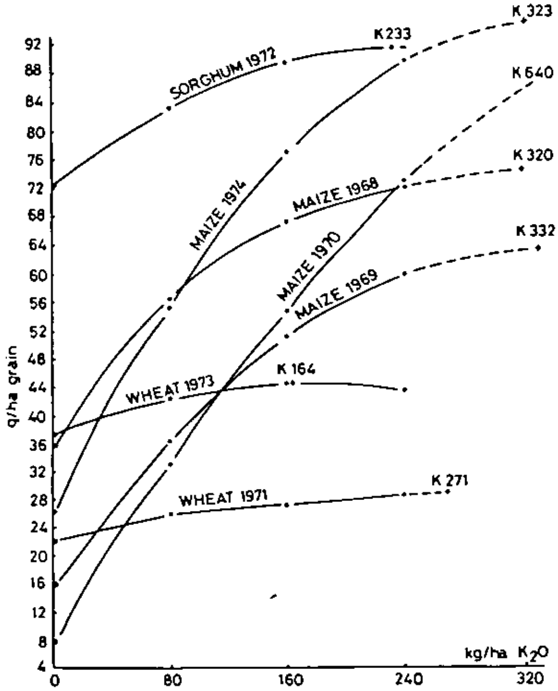


Fig. 15. Potash response by various species in different years at La Sauvetat/France *(Loué [1969])*

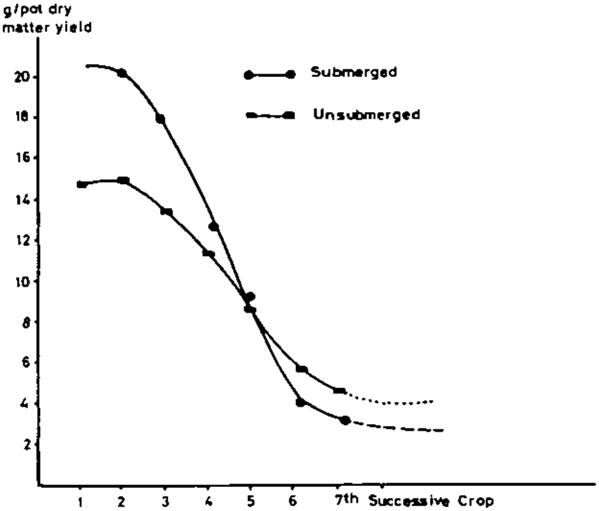


Fig. 16. Decline in rice yield on soil receiving no K fertiliser *(von Uexküll [1976])*

a more usual level would be a little under 4 kg for dry farming and a little over 5 kg grain per kg K_2O under irrigation. Responses higher than 2 kg grain/kg K_2O are quite common throughout the world for both wheat and barley.

Similar variability is found in field experiments on maize. Responses as high as 13 kg grain per kg K_2O have been recorded on K fixing soils *(Loué [1977])* while, at the other extreme there may have been no response to high rates of applied K. Because there is such variability and because responses to K usually increase with time, cereal fertiliser trials, like those on other crops should be long-term; it is unsound to base recommendations on single season trials.

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Potassium Requirements of Grain Legumes

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1. Introduction

The general term 'grain legume' embraces many wild plants including trees and shrubs but the present treatment is limited to the main cultivated species: soya *(Glycine max.* L.), bean *(Phaseolus vulgaris* L.), pea *(Pisum spp.* L.), groundnut *(Arachis hypogea* L.) and cowpea *(Vigna unguiculata).* Their importance is in large measure due to their high protein content.

2. Response to potassium fertiliser

Potassium usually increases the yield of grain legumes and improves quality. Symptoms of potassium deficiency have been described by many authors *(Chevalier [1976, Courpron* and *Tauzin [1975], Gillier (1955), Kamprath [1974], de Mooy [1973]*, etc.).

The function of potassium in the metabolism and morphology of these plants is the same as that in other species, the effects of shortage are shown in various ways:

Effect of deficiency

On stem height:	Short stems, short internodes
On foliage:	Reduced photosynthesis, yellowing, necrosis
On roots:	Reduction in number and weight of nodules
On fruiting:	Fewer inflorescences per plant, fewer grain per pod, and reduction in grain weight.

K content of the grain of certain legumes is particularly high: normally 2 to 2.5% in soya and beans, over 3% in peas, compared with only 0.7% in groundnut and 0.4–0.45 in wheat and maize. *IRAT* say that soya is more sensitive to fertilisation than groundnut.

Review of a large number of experimental results shows that *K response is variable* and affected by a number of different factors.

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The predominant factor appears to be the *potential production of the field (Lin [1965], Nelson [1970]* etc.) resulting from the physical and chemical characteristics of the soil, cultural methods, species and variety, climate and, most important, water supply. The level of potential production determines the potential development of the plants, the weight of biomass produced and, consequently, the pattern of potassium supply required. Thus, good responses have been recorded in good crops of soya, peas, kidney beans or groundnut yielding 2.5 to 3 tonnes of grain per hectare and smaller responses in crops of dolichos or lentils yielding only 1 or 1.5 t/ha. This appears to be an example of *Liebig's Law of the Minimum* in that potassium cannot exert its full effect unless all other factors are optimal. It also illustrates the interdependence between K and other nutrients.

The second factor is the *potassium status of the soil*, particularly its ability to supply potassium rapidly at periods of peak demand. Many authors have tried to determine the critical level of exchangeable potassium (50–80 ppm for soya in Brazil) but generally fail to take into consideration C.E.C.

An important point for soya, beans and peas is the *form of potassium* fertiliser and *method of application:* these plants are sensitive to salinity. Several cases of lack of response on low potassium soils can be explained by the salt effect of KCl applied by placement too near to the seed. It also explains why some have found a better response when potassium is applied to the previous crop *(Fouilloux [1976]), Nelson [1975])*.

3. Potassium requirements during growth

3.1 Production and K uptake

The patterns of dry matter production and potassium uptake are similar *(Michaelis-Menten* kinetics). Maximum yield of groundnut can be obtained at a concentration of 200 μMK in the nutrient solution *(Fageria [1976], Leggett [1970])*.

Comparison of the patterns of K uptake and dry matter production well illustrates the relations between K absorption, dry matter production and grain yield *(Chevalier [1976])* (Figures 1 and 2).

The uptake of potassium by grain legumes has also been studied by *Bataglia [1976], Courpron [1975], Egly [1975], Puech [1974], Haag [1967]* and *Bromfield [1973]*, (Figures 3 and 4).

3.2 Daily absorption rates

The duration of vegetative growth varies with climate; for example the usual varieties of soya mature in 100 to 150 days at 30° latitude and in 90 to 100 days in the tropics. The maximum rate of K uptake is found between flowering and grain formation. Theoretically, a higher rate of K uptake would be expected for equivalent biomass production in hot climates. Some varieties are capable of forming dry matter at two to three times the rate of other varieties of the same species (Table 1).

The mean daily rate of dry matter production of soya can vary from 15 to 50 kg/ha. Daily K uptake rates are less well documented but must vary in the same proportion.

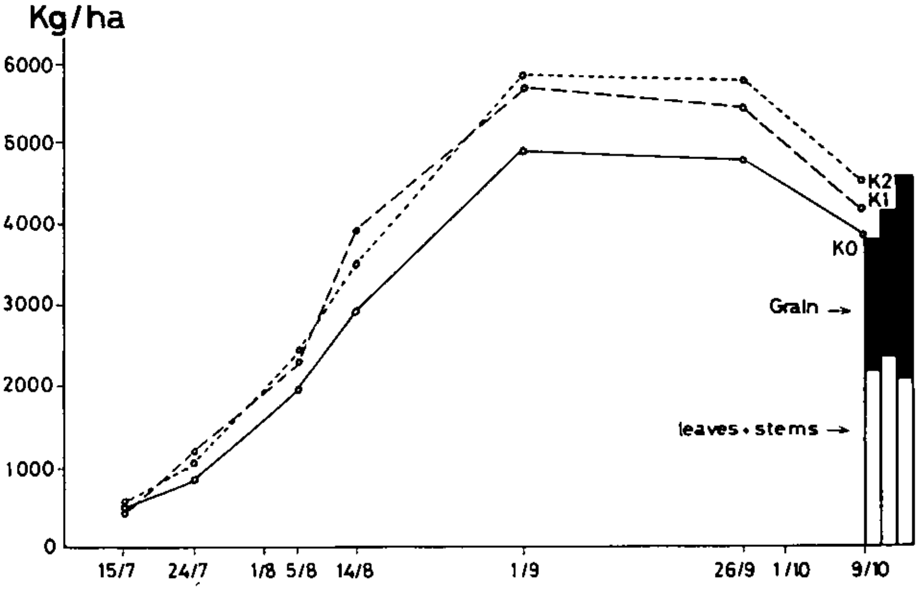

Fig. 1. Production of dry matter (leaves, stems and grain) over time for soya *(cv.* Altona) at 3 levels of K *(Chevalier [1976])*

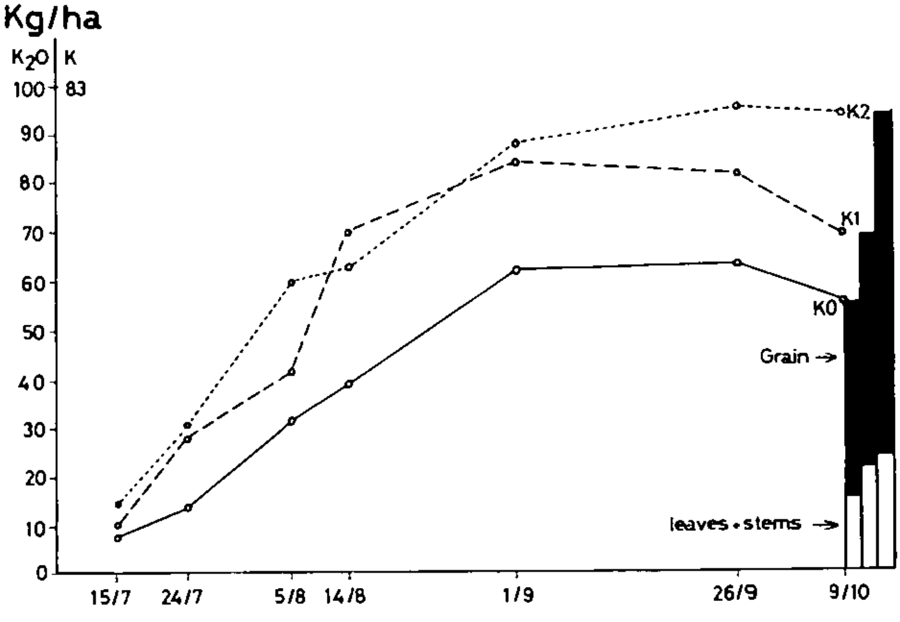

Fig. 2. Uptake of potash (kg K_2O/ha) by soya *(cv.* Altona) at 3 levels of K *(Chevalier [1976])*

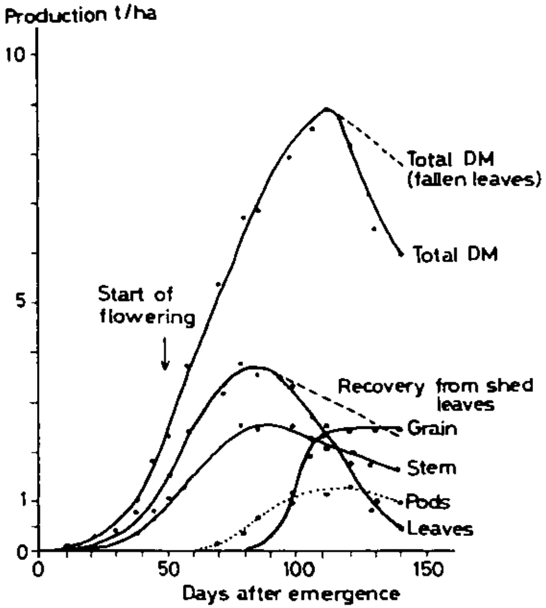

Fig.3. Production of dry matter (whole plant) over time (Soya *cv.* Amsoy)

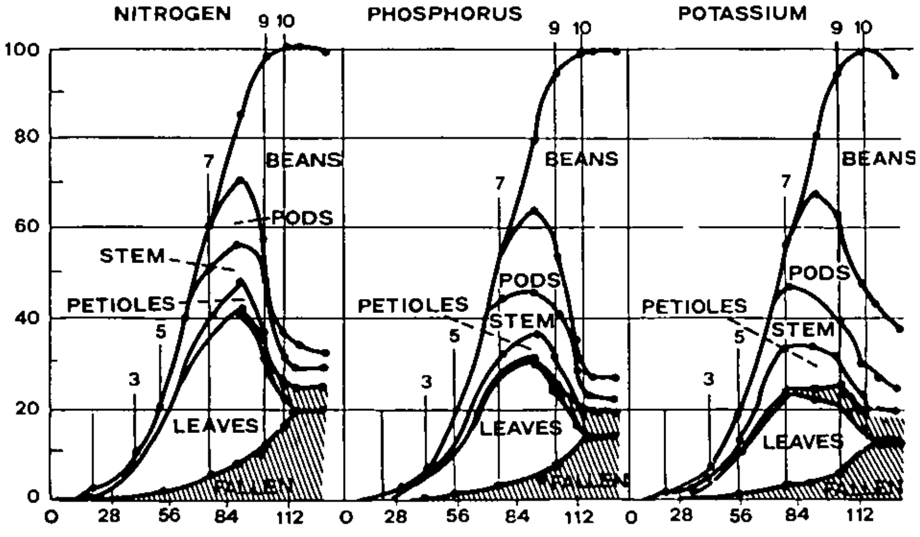

Fig.4. Relative rate of N, P and K accumulation in soybean plant parts during the growth

Table 1. Comparative yields of Dolichos *(Vigna sinensis)* cultivars *(Singh* and *Manjhi [1975])*

Cultivar	Maturity	Grain yield	
	(days)	kg/ha	kg/ha/day
C 19	75	985	13.1
C 20	80	1.053	13.1
C 2	80	917	11.4
RS 9	120	536	4.4
T 2	125	928	7.4

There are thus great differences within and between species. Maximum daily K uptakes vary between 1.5 and 6 kg K (Table 2 and Figure 5).

More research is needed into the relations between peak K uptake, biomass production and grain yield as few results are available on this important point.

Table 2. Daily K uptake rates

Species	Period	Daily biomass production	Uptake rate		Source
Soya	50th–100th day	176 kg/ha	4.5	1.05	*Hanway [1971]*
Soya		n.c.	4.9	1.90	*Hammond [1949]*
Soya		n.c.	7.7	4.60	*Henderson [1970]*
Soya	60th–80th day	333 kg/ha	6.6	6.0	*Mascarenhas [1973]*
Soya		n.c.	10.0	6.6	*Trocmé [1977]*
Beans	50th day	n.c.		4.00	*Haag [1967]*

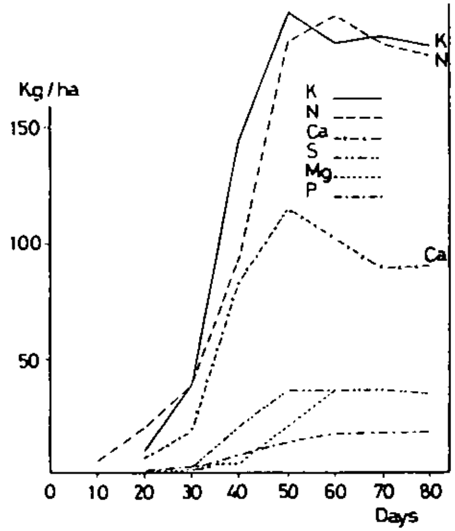

Fig. 5. Major nutrient uptake by beans (250 000 plants/ha)

3.3 Amount and distribution of K uptake (Table 3)

For dolichos, *Silvestre [1965]* gives 17 kg N, 7.4 kg P and 40 kg K per tonne grain. For cowpea *Nicou [1967]* gives 37 kg K per tonne grain compared with only 20 kg/t for groundnut. For groundnut, *Pouzet [1974]* quotes uptakes of 26.9 kg N, 2.27 kg P and 9.04 kg K per tonne of dry matter (that is 378 kg grain, 132 kg shells and 490 kg straw). Groundnut is thus not a very demanding crop,
It may be noted that the level of K in the soya plant declines in an approximately linear manner after the twentieth day from emergence (Table 4).

Table 3. Amount and distribution of K uptake

Species		Yield kg/ha	Uptake (kg/ha)		
			N	P	K
Soya *(Ohlrogge* and *Kamprath [1968])*	grain	4030	246	28	78
	straw	n/a	78	11	50
	stubble, root	n/a	39	5	28
Soya *(Bataglia et al. [1976])*	grain	2093	135	11	47
	straw	3539	11	2	33
Soya *(Trocmé [1977])*	grain	3500	205	26	41
	whole crop		480	39	95
Beans *(Cobra [1967])*	whole crop		102	9	93
Beans *(Haag [1967])*	whole crop		201	35	200
Groundnut *(Gillier [1955])*	grain	1278	58	5	9
	leaves and shells	1891	25	2	16

Table 4. K content in dry matter, soya cv. Altona at 3 K fertilizer levels (0–100–200 kg K_2O/ha) on soil containing $1.07^{0}/_{00}$ exchangeable K_2O *(Chevalier [1976])*

Date and growth stage	K_0	K_1	K_2
15/7 4 trifoliate leaves	1.40	1.97	2.49
24/7 Flower differentiation	1.27	1.91	2.22
5/8 Beginning of flowering	1.34	1.88	2.07
14/8 Full flower	1.10	1.49	1.46
18/8 Start of grain formation	1.05	1.24	1.00
1/9 50% grain formed	1.12	1.24	1.32

3.4 Comparison with other crops

It is seen that the K demand, in terms of total need and maximum daily uptake, are very similar for a 3.5 t soya crop and a 6 t wheat crop. Soya needs more K than maize, but the latter crop has a higher peak absorption. (Table 5).

Table 5. Nutrient element uptake of other crops *(Trocmé [1977])*

	N	P	K
Wheat 6 t/ha			
Maximum uptake	160	32	249
Content at harvest	150	32	103
Content of grain	120	26	24.9
Maximum daily uptake	2.5	0.43	5.81
Maize 8.5 t/ha			
Maximum uptake	195	39	166
Content at harvest	195	39	112
Content of grain	135	26	29
Maximum daily uptake	8	1.31	9.96
Rape 2.5 t/ha			
Maximum uptake	160	26	232
Content at harvest	150	26	182
Content of grain	90	17.5	25
Maximum daily uptake	9	1.31	12.45
Soya 3.5 t/ha			
Maximum uptake	480	65.5	166
Content at harvest	250	39.3	95.4
Content of grain	205	26.2	41.5
Maximum daily uptake	10	1.75	6.64

4. Conclusion

The response of grain legumes to potassium fertiliser depends upon potential production of the crop (availability of water, levels of other nutrients, species and variety and cultural methods).

It depends also on potassium availability in the soil both as regards intensity and buffering capacity. The rate of K supply (replenishment of the soil solution) is critical at periods of peak growth.

In the absence of other limiting factors, it seems that soya and peas, in which biomass and grain yields are relatively high and in which grain K content is high, are the most responsive to potassium.

In groundnut, where biomass production is relatively lower and the grain has a low K content, response to K is less and only to be expected on low K soils. Consequently it seems that, in order to satisfy the K needs of grain legumes, it is necessary that soil and fertilisers should be able to supply K at a sufficiently high rate at all growth stages. At peak periods this is high, in the case of soya exceeding 6 kg K/ha/day. Soya, beans and peas can be affected by the anion accompanying the K, particularly when KCl is placed near the seed.

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Potassium Requirements of Root Crops

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1. Introduction

From a strictly botanical point of view, the root crops should be defined as crop plants grown for their storage roots, but usually, as in this paper, they are more generally defined as crops which develop storage organs at or below the soil surface. Botanically these storage organs may be roots, stems, or even leaves. The storage organs are used by the plants for propagation or as means to survive adverse climatic conditions – drought periods or cold winters. The root crops are well distributed throughout the plant kingdom (Table 1) and they are grown under a great variety of soil and climatic conditions.

Table 1. A variety of root crops

Botanical family	Latin name	English name	Storage organs
Compositae	*Helianthus tuberosum* L.	Jerusalem artichoke	Stem tubers
Convolvulaceae	*Ipomoea batatas* (L.) Lam.	Sweet potato	Root tubers
Solanaceae	*Solanum tuberosum* L.	Potato	Stem tubers
Cruciferae	*Brassica napobrassica* (L.) Milt.	Swede, turnip	Fleshy taproot
	Brassica rapa L.	Rutabaga	Fleshy taproot
	Raphanus sativus L.	Radish	Fleshy taproot
Euphorbiaceae	*Manihot esculenta* Crantz	Cassava	Root tubers
Chenopodiaceae	*Beta vulgaris* L.	Sugar beet	Fleshy taproot
	Beta vulgaris L.	Fodder beet	Fleshy taproot
	Beta vulgaris L.	Table beet	Fleshy taproot
	Beta vulgaris L.	Beetroot	Fleshy taproot
Umbelliferae	*Daucus carota* L.	Carrot	Fleshy taproot
	Pastinaca sativa L.	Parsnip	Fleshy taproot
Liliaceae	*Allium cepa* L.	Onion	Bulbs
	Allium porrum L.	Leek	Bulbs
	Allium sativum L.	Garlic	Bulbs
Araceae	*Colocasia* spp.	Cocoyam, taro	Corms, cormels
	Xanthosoma sagittifolium (L.) Schott	Cocoyam, tannia	Corms, cormels
Dioscoreaceae	*Dioscorea* spp.	Yam	Corms, cormels

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The vegetative, waterholding and fleshy storage organs of the root crops are rich in energy and are mainly grown for their carbohydrate content; they are used as important staple foods in most cultures of the world, in the temperate and the tropical climatic zones. They, or preparations from them, are used as feedstuffs and for industrial processing, being important sources of starch and sugar and of derivatives from these basic substances.

The aerial parts of the root crops – leaves and stems – are often rich in protein and mineral nutrients. Many of them are used as vegetable food and as feedstuffs.

2. The major root crops, general features

Only a few of the very many root crops grown throughout the world are of major importance as sources of carbohydrate foods, feeds and raw materials. While this paper concentrates on the few important crops, the large number of more or less special root crops of only limited or local importance should be mentioned. They are grown on a small scale for direct human consumption as garden vegetables or to add savour to and to diversify otherwise monotonous basic diets. Most of such crops have been little, if at all, developed by plant breeding and their environmental requirements have not been scientifically investigated.

The major temperate root crops are the potato and the beets, primarily sugar beet. The major tropical root crops *(Ezeilo [1977])* are cassava, sweet potato, yams and the cocoyams.

Modern agriculture, including the use of fertilisers, was developed in the temperate regions during the last century; consequently much plant-breeding work has been devoted to the temperate root crops and their nutritional and other environmental requirements have been extensively investigated in scientific research. In contrast, though, the major tropical root crops represent very old cultivated plants, they are still in a primitive condition with regard to plant-breeding and their environmental requirements have not been thoroughly investigated. However, in connection with the general efforts to improve the agriculture of the developing world, much work is now being directed towards genetic improvement of these crops and to improving cultivation methods.

2.1 The potato

The potato, *Solanum tuberosum* L., is a perennial plant of the *Solanaceae* grown as an annual crop *(Burton [1966], Brouwer [1973–1974])*. The storage organs, rich in starch, are stem tubers developed beneath the soil surface. The tubers may be able to remain in the soil during the winter but normally they are harvested before winter begins. The plant may develop flowers, fruits and seeds but normally it is propagated by planting small tubers. The crop normally matures in three to six months from planting. At the stage when the tubers begin to mature, the aerial parts constitute 20 to 30 per cent of the total organic matter produced *(von Boguslawski* and *von Gierke [1961], Evans [1977])*. As they wilt and die rapidly, most of the nutrient content of these parts is returned to the soil. Mature tubers normally contain 22–25 per cent dry matter, of which 70–80 per cent is starch.

Though it is mainly cultivated in the temperate zones of the northern hemisphere, the potato is by no means restricted to this area and it is cultivated all over the world and even in the tropics. Thus, it is the most widespread and generally cultivated of the major root crops. It is a staple food in many human diets. Besides this it is much used as a feedstuff and for industrial starch and ethanol production. The aerial parts of the crop are not normally harvested.

2.2 Sugar beet and root crops with similar botanical characteristics

The sugar beet, *Beta vulgaris* L., is a biennial plant of the *Chenopodiaceae (Draycott [1972], IPI [1955])*. The storage organ, rich in sucrose, is a taproot growing in the soil surface. The foliage and taproot develop during the first year, the growing period being 7 to 10 months, after which the crop is harvested. If the plant is left in the soil, the taproot may overwinter and the following year develop a stem with flowers which produce seed.

At harvest the foliage and the neck (the hypocotyl) of the beet are separated from the taproot. These aerial parts of the crop (the tops) constitute a valuable feedstuff for ruminants and are often used for this purpose, either fresh, dried, or as silage. At harvest about one third of the total dry matter production is in the tops and two thirds in the roots. The taproot contains about 25 per cent dry matter, of which 60–75 per cent is sucrose. The beet pulp, after the sucrose has been extracted, constitutes a valuable ruminant feedstuff. The sugar-beet crop is grown in the climatic zones of the earth where sugar cane cannot be grown.

The garden and fodder beets are closely related to sugar beet. Normally the storage taproots of these crops have lower dry matter and sucrose contents than the sugar beet.

The many garden and vegetable root crops of the *Umbelliferae* family have a taproot and other characteristics quite similar to those of the beets. This is also the case with the root crops of the *Cruciferae*, swedes, rutabagas and turnips *(McNaughton* and *Thow [1972])*, which are widely used as garden and vegetable crops, but in some temperate parts of the northern hemishpere they are also important fodder crops.

2.3 Cassava

The cassava plant, *Manihot esculenta* Crantz, is a tropical perennial shrub of the *Euphorbiaceae (Purseglove [1968], Jennings [1970], Williams [1975], Rogers* and *Appan [1973], Coursey* and *Booth [1977], Ezeilo [1977])*, though it may be cultivated as an annual. The storage organs are tuberous roots, mostly adventitious, developed from stem cuttings. The tubers are rich in starch. It is normally propagated by stem cuttings and rarely develops flowers or seed. Though the plant may remain in the soil for many years and be sporadically stripped of tubers, the normal vegetation period is from 7 to 15 months. The longer period, of course, gives the higher yields. In good cultivars the dry matter production in tubers is about equal to the production in aerial parts. The dry matter content of the tubers varies between 25 and 35 per cent, about two thirds of this being starch. The protein content of the tubers is low but the foliage is rich in protein, 18 to 35 per cent of the dry matter being crude protein. The leaves are often eaten as spinach and are used as feed for cattle and pigs. Cassava has for long been an important human food and now there is an increasing demand for use as a feedstuff and for industrial starch production *(Obigbesan [1977a])*. In terms of area planted, the cassava crop has acquired the leading position among the tropical root crops *(Ezeilo [1977])*.

2.4 Sweet potato

The sweet potato, *Ipomoea batatas* (L.) Lam., is a perennial plant of the *Convolvulaceae* family. The storage organs are root tubers developed beneath the soil surface. They are rich in starch and other carbohydrates *(McDonald [1963], Purseglove [1968], Coursey* and *Booth [1977], Tsuno)*. Normally the plant is grown as an annual and takes 4 to 8 months to produce a crop. At the end of the year's growth, normally with the onset of the dry season, the leaves wilt and die off and the tubers survive in the soil. The plant, whose habit is normally twining, sometimes develops flowers and seed: in practical cultivation it is propagated both from stem cuttings and cut tubers.

The tubers are higher in dry matter and energy than are those of the potato; their dry matter content varies between 25 and 35 per cent. Of the total dry matter production of the crop up to 75 per cent is in the tubers. The foliage is edible. On dry matter basis it contains 10–15 per cent protein, 3 per cent fat and about 45 per cent carbohydrate. It is also used as animal feed.

The sweet potato seems to have the lowest yield potential of the major tropical root crops. It is less restricted to the truly tropical regions; thus it is grown in large parts of the United States and Japan.

2.5 The yams

The true yam, *Dioscorea esculenta* (Lour) Burk., and related subspecies, belong to the *Dioscoreaceae (Waitt [1963], Coursey [1967], Sobulo [1972], Obigbesan et al. [1976], Coursey* and *Booth [1977])*. The storage organ is a subterranean stem or corm. The yam is a climber and the vines die back at the end of the rainy season of the tropical climate. Its cultivation is strictly confined to the true tropics. It is a very old crop plant propagated from corm or cormel sets. This means that it seldom flowers and produces seeds.

The dry matter content of the tuberous corms may vary between 20 and 40 per cent. Besides the starchy carbohydrates the corms contain saponines, which are used in cortisone manufacture. Of the total dry matter production of the crop about 40 per cent is in the vines and foliage, 60 per cent in the corms.

2.6 The cocoyams

The cocoyam crops include two genera, *Colocasia esculenta* (L.) Schott and *Xanthosoma sagittifolia* (L.) Schott, which are closely related to each other and both belong to the monocotyledonous *Araceae (Plucknett et al. [1970], de la Pena* and *Plucknett [1972], Coursey* and *Booth [1977])*. Their storage organs are stems, *i.e.* corms and cormels, subterranean and rich in starch. The cocoyams are strictly tropical plants. They can be grown under waterlogged as well as upland conditions. Their vegetation period is normally 9 to 14 months. They are propagated by setts, *i.e.* cuttings from the upper parts of corms or cormels. The leaves of the cocoyams are edible and are used as food. The entire plant can be used for stock-feeding.

3. General conditions affecting the nutrient requirements of the major root crops

Root crops have a long growing season and a higher potential yield than many other annual crops. Even so, they can give reasonable yields under low fertility conditions. This applies particularly to tropical root crops, especially cassava *(Obigbesan [1973], Ezeilo [1977])* which has a reputation of having small nutrient requirements. This is because, in the primitive cultivation systems still prevailing in large parts of the tropics, cassava is often grown on the most exhausted soils at the end of the crop rotation. However, the idea that root crops have low nutrient requirements is entirely false. If they are to realise their high yield potential, their nutrient requirements are high and they have to be well fertilised *(Greenland [1974], Kanwar [1974])*.

Maximum yields realised in practice are of about the same size for all the major root crops. The practical top yield level may be put at 50–60 tons per ha of fresh storage organs, tubers, roots or corms. This yield level will be equivalent to about 15 tons of dry matter per ha which, in terms of energy, is about twice as much as is obtainable from most other crops, for example, cereals. Most root crops contribute a considerable amount of valuable organic matter in the form of foliage and other aerial parts. The potential yields of the potato and sweet potato may be somewhat lower than those of other major root crops. It is to be expected that intensified plant breeding will considerably raise the potential yield especially of cassava, yams and cocoyams.

Since the root crops are mainly carbohydrate producers, they have an especially high requirement for potassium which has a special role in carbohydrate synthesis and translocation *(Müller [1964], Jackson* and *Volk [1968], Liebhart [1968], Mengel [1977])*. Abundant K supply favours the primary processes of photosynthesis. It also regulates the balance between assimilation and respiration in a way that improves net assimilation. This is a prerequisite for vigorous growth and formation of reserve assimilates.

The translocation of photosynthates from the green parts of the plant is of the utmost importance for the building up of the storage organs. An abundant supply of K is needed for both short and long distance translocation *(Haeder et al. [1973], Addiscott [1974], Haeder [1977])*. This applies to the 'push' side of the translocation – the formation of assimilates in the green parts of the plant – as well as the 'pull' side – the conversion of the translocates in the building up of the storage organs. The osmotic effects of the K concentration as well as more specific effects of the K^+ ion seem to be involved in the translocation processes. An expression of this is probably the very high and varying K content of the petioles of the root crops. The petioles are much concerned in translocation and consequently petiole analysis is a useful indicator of the K status of the crop *(cf.* Table 5).

The total potassium uptake of the major root crops which is required for the top yields mentioned above can be estimated at about 400 kg K per hectare which is much higher than that of most other crops. Table 2 lists the usual potassium contents of aerial parts and storage organs of the major root crops at harvest time.

Table 2. Potassium contents of some major root crop products at harvest time. K, per cent of dry matter

Crop	Aerial parts	Storage organs	Reference
Potato	–	1.0–2.9	*Vork Nielsen* and *Nielsen [1969]*
	–	1.1–2.6	*Henkens [1970]*
	–	1.0–2.3	*Loué [1977]*
	3.6	1.3	*Carpenter [1957]*
	3.6	2.2	*von Boguslawski* and *von Gierke [1961]*
	4.6	1.9	*Werner [1962]*
Sugar beet	3.2–4.3	0.6–0.7	*von Boguslawski et al. [1961]*
	1.7–3.9	0.6–1.0	*Draycott [1973]*
	3.5	0.7	*Lüdecke* and *Nitzsche [1957]*
	3.5	0.8	*Loué [1972]*
Sweet potato	2.7	1.2	*Tsuno*
Cassava	–	0.3–0.8	*Ngongi et al. [1976]*
	–	0.9–1.2	*Obigbesan [1977b]*
Yam	–	1.2–1.8	*Obigbesan et al. [1976]*
Cocoyam	2.2–4.1	–	*de la Pena et al. [1972]*

The grower of root crops not only aims for high yield but also for produce of high quality, high nutritional value, fitness for storage and processing, etc. These requirements can be summarised in the term 'quality' and vary for different crops and according to the purpose for which the produce is destined. In most root crops and for most purposes high dry matter and carbohydrate contents are basic requirements for high quality. The ratio root/shoot D.M. should be high. These general quality criteria and many others are closely related to the nutrient supply to the crop, the pattern of nutrient uptake and nutrient balance.

Yield level is primarily determined by nitrogen supply. An ample supply of nitrogen is a must for high yields of root crops. However, the nitrogen supply also determines the protein content and affects several other qualitative properties of the plant material. An increased protein content entails a reduced carbohydrate content. At the same time the dry matter content tends to decrease and the susceptibility to many fungal and bacterial diseases is often increased.

The increased rates of assimilation and growth caused by abundant nitrogen supply often result in an accumulation of precursors and intermediates in the processes of carbohydrate and protein formation. Examples of this kind are accumulations of reducing sugars in potato tuber *(Müller [1964])* and of soluble amino and amide compounds in the tubers of several root crops. These increased contents of simple and soluble organic compounds often lower the quality of the harvest. This applies, for example, to the increased contents of soluble organic nitrogen compounds in potatoes and sugar beet. In the processing of the potatoes the soluble nitrogen (and the reducing sugars) cause discolorations – darkening, blueing *(Hesen [1964])*. In sugar beet processing the soluble nitrogen decreases juice purity and depresses the crystallisation of the sugar from the juice *(Winner [1966], Draycott* and *Cooke [1966])*. Thus, the soluble organic nitrogen is often called noxious nitrogen.

Several of the root crops contain unpleasant, bitter or toxic substances, for example alkaloids, which limit or complicate their use as food and feed. The most severe problem of this kind probably is the presence of cyanogenic glucosides in cassava. These glucosides give rise to the highly poisonous hydrocyanic acid *(De Bruijn [1971])* which must be removed in the preparation of food from cassava tubers and leaves. Abundant nitrogen supply to the crops often increases their contents of these noxious constituents and thereby lowers crop quality. The qualitative disadvantages associated with the ample supply of nitrogen needed to obtain top yields are reduced if a proper balance is maintained with the other necessary nutrient elements. A good supply of K is especially effective in controlling the qualitative drawbacks of abundant nitrogen *(Winner [1966], Herlihy* and *Carroll [1969], Pushpadas* and *Aiyer [1973])*. Both the absolute supply of potassium to the crops and the nitrogen-potassium relationship and interactions have to be taken into account *(Alblas [1973], Prummel [1973], Steineck [1974], Köchl [1977])*.

3.1 Phases of development of the root crops

When grown as annuals, the root crops have a comparatively long growing period. Initial development is slow.

Within the total period of development there are two main phases:

1. Building up of the vegetative and assimilative apparatus of the plants, feeding roots, stems, leaves.
2. Development and growth of the storage organs. Formation and translocation of reserve assimilates to the storage organs.

Generally, the first phase comprises the first two thirds of the vegetation period of the crop, the second phase the last third. The first phase has two characteristics: initial growth is slow and there is a risk that the young crop will be suppressed by weeds; secondly, nutrient uptake runs ahead of assimilation and growth so that the nutrient requirements of the young crops are considerable and it is important for later development that an ample supply of readily available nutrients, among them potassium, are present in the soil at this early stage of growth. When fully developed, the aerial assimilation apparatus of the root crops is rich in mineral nutrients including potassium, while the nutrient contents of the storage organs are relatively low (Table 2). A result of this is that the nutrient content of the crop reaches a maximum by the end of the first phase of growth or at the start of the second, the building up of the storage organs and their filling with carbohydrate assimilates.

During the second phase the assimilative apparatus is normally no longer growing in size and some of its nutrient contents are translocated to the storage organs. This applies to nitrogen and potassium. It may even happen that the total nutrient content of the crop decreases during the last part of the second phase, at the end of the growing period. The running down of the assimilative apparatus is not fully counterbalanced by the growth and nutrient accumulation of the storage organs. For example, leaves and feeding roots may die back. Nutrients may be leached out from the tissues and find their way back to the soil. Potassium is liable to such losses. A consequence will be that determinations of nutrients in the crop undertaken at harvest time may underestimate the total requirement of the crop though, of course, they give a true measure of removal of nutrients in the harvested crop.

3.2 Growth rates and potassium rate requirements

The above considerations of different phases of crop development and nutrient uptake point to the importance of the relation between growth rates and nutrient (potassium) rate requirements, *i.e.* uptake of nutrient per unit time. For optimum development it is not sufficient that the total nutrient requirement be fulfilled during the growing period. It is equally important that the top rate requirements over short periods of rapid growth can be met.

Growth rates and potassium rate requirements over individual stages in crop development have been little studied. Existing data refer to the temperate root crops, the potato *(Carolus [1973], Werner [1962], Soltanpour [1969], Mengel* and *Forster [1973] Favart* and *Leblanc)* and sugar beet *(IPI [1966], von Boguslawski et al. [1961]).* Similar data for tropical root crops is almost totally lacking. In table 3 some data on growth rates and potassium rate requirements from high-yielding sugar-beet experiments performed in Germany *(Lüdecke* and *Nitzsche [1975])* are summarised. In table 4 the growth and potassium uptake rates for a potato crop are illustrated in a similar manner. The experimental crop was grown in Maine, USA *(Carpenter [1957]).*

Though there is a lack of data, it may be assumed that the growth rates and potassium rate requirements follow approximately the same general pattern for all the major root crops. There are cultivar differences but they do not upset the general scheme. Growth rates and potassium rate requirements follow the same pattern in relation to time whether they are low-yielding on low fertility soils or high-yielding and well fertilised *(von Boguslawski et al. [1961]).*

The data of Tables 3 and 4 confirm the general statements on the time relationships between nutrient uptake and dry matter production earlier discussed. For both sugar beet and potatoes the tables justify the following statements:

The initial development of the crops is quite slow.

The maximum K rate requirement runs ahead of the dry matter production.

The aerial assimilative apparatus of the crops is almost completed before the rapid development of the storage organs begins. This applies to potassium uptake as well as dry matter production.

During the last part of the vegetative period the aerial parts of the crop start to die back, and lose potassium as well as total dry matter. Loss of potassium starts earlier and is more obvious than that of total dry matter.

The potassium and dry matter from the aerial parts are mainly translocated to the storage organs, though some is lost to the environment.

Both translocation of reserves and running net assimilation of the crop contribute to growth of the storage organs.

Maturity of the crop is indicated by net reduction of the aerial parts in combination with a standstill in the net growth of the storage organs. This applies to potassium as well as total dry matter.

Table 3. Growth and potassium uptake by sugar beet grown under favourable conditions. Means of 5 experimental years and 4 cultivars *(Lüdecke* and *Nitzsche [1957])*

Days from emergence	Growth rate Dry matter, kg/ha/day			K rate requirement kg/ha/day		
	Tops	Roots	Total crop	Tops	Roots	Total crop
0– 45	10	2	12	0.49	0.05	0.54
46– 77	116	53	169	3.96	0.81	4.77
78–107	83	120	203	2.92	1.00	3.92
108–138	39	113	152	0.45	0.39	0.84
139–167	–7	66	59	–0.07	0.13	0.06
168–198	–32	23	–9	–0.43	0.05	–0.38

Days from emergence	Accumulated dry matter production, kg/ha			Accumulated K uptake kg/ha		
	Tops	Roots	Total crop	Tops	Roots	Total crop
45	450	70	520	22	2	24
77	4200	1800	6000	149	28	177
107	6700	5400	12100	236	58	294
138	7900	8900	16800	250	70	320
167	7700	10800	18500	248	74	322
198	6700	11500	18200	235	76	311

Table 4. Growth and potassium uptake by potatoes. Results from field experiments in Maine, USA *(Carpenter [1957])*

Days from planting	Growth rate Dry matter, kg/ha/day			K rate requirement kg/ha/day		
	Tops	Tubers	Total crop	Tops	Tubers	Total crop
0–28	4	–	4	0.18	–	0.18
29–41	34	–	34	3.00	–	3.00
42–55	79	26	105	3.71	0.71	4.42
56–74	57	104	161	1.42	1.74	3.16
75–98	–18	178	160	–1.62	1.87	0.25

Days from planting	Accumulated dry matter production, kg/ha			Accumulated K uptake kg/ha		
	Tops	Tubers	Total crop	Tops	Tubers	Total crop
28	100	–	100	5	–	5
41	540	–	540	44	–	44
55	1650	360	2010	96	10	106
74	2730	2340	5070	123	43	166
98	2310	6620	8930	84	88	172

3.3 Disease and potassium nutrition

Like all other crops, the root crops are attacked by various pathogens and pests. To some extent the nutritional status of the crop determines its susceptibility to attack by parasitic diseases *(Perrenoud [1977])*.

Diseases caused by fungi and bacteria – blights, wilts, rots – are particularly dependent on the nutritional status of the crop, and such diseases are especially important in root crops. As well as affecting the crop during growth they are responsible for heavy losses in store. A well-nourished crop in a well-balanced nutritional status shows the best resistance to pathogenic attack and has greater ability to recover from the effects of infection. Two types of unbalanced nutrition especially increase the susceptibility of root (and other) crops to fungal and bacterial diseases, namely nitrogen excess and potassium deficiency. Generally, abundant potassium supply is to be recommended for obtaining healthy crops *(Adeniji* and *Obigbesan [1976])*. Nitrogen-potassium relationships are of special importance. The effects of surplus nitrogen; decreased dry matter contents of the plant tissues, weakened cell walls and supporting tissues and accumulation of soluble intermediates of the assimilation processes are apt to increase the susceptibility of the plants to fungal and bacterial attacks. Thus, in the interests of crop health, it is advisable to remedy potassium deficiencies by regular potassium fertilisation and to balance the intense nitrogen fertilisation needed for high production by an ample potassium supply.

3.4 Determination of the potassium status of the root crops

As already pointed out, the root crops are heavy consumers of potassium. Their total requirements are high, higher than for most other crops, and so are their potassium rate requirements, at least during critical periods of growth. In order to be able to decide whether potassium is or will be a limiting factor of growth and quality, it is necessary to be able to determine the crop's potassium status.

Fertiliser recommendations are usually, and rightly, based on soil analysis. However, plant analysis can give direct information on the nutritional status of the crop. Both methods should be tested in field experiments with fertiliser.

The value of plant analysis as a method of estimating the nutritional status of the crop depends upon there being considerable variation in the contents of the individual nutrient elements in the plant tissues and upon such variation being related to the health, vigour and performance of the crop. From these points of view, plant analysis may appear applicable to potassium and to root crops. Plant analysis can be carried out on the entire plant or on some well-defined part of it. The part chosen for analysis should be easy to define with regard to age and stage of development. There should be a considerable range in the analytical values and these should be closely related to the performance of the crop.

In table 5 some analytical data from root crops are assembled, showing the range of potassium content in different parts of the plant which might be used for diagnostic plant analysis. The storage organs are least suitable *(Ulrich* and *Fong [1969])*. Their potassium contents are low and the range is rather limited. From the diagnostic point of view the analysis of young petioles or young leaf blades is most attractive. The potassium contents of these organs are high and the range from deficiency to

Table 5. Range of potassium contents in root crop plants

Crop	Part of plant	Stage of development	K, % of dry matter			Reference
			Deficiency	Normal	Surplus	
Potato	Petioles	Early in growth season	–9	9–11	11–	*Tyler et al. [1960]*
	Petioles	Midseason	–7	7–9	9–	*Tyler et al. [1960]*
	Petioles	End of season	–4	4–6	6–	*Tyler et al. [1960]*
	Petioles	60–70 days after planting	0.4–8.0	8.0–10.0	10.0–12.0	*Loué [1977]*
	Leaf blades	60–70 days after planting	0.4–4.0	4.0–5.0	5.0–6.0	*Loué [1977]*
	Tubers	Mature	1.6–1.7	1.7–2.0	2.0–	*Loué [1977]*
	Leaves	At harvest	Total span 0.3–4.3			*Mengel* and *Forster [1973]*
	Leaves	30 days after emergence	Total span 1.0–4.2			*Ward [1959]*
	Stem	30 days after emergence	Total span 0.9–8.9			*Ward [1959]*
	Tubers	At harvest	Total span 1.1–2.0			*Ward [1959]*
Sugar beet	Petioles	Fully developed Ample Na supply	0.2–0.6	1.0	1.0–11.0	*Ulrich [1961]*
	Leaf blades	Fully developed	0.3–0.6	1.0	1.0–6.0	*Ulrich [1961]*
	Petioles	Na deficiency	0.5–2.0	–	2.5–9.0	*Ulrich [1961]*
	Leaf blades	Na deficiency	0.4–0.5	1.0	1.0–6.0	*Ulrich [1961]*
	Roots	Mature	–0.6	0.85	1.0–	*Loué [1972]*
Cassava	Petioles	32 weeks after planting	0.4	1.6–2.2	2.6	*Ngongi et al. [1976]*
	Leaf blades	32 weeks after planting	1.0	1.4–1.6	1.6	*Ngongi et al. [1976]*
	Tubers	38 weeks after planting	0.3	0.5–0.6	0.7	*Ngongi et al. [1976]*
Sweet potato	Petioles	40 days after planting		9.5		*Tsuno*
	Leaf blades	40 days after planting		3.7		*Tsuno*
	Tubers	40 days after planting		2.1		*Tsuno*
	Petioles	At harvest		3.7		*Tsuno*
	Leaf blades	At harvest		2.9		*Tsuno*
	Tubers	At harvest		1.2		*Tsuno*
Yam	Petioles	Young plants		4.1		*Sobulo [1972]*
	Leaf blades	Young plants		2.1		*Sobulo [1972]*
	Tubers	Young plants		2.5		*Sobulo [1972]*
	Petioles	Old plants		1.0		*Sobulo [1972]*
	Leaf blades	Old plants		0.5		*Sobulo [1972]*
	Tubers	Old plants		0.8		*Sobulo [1972]*
Cocoyam	Petioles	Plants 3 months old	Total span 3.0–9.2			*de la Pena [1972]*
	Leaf blades	Plants 3 months old	Total span 3.3–5.1			*de la Pena [1972]*
	Petioles	Plants 9 months old	Total span 2.3–4.2			*de la Pena [1972]*
	Leaf blades	Plants 9 months old	Total span 3.3–3.9			*de la Pena [1972]*

surplus is wide. It must be stressed, however, that the sampling of these organs must be carefully carried out in relation to stage of development, age and position on the plant. Otherwise unrepresentative or even erroneous analytical results may be obtained. Values in Table 5 listed under the heading 'deficiency' indicate that the potassium supply should be improved. 'Normal' values are considered sufficient for full yield and quality, while 'surplus' indicates that there is luxury consumption and that the level of K fertiliser could be reduced.

3.5 Ability to utilise soil potassium

Generally, root crops are grown on soils which have some reserve of potassium held in non-exchangeable form. Potassium is slowly released by weathering into a plant-available form and the crop's roots are not without influence on the release process. Young soils may contain easily weathered minerals rich in potassium and on such soils even root crops, with their high total potassium demand and high rate requirements, may be able to obtain their requirements from soil sources alone. However, such conditions are very rare and in any more or less intensive cropping systems where yields are maintained at a high level the full yield potential cannot be realised if reliance is placed on soil potassium alone and the crops will respond to potassium fertiliser.

Crops vary in their ability to exploit the potassium reserves of the soil. Those which are able to deplete soil potassium in this way are said to be non-demanding. Thus the cassava crop is often said to have a low potassium demand. This may be superficially true if the farmer is content with low yields but if anything approaching the full potential yield is to be achieved none of the root crops would fall into the low nutrient demand category. In comparison with the *Graminae* their ability to exploit soil potassium is weak while their total K need and rate requirement are much higher. However, the root crops do vary in their ability to exploit soil potassium and, in this respect, cassava may be relatively efficient, though few experimental data are available on this point. Among the temperate root crops the potato is a particularly ineffective exploiter of soil potassium; it requires an ample supply of soluble or exchangeable potassium in the soil, which can only be ensured by applying potassium fertiliser.

3.6 Potassium fertilisation of root crops

There is no difficulty in estimating the total potassium requirement of a crop from total yield (roots+tops). Neither is it difficult to determine its rate requirements. However, because the soil is normally able to provide some potassium to the crop, such determinations are not accurate measures of potassium fertiliser need which is given by the difference between total requirement and soil supply. Because the soil is a dynamic and flexible pool of potassium, the proper level of fertiliser can only be arrived at by taking into account the potassium balance of the cropping system over the long term. Return of K to the soil in crop residues and farmyard manure must be included in the balance.

On the other hand, it may sometimes – for example on potassium-fixing soils – be necessary to improve soil potassium supply by applying potassium in excess of crop requirements over an appropriate period. Normally, though, the fertiliser recommendation would be somewhat less than the total potassium requirement of the crop and, in intensive agriculture, it would be from one quarter to one half of the total requirement.

Soil is complicated and variable and, in practice, fertiliser recommendations are mainly based on empirical field experiments testing varying rates of fertiliser under specific soil conditions. In a broad review of the present kind it is not possible to delve into the vast amount of such data available and, in any case, the temptation to generalise from such data should be resisted. In general it is true to say that the root crops, which have a high yield potential and high potassium requirement in terms of both total amount and rate in comparison with most other crops, require abundant potassium fertiliser.

It is important to be aware of the cation balance needed by the root crops and to add fertilisers containing balancing ions. In the first place this applies to magnesium. Heavy dressing of potassium often calls for an intensification of the magnesium supply. Sugar beet and other crops of the *Chenopodiaceae* require sodium, and sodium-potassium relationships have attracted special consideration *(Marschner [1971])*. To some extent the two cations are interchangeable but potassium cannot be entirely replaced by sodium and some potassium should always be applied.

There is no great difference in efficiency between potassium chloride and potassium sulphate so that, except in special circumstances, *e.g.* potatoes grown for processing, chloride is to be preferred on grounds of cost. The chloride anion, being very mobile in the soil solution and easily taken up by the root crops (luxury consumption), leads to a higher potassium uptake than does the sulphate anion. This may result in luxury consumption of chloride and also, to some extent, of potassium so that potassium chloride fertiliser may depress the dry matter and carbohydrate contents of the root crop and thereby lower its quality. The potato crop is known to react unfavourably to potassium chloride fertiliser and for this crop potassium sulphate is usually recommended. It should also be stressed that sulphur is a major plant nutrient and, especially under humid tropical conditions, the use of potassium sulphate may have a clear beneficial effect not shown by the chloride in relieving sulphur deficiency in the crop *(Ngongi et al. [1976])*.

3.7 Root crops and fertiliser policy for the rotation

While, at least in advanced agricultural systems, individual crops are monocultures with specific requirements for fertilisers and other inputs, each individual crop is only a unit in the agricultural ecosystem. Rotational cropping is designed to suit the prevailing conditions of climate and soil, to satisfy biological considerations and to be technically and economically sound. From this point of view the individual crops must always be treated as integral parts of the whole production system.

This means that the fertilisation of the individual crop must be adapted to the nutrient requirements and nutrient balance of the whole system. Of course, the main aim will always be to meet the specific nutritional requirements of the individual plants making up the crop, but this must be done within a framework constituting rational fertilisation of the whole rotation and involves consideration of long term and residual effects. The fertiliser programme must provide the correct nutrient balance for each crop and maintain or improve soil fertility. It must take account of nutrients in the cycle, in crop residues and farmyard manure. It must take into account cost-benefit relationships and the availability of labour and machinery. So far as potassium is concerned, root crops occupy a key position in the rotation because of their high potential productivity, their large nutrient requirements and their large contribution to the potassium cycle *via* crop residues. It is thus convenient and efficient to apply a large part of the total potassium requirement of the rotation to the root crop so that its needs are covered from the newly added source. The less potassium-demanding crops, mainly cereals, can then use the fertiliser residues from the root crop and may be able largely to satisfy their potassium needs from such sources. Such a system is easy to handle as well as labour-saving.

Normally potassium fertilisers should be worked into the soil before the planting of the root crop. As pointed out above, the potassium uptake runs ahead of the dry matter formation and, in the early stages of crop growth, it is important that potassium should be readily available in the top soil. Because of the slow movement of potassium in the soil, the whole potassium dressing should be applied before planting and top-dressing is inefficient. Especially under humid temperate conditions and where, as in potato growing, chloride may have indesirable effects, it may be advantageous to apply potassium chloride fertiliser in the autumn before planting the crop in the following spring so that excess Cl^- plus Ca^{2+} ions is leached by winter rain. Unless the soil is extremely light (poor in colloids) the potassium will remain within reach of the root system of the spring-sown crop.

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The Potassium Requirements of Fruit Crops

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1. General considerations

Fruit crops differ considerably from annual agricultural or horticultural crops with regard to mineral nutrition and its effects on yield and quality. Annual crops grow to maturity in a matter of months and it is relatively easy to carry out controlled experiments. Most fruit crops on the other hand are perennial and their growth cycles may be annual, biennial or poly-annual. It is much more difficult to study the physiological effects of the various nutrients in such crops, especially so in the case of field experiments. Among the various factors involved are: the duration of the vegetative cycle, the physical properties of the soil as they affect nutrient and water availability, and climatic factors. Further, the uptake of a nutrient is affected by interactions with other nutrients. It is self-evident that tests to determine the nutrient level requirements of fruit trees require periods of several years, in contrast with annual crops, where results can be obtained within a season.

Experimental data obtained in the international bibliography dealing with the nutrition of fruit in the traditional growing areas such as Europe, are few and fragmentary. In such areas, fertilisers are mainly applied according to empirical formulae established through long practical experience. However, the increasing specialisation and commercialisation of fruit growing demands more precise information on the nutrient needs of the different varieties. In recent years there has been much progress in plant analysis which has proved to be the quickest and surest means of determining nutrient level and its variation through the season, and it has been possible to establish critical values indicating sufficiency or deficiency of a particular nutrient. Most investigations of nutrient requirements made in the last twenty years have been based on leaf analysis, the results of which have been correlated with soil analysis.

It has been somewhat easier to obtain more precise indications in the case of the tropical non-woody fruits, where development is more rapid and nutrient turnover more easily related to cropping under the conditions of high temperature and rainfall applying in the areas where they are grown.

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We shall deal first with some general considerations before describing in more detail the individual needs of the main groups of fruit crops.

Under our climatic conditions, the effects of potassium in annual field crops are not so easily seen as are those of nitrogen. In contrast however, potassium effects on fruit trees are easily visible on the fruit in intensifying colour, increasing fruit size, producing a finer peel, etc. Such effects are easily demonstrated on K deficient soils. It is well known that potassium is an essential plant nutrient. In fruit the effect of potassium, unlike that of nitrogen or phosphorus, is mainly shown in fruit quality rather than in yield.

Qualitative parameters are difficult to define and measure. Potassium is particularly valuable in compensating for the adverse effects on quality of excess of other nutrients. This is particularly true in the case of nitrogen, which adversely affects fruit flavour, colour, pulp strength and resistance to cold and pathogens. The beneficial effects of potassium are especially seen when tree fruits have received too high applications of nitrogen.

When working with annual crops, it is easy to determine accurately the amounts of nutrient taken up because almost the whole of the aerial portion of the plant is removed from the field every year. With fruit trees, however, it is essentially only the fruit which is removed. Nutrients contained in the leaves and prunings are returned to the soil. Thus the nutrient requirements of fruit trees are usually related to the production of fruit and do not take account of the amounts involved in leaves or accumulated in the framework of the tree. The latter quantities can only be determined with difficulty.

Table 1 gives general mean values for the amounts of N, P and K removed per 10 tonne marketable produce per hectare for representative agricultural field crops, tree fruits and two non-woody tropical fruits. Apart from the latter, nutrient removal in harvested fruit is usually much lower than in the produce from annual crops – especially so in the case of potassium. Even if allowance is made for removals in leaves and prunings, the values will be only slightly increased and be less than those in annual crops. It is to be noted, however, that more potassium than nitrogen is contained in the fruits. This emphasises the relative importance of potassium in the nutrition of tree fruits.

Table 1. Nutrients removed (kg) in 10 tonne harvested produce of selected crops

Crop	Product	N	P	K	K:N
Wheat	10 t grain + 17 t straw	320	51.3	178.4	0.55
Maize	10 t grain + 18 t straw	250	50.6	262.0	1.05
Potatoes	10 t tubers	50	9.6	78.8	1.57
Sugar beet	10 t roots + 6.7 t tops	39	6.1	78.3	2.0
Apple	10 t fruit	65	8.4	68	1.05
Peach	10 t fruit	78	9	67	0.85
Grape	10 t fruit	80	13	82.9	1.03
Citrus	10 t fruit	25.8	2.2	30	1.16
Pineapple	10 t fruit	40.5	3.8	72	1.78
Banana	10 t fruit	64	4.6	185	2.89

The pattern of K uptake by fruit trees as shown by leaf analysis is similar in all the crops in that there is massive uptake in the pre-flowering period, following which there is a continuous decrease in leaf K content due to translocation from the leaves to other organs *(e.g.* the fruit). K is also lost from the leaves by leaching and from the roots.

Figure 1 illustrates the pattern of K uptake as shown by leaf analysis of the vine and accumulation in the grapes over the period May–October *(Lafon et al. [1964]).* Successional analysis of leaf samples does not of course give as complete a picture of K uptake as can be obtained in annual crops by whole plant analysis, but leaf levels are well related to optimum and deficiency conditions in plant nutrition and to fruit yield.

Soil analysis is essential before planting in order to determine the amounts of fertilisers which should be incorporated. This is especially important for potassium and also for those elements such as Ca and Mg which compete with K for uptake by the roots.

Cultural practices which affect root development are very important. Thus it is well known that mulching promotes root development so that uptake of minerals is improved as shown by increased leaf K content.

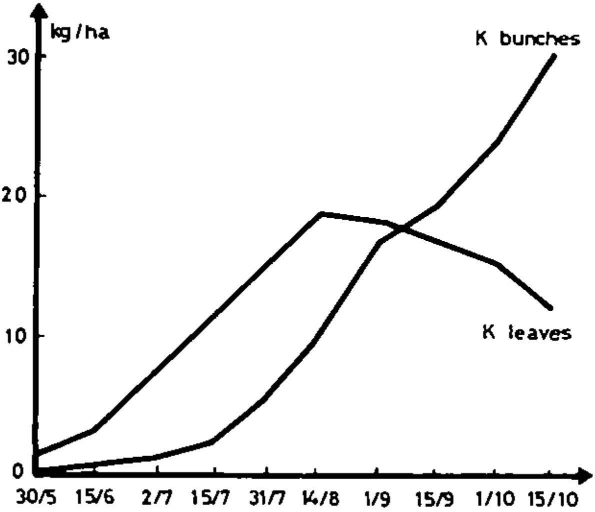

Fig. 1. K uptake by leaves and bunches of the vine over the period May–October *(Lafon et al. [1964])*

In the following more detailed consideration of fruit nutrient requirements, we shall limit ourselves to the four most important fruit crops of the Mediterranean and temperate regions and two tropical non-woody crops (pineapple and banana). Because of the interdependance between the individual nutrients, potassium will not be considered in isolation but in connection with P and, particularly, with N nutrition.

2. Apples

This is probably the fruit crop which has been most thoroughly investigated with regard to mineral nutrition. N and K are absorbed in approximately equal quantity by apples (K:N ratio 1:1.05 – Table 1) though the functions of the two elements are quite different as are their mobilities and final destinations within the plant. K is very mobile, but leaf K content remains steady during the summer, decreasing with the onset of fruit formation and at the end of the season due to migration and leaching from the leaves *(Boynton* and *Oberly [1966])*. It is not easy to establish critical leaf K levels for the apple because there is great variation between plants regardless of their nutrient status *(Cobianchi* and *Marro [1966])*. Again, leaf analysis can only give information about nutrient status during the summer months. There is a lack of information on nutrient uptake and mobility during the winter rest. Investigation of the effects of potassium fertiliser by means of leaf analysis during the past twenty years *(Cobianchi* and *Marro [ibid.])* have shown that K (and P) level depends more upon nitrogen fertilisation than on K (or P) fertilisation. Thus, there are records of K fertiliser having no effect on K content in the absence of N fertiliser *(Walker* and *Mason [1960])*.

With regard to fruit quality, the effect of K fertiliser is easily seen in K-deficient conditions when K fertiliser not only eliminates leaf scorch symptoms but also improves fruit colour and flavour, by increasing acidity. K has little effect on fruit storage of apples, though in other fruits it does improve keeping properties. A N:K ratio of 1:1 to 1:2 in the complete fertiliser is recommended *(Quidet* and *Richard [1964])* and a mean leaf K content of 1% of D.M. is regarded as optimum. It is to be noted that the leaves exhibit marked differences in nutrient status between years with heavy and light crops *(I.R.H.O. [1956])*. Yield increases due to an application of potassium as a sole fertiliser have been reported without any influence on leaf K content, which is only increased when N is also given *(Shadmi et al. [1966])*.

Stock characteristics greatly influence leaf K level *(Koo [1968])* which is lower with more vigorous stocks, presumably due to increased Ca-K antagonism. Excess K can induce deficiencies of other nutrients, notably Mg, K × Mg interaction being very evident.

3. Peach

As seen in Table 1, peach has a relatively high N requirement. But, leaf K content is higher in peach (mean 2.14%) than in apple (1.48%) *(Lalatta* and *Fontana [1960])*. The nutrient ratio for the peach is (N:P:K) 1:0.1:0.8, the K:N ratio being lower than for apple. Excess N reduces fruit colour by hindering the formation of anthocyanin, while K increases the colour intensity and improves fruit size *(Lalatta [1964])*. Adequate N is needed for growth, flower bud differentiation, fruit setting and yield, while potassium is needed for quality, regular ripening, taste (higher acidity and improved acid: sugar ratio) and improved resistance to adverse factors. Under K-deficient conditions, K fertiliser increases yield and, in such cases, the effect of K on quality is particularly marked *(Koo [ibid.])*. However, peach is often slow to react to K fertiliser and its effects are usually observed only after about five years from planting, when it increases number of fruit per tree and average weight per fruit.

Optimum leaf K level for peach lies between 2 and 3% of D.M., *i.e.* a higher level than for apple *(Balo et al. [1974])*. On K-deficient soils there is good correlation between leaf K level and K application. Also, when N fertiliser produces the main effect, the colour of skin and pulp is better the higher the K:N ratio in the leaf. Rootstock influences K uptake, though there is a lack of precise data in this respect. N-K, Ca-K and Mg-K antagonisms are all important in connection with nutrient deficiency, high K reducing uptake of the other cations.

4. Grapes

The grape, with the olive, is symbolic of Mediterranean agriculture; it is also one of the most thoroughly investigated crops from the point of view of nutrition. K is, for this crop, the dominant nutrient, not so much from the point of view of grape yield but rather for its influence on sugar content *(Depardon [1956])*. The N:P:K ratio shown in Table 1 indicates that K is predominant and that P is taken up in larger amount than by other fruit crops. Investigations on K nutrition have confirmed the influence of K supply on various metabolic processes. For example, *Bouard [1968]* showed that increased K content of the shoot is accompanied by increased photosynthetic activity through which the number of fruit per plant is increased. K has a dual effect on the vine, directly influencing the quality of the grapes and indirectly influencing the quality of the wine. Both effects are favourable, mainly due to the element's function as an enzymatic activator. Potassium clearly improves frost resistance.

Recent leaf analysis studies have confirmed *(Crescimanno [1973])* that, during the period May to October, K content decreases from a maximum value of 0.96% to half this value while N and P content fall similarly. The main fall in K content is between fruit set and maturity. The opposite trend is seen in Mg and Ca contents, the Ca content being doubled (4%) at the end of growth. There is naturally variation in these values between cultivars and rootstocks. Mean leaf K contents vary from 0.75–1.05% K between rootstocks, while N varies between 2.15 and 2.50 and P between 0.39 and 0.49 *(Kozma* and *Polyak [1964])*.

5. Citrus

Most of the work on this group has been done with oranges, results for which are regarded as being applicable, with few reservations, to grapefruits, lemons and mandarins. These crops are more demanding culturally than the preceding crops; the K:N ratio for uptake (Table 1) is slightly higher than for the other crops, though there is some variation between crops and cultivars. The effect of potassium is very much dependent upon nitrogen level, and K effects should always be considered in relation to N nutrition because of the interrelation of N and K in metabolism and hence in yield and quality. Except under conditions of K deficiency it is difficult sometimes, even over several years, to see any effects of potassium on yields of fruit *(Funabiki* and *Sakamoto [1968])*.

Increased K uptake by oranges results in increased fruit size due to increased hydration of the tissues *(Boynton* and *Oberly [1966])*. K favours the acid: sugar ratio and this is particularly true for lemons, where K fertiliser can increase acid content by 15% *(Koo [1963])*. Too high potassium can cause Mg and Ca deficiency and also Mn and Zn deficiency. Potassium-deficient trees produce small fruit and show premature fruit drop which will be evident before K deficiency is recognised from leaf chlorosis and necrosis; in K deficiency fruit matures early, root development is impeded and the trees are more susceptible to disease. K is directly correlated with vitamin C content. Optimum K nutrition gives lemons better resistance to adverse conditions, makes the peel thinner and gives a brighter colour *(Crescimanno [1961])*. During growth, the K content of the fruit is higher than N content and both increase steadily up to maturity.

Leaf analysis puts the critical K content at 1.1 to 1.2% below which level the tree will respond to K fertiliser. The limiting value for grapefruit is higher (1.45–1.55%) *(Koo* and *Reese [1973])*. For orange the optimum level is 1.2–1.7% of D.M. As in other tree crops, leaf K content decreases steadily from flowering time to ripening of the fruit. K absorption is at a low level in winter and takes place mostly from March to November. During the autumn the leaves lose up to 60% of their K which migrates to both the fruit and woody tissues *(Cohen [1976])*.

6. Pineapple

This non-woody tropical crop begins to yield one year after planting. The nutrient removals in Table 1 refer to entire plants producing 10 tonne fruit of average size 2 kg. The crop has a high K requirement. Large amounts of K are translocated to the fruit in line with D.M. accumulation and there stored. The root system is confined to the surface soil layers and thus explores only a limited volume of soil. The result is that K fertiliser is effective even on soils well supplied with potassium. It is, thus, easy to understand that K is the fundamental nutrient for this tropical fruit. It balances the unfavourables effects of nitrogen increasing fruit acidity which decreases at low K:N ratios. Pulp consistency and transportability of the fruit is also improved.

On low K soils there is a direct relation between K fertiliser application and yield and K has an effect on quality even beyond the stage at which there is no further increase in yield *(de Geus [1973])*. Excessive K may cause too high acidity of the fruit and can lead to Mg deficiency. Optimum N:K ratios in the fertiliser vary from 1:1.5 on high K soils to 1:2 on low K soils. Fertilisers have to be applied at high rates (more than needed to replace crop removal and leaching losses) both for yield and in order to secure fruit of good quality *(Su [1969])*.

Foliar analysis has been used in this crop to study patterns of nutrient uptake. Leaf K content rises up to flowering time; when fruit are set K migrates from the leaves to the fruit, higher amounts being translocated at high rates of fertiliser *(Lacoeuilhe [1973])*.

7. Banana

This is the most widespread of tropical fruits. It is a perennial monocotyledon with an annual fruiting cycle. Most of the roots are found in the surface layers of the soil and the roots are little branched. Nutrient requirements are high, especially for potassium, as shown in Table 1. The crop requires well-drained soil of good structure, high in organic matter and with good levels af available nutrients. Fertiliser application rates are high and have to take into account leaching losses in the rainy season. Nitrogen undoubtedly stimulates vegetative growth, thereby creating an additional need for K. The desirable K:N ratio is 3, higher than for the other crops considered. K uptake measured by leaf analysis proceeds in step with dry matter production, reaching a peak at flowering, after which K content of the leaf falls, due to translocation to the developing fruit. Balanced nutrition is particulalry important for this crop, which is very sensitive to excess and deficiency. Leaf development is great and some of the earliest work on leaf analysis was done with banana *(Hewitt [1955])*. It appears that the optimum K level is between 4.2 and 4.5% in D.M. *(Jambulingam et al. [1975])*, while the critical level is 2.7% *(Prévot* and *Ollagnier [1958])*. Leaf analysis has been a valuable tool in controlling fertiliser application to the best effect *(Martin-Prével [1970])*.

This crop has a high K demand *(Twyford* and *Walmsley [1974])* and leaching losses are high on most of the soils where it is grown – K deficiency is more usual than K excess. Deficiency shows in yellowing of the leaf lamina with necrotic spots and a slowing of growth. Excess of K may depress Ca and Mg uptake. At optimal rates, K speeds up flower initiation and ripening of fruit and increases both number of bunches and hands per bunch. It improves the acid: sugar ratio and storage properties of the fruit and improves resistance to disease. One of the effects of K deficiency worthy of particular mention is that of premature yellowing of the fruit pulp, which can also be due to excess Ca or Mg *(Melin [1971], Echeverri-Lopez* and *Garcia-Reyes [1976])*.

8. Conclusion

This short and very limited report underlines the importance of potassium in fruit nutrition for both tree crops and non-woody plants. In the limited selection of crops reviewed, the pattern of K uptake is remarkable similar. It can be studied by means of leaf analysis and it would seem that the results reviewed here could be extended to other similar crops. Potassium has a particular beneficial effect upon fruit quality.

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Potassium Requirements of some Tropical Tree Crops (Oil Palm, Coconut Palm, Rubber, Coffee, Cocoa)

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1. Introduction

The seed based 'Green Revolution' has received wide publicity and has been considered the 'most exciting development story of the past two decades'. By comparison, very little is known about recent developments that have taken place in the breeding and agronomy of tropical industrial crops such as oil palm, coconut, rubber, coffee, cocoa, tea, cotton, etc. Unlike rice, where the yield potential, developed by the breeder and demonstrated by the agronomist, has rarely been properly utilised by the farmer, potential gains in genetics and agronomy have been immediately translated into actual production by most growers of commercial tree crops in the tropics.

Potassium is required by most plants in amounts greater than any other nutrient but supply from natural sources is limited. Potash fertiliser has little practical importance in crop production as long as yields are low but it becomes a key production component when yields are high.

Though the tree crops covered in this paper are botanically different, all tropical tree crops have certain characteristics in common that separate them clearly from annual crops.

1. Provided that water supply is adequate, photosynthesis, growth and production goes on uninterrupted for 365 days of the year. (With the exception of rubber.)
2. Roots of tree crops are coarser, less evenly distributed and less efficient in utilising nutrients in the top soil than roots of most closely spaced annual crops.
3. Roots of tree crops can make better use of water and nutrient resources of the sub-soil.
4. Tree crops are often grown on soils not suitable for annual crops for reasons of topography (erosion), depth of surface soil (unsuitable for ploughing), water holding capacity of the top soil, etc. Such soils are often of low fertility.

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5. As soils under tree crops cannot be ploughed regularly, corrections of structural and chemical deficiencies are more difficult than on arable land. For the same reason, fertilisers cannot be distributed and mixed as evenly within the top soil.
6. As a general rule, tree crops are less sensitive to phosphate (and nitrogen) deficiency and more sensitive to magnesium (and potash) deficiency than annual crops would be on the same soil.

Potassium requirements of some tropical tree crops

2. The Oil Palm

2.1 General

In terms of oil output per unit area, modern D × P (*Dura × Pisifera)* oil palm hybrids dwarf all other oil crops, though in the future hybrid coconuts will become a close second. Current yields of various edible oil crops are shown in Table 1.

Table 1. Yields of various oil crops

Crop	Oil kg/ha	Palm kernel oil kg/ha	Total oil kg/ha
Cotton seed	190	–	190
Soybean	380	–	380
Rapeseed	420	–	420
Sunflower	620	–	620
Peanut	875	–	875
Coconut (average)	700	–	700
Coconut – Estate average	1255	–	1255
Coconut – Estate recorded	2690	–	2690
Coconut – Modern hybrids	5200	–	5200
Coconut – Future potential	6500	–	6500
Oil palm – Malaysian average	3700	410	4110
Oil palm – Malaysian recorded	8295	915	9210
Oil palm – Future Potential	11000	1200	12200

Source: Adapted from *Bek-Nielsen [1977]*

It is safe to assume that within this century oil yields of 10–12 tons or more will be achieved on the better estates. The current D × P hybrids will be augmented by clonal planting material obtained through cell culture. Oil quality (and yields) will be improved by crossing the *Tenera* hybrid with the South American *Elaeis oleifera (Melanococca)*. 40 years progress in oil palm breeding and agronomy is shown in Figure 1.

The biggest gains were made between 1960 and 1980; with a further quantum jump expected in the late nineties, once clonal planting material becomes available.

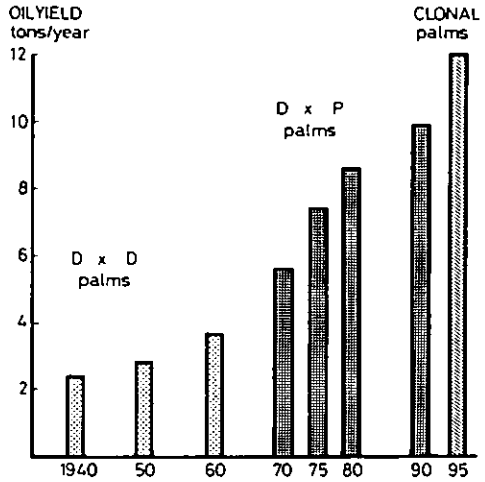


Fig. 1. Recorded and estimated progress in oil palm breeding and agronomy (Source: ***Bek-Nielsen*** *[1977])*

2.2 Potassium requirements of young palms

The oil palm comes into bearing 3 years after field planting. It used to be assumed that the main need in young palms was for nitrogen. Heavy potash application usually starts only after the third year when the trees come into production.
Recent studies *(Ng [1977])* showed that after the first year in the field there is a very steep increase in the potassuim demand (Figure 2). It is now clear that, in order

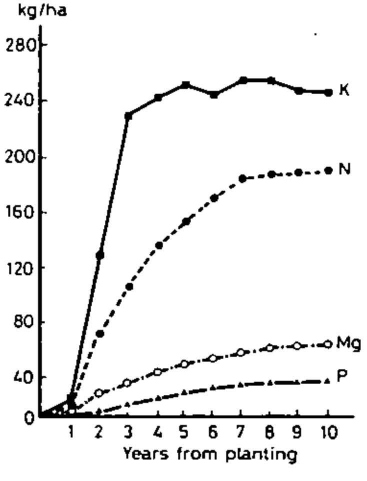


Fig. 2. Nutrient uptake of oil palms up to 10 years from planting (Source: *Ng [1977])*

to obtain high yields early, the young palm must be 'loaded' with potassium in the second year. It is not always easy to achieve this as the root system is not yet fully developed and as K uptake may be inhibited by lime and rock phosphate applied in the planting hole.

Young palms have less storage capacity in the trunk than old palms and consequently they need higher K levels in their tissues to produce a heavy crop. A dramatic example of what can be done by a combination of breeding, good culture and correct fertiliser application is shown in Figure 3, depicting the actual yields obtained at United Plantations in Malaysia in the first 3 harvest years. The 1962 plantings yielded only 5 tons of fresh fruit bunches/ha (FFB/ha) or about 1 ton of oil/ha. The 1974 planting yielded over 25 tons of fresh fruit bunches/ha in the first year of harvest (over 5 tons of oil/ha). Apart from improvements in the genetic make-up of the 1974 plantings, a better understanding of the oil palm's early nutrient requirements has contributed much towards this 5-fold increase in the first year's yield.

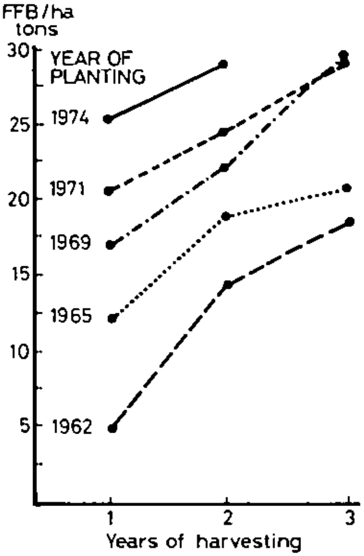


Fig. 3. Recorded yield from D × P oil palms with harvesting commencing 36 months from planting (Source: *Bek-Nielsen [1977]*)

2.3 Role of K in adult palms

The oil palm appears to partition its assimilates in favour of vegetative growth. If lack of potassium limits total photosynthesis and translocation, vegetative growth continues at the expense of bunch production *[Ng (1977])*. There is very little difference in vegetative growth between West Africa (low K soils, lower solar radiation) and Malaysia. In terms of yield per unit area, however, differences are very substantial. A palm under stress will produce more male inflorescences, fruit bunches produced will be fewer in number and smaller in size. A limited carbohydrate supply may eventually cause abortion of fruit bunches. This feature is unfortunate as it does not provide any early warning because damage has been done before corrective measures can be taken *(Ng [1976])*.

2.4 Leaf potassium levels

As the oil palm produces leaves and fruit in a regular pattern throughout the year (provided there is no distinct dry season), leaf K usually provides a reasonably accurate guide to the K status of the palm. Currently, the following 'guideline' levels are widely used (Table 2).

Table 2. Guideline K-levels in young and mature oil palms (% K in leaflets from frond No. 17)

Type of soil	Young mature palm	Mature palm
(Rich) Alluvial clays and clay loams	0.95–1.05	0.85–0.95
Non-alluvial clays and clay loams	1.10–1.20	1.00–1.10

'Critical' leaf K levels vary with the age of the palm, the type of soil, the climate, the levels of other nutrients present, etc., and it requires long practical experience to 'read' nutrient levels correctly. *Prévot* and *Ollagnier [1961]* showed that there was a positive correlation between K levels and yield only when leaf N levels had reached 2.70%. There are similar relationships between K and other nutrients *(Hartley [1977])*. *Ruer [1966]* showed that the 'effective sunshine factor' and other climatic factors affected 'critical' K levels (Table 3).

Table 3. K-levels as affected by effective sunshine hours

	Malaysia	Ivory Coast	Benin
% K in frond No. 17........................	1.2–1.3	1.0	0.7–0.8
Effective sunshine hours	Over 1800	1600	Dry climate

It can be assumed from existing data that higher K levels will be needed in areas where climatic conditions permit high yields (no or little moisture stress) and adequate sunshine (2000 or more hours/year). Apart from the 'climatic yield potential factor', 'critical' K levels will depend on the pool of readily available K the plant can draw upon. This includes K in the trunk, K in the soil solution, soil K intensity and quantity factors and fertiliser K. The smaller the total pool, the higher the 'critical' K level is expected to be.

2.5 Lowering of leaf K by K fertiliser application

On certain soils (usually oxysols derived from volcanic material) it is very difficult to raise leaf K. It has often been observed that application of potassium chloride significantly decreased leaf K while increasing leaf Ca and leaf Cl *(Ollagnier [1973])*. *Ollagnier [1973]* and *Ochs* and *Olivin [1976]* suggested that the decrease in frond K following the application of muriate of potash may be related to the mobilisation of soil calcium. In *Breure* and *Rosenquist's* (Table 4) experiment application of KCl increased exchangeable soil K and decreased soil Ca. Yet K in the level decreased while Ca increased.

Table 4. Effect of potassium chloride on yield, leaf K, Ca, Cl and B on a young volcanic soil *(Breure* and *Rosenquist)* (Frond 17, April 1975)

Treatment (kg KCl/palm)	Yield, FFB 10.71–R. 75 tons/ha/year	Nutrients in % or ppm OM			
		K	Ca	Cl	B
		Frond No. 17, April 1975			
0	17.48	0.811	0.92	0.34	11.3
1.50	17.83	0.773**	0.98*	0.48***	10.5*
3.00	19.18**	0.766**	0.96	0.53***	10.2**
4.50	19.08**	0.751**	1.05**	0.56***	9.8**
MSD 5%	1.07	0.03	0.06	0.05	0.8

2.6 Potassium fertiliser application rates

Rates of potash fertiliser application will of course vary widely according to soil, climate (sunshine hours and water supply), and genetic quality of the plants. Application rates for high yield normally range as follows:

	Years from planting in the field (143 palms/ha)			
	1	2	3	Over 3
kg K/ha	37–50	83–200	166–250	166–290

On deficient soils much higher rates are often used. In extreme cases, up to 800 kg K/ha have been applied in order fully to realise production potential. Such heavy rates are sometimes needed to correct deficiencies and/or imbalances but they should not be maintained for long as it is likely that such high rates of nutrient input may induce nutrient imbalances (especially N, P, Mg, B and Ca).

The higher the yield the more important nutrient balance becomes. Potassium applied at more than 210 kg K/ha, normally more than the removal, may appear excessive but the active root surface does not usually expand in proportion to the yield potential. The rate of nutrient uptake per unit root surface must therefore increase and this is possible only if the nutrient concentration in the soil solution around the roots is increased. It is inevitable that leaching losses will also increase.

For low to medium yields, on the other hand, it is not sound practice to replace all the nutrients removed by the crop. The relationships between nutrient uptake, nutrient removal and nutrient replacement needs are shown in Figure 4.

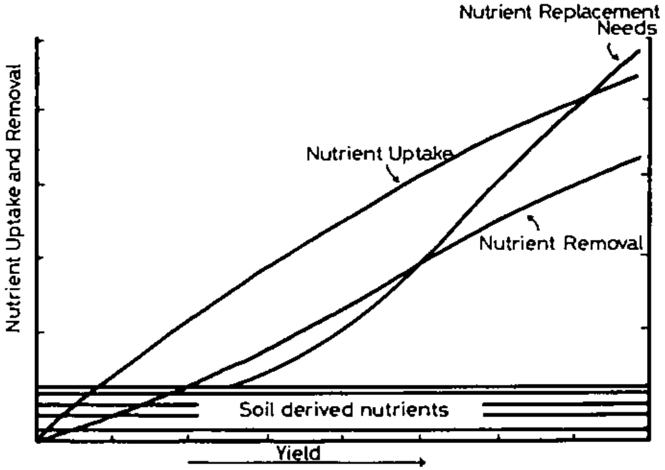


Fig. 4. Nutrient uptake, removal and replacement needs as affected by increasing yield levels

3. The Coconut

3.1 General

Until recently the coconut was a 'sleeping beauty', usually grown without any care as the 'lazy man's crop'. Although potassium has long been recognised as the most widely needed element for coconuts *(Habord [1913], Lyke [1915], Georgi* and *Teik [1932], Foster [1937], Salgado [1946], Menon et al. [1958], Fremond et al. [1966]).* the use of potash fertiliser remained low.

The traditional tall coconut is a slow maturing tree that is also slow to respond to improvements in its environment. A new chapter for the coconut has begun with the rapid spread of hybrids. Though hybrid vigour in coconuts was recognised a long time ago *(Patel [1937, 1938], Rao et al. [1952])*, it is only the recent breeding work pioneered by IRHO that has resulted in worldwide recognition of the superiority of the hybrids.

While the traditional tall coconut tree usually comes into bearing 6–9 years after field planing and reaches full bearing age at 12–15 years, modern hybrids commence bearing in the 4th year and reach full bearing in the 7th year. Moreover, they produce 2–3 times more nuts than the unimproved talls. In the very near future, copra yields of over 10 tonnes/ha appear to be well within reach *(Frémond [1978]).* It is obvious that for such high yield nutrient requirements will be very high. There is still little research data on hybrid coconuts and the following discussion is based mainly on results with the traditional type of tree.

3.2 Nutrient removal

Nutrient removal by coconuts has been estimated by *Georgi* and *Teik [1932]* as follows (Table 5):

Table 5. Removal of nutrient, kg/ha (tall type, 7400 nuts/ha)

Part of palm	N	P	K	Ca	Mg
Fronds	30–48	4.4–11	15–65	2–18	2.4–25
Inflorescence	2–3	0.4	7–16	0.7	0.6–2
Nuts	31–39	5.7–8	60–170	0.7–2.9	2.4–5.4
Total	63–90	10.5–19	81–250	3.5–22	5.4–32

Very similar removal figures have been reported from India *(Thampan [1970])* and from East Africa *(Copland [1931])* and many others, *(Ramadasan* and *Lal [1966])*. Recently a very comprehensive study on the nutrient removal of high-yielding 'MAWA' hybrids has been made in the Ivory Coast *(Ouvrier* and *Ochs [1978])*. For the first time chlorine was included (Table 6).

Table 6. Nutrient removal of high-yielding hybrid coconuts, kg/ha (138 bearing trees yielding 6700 kg copra/ha)

Component	Dry weight kg	N	P	K	Ca	Mg	Cl	S
Spikelet	0.492	3	0.4	14.0	2.0	2.0	11	1.0
Stalk	0.349	1	0.13	7.0	0.3	1.0	6	tr.
Husk	7.843	19	1.0	116.1	5.0	4.0	92	1.0
Shell	3.849	5	0.13	9.0	1.0	0.4	4	0.5
Albumen	6.375	80	13.0	47.0	1.0	8.0	12	6.0
Total	18.908	108	14.7	193.1	9.3	15.4	125	8.5

Our own data suggest that, as a rule of thumb, it can be assumed that around 10.5 g K are lost and immobilised for every nut harvested. On this basis K removal and replacement needs have been calculated as follows (Table 7):
It will be noted that low yields (below 40 nuts/tree/year) can usually be sustained without the need to replace the potassium removed. At about 150 nuts/tree yields can usually only be maintained if the total amount removed is replaced. At the highest yield levels application should exceed actual removal because applied K is used less efficiently at that level and K concentration in the soil solution should be raised.

Table 7. Potassium removal and replacement needs at different yield levels

Number of nuts per tree/year	Number of nuts/ha*	Copra yield kg/ha**	K removal kg/ha***	K replacement need, kg/ha****	kg K per tree
25 Ordinary	3 500	980	37	–	–
50 tall	7 000	1960	75	33	0.23
100	14 000	3920	145	100	0.70
150 Hybrid	21 000	5880	216	208	1.5
200	28 000	7840	290	324	2.3
250	35 000	9800	365	456	3.2

* 140 palms/ha (9 × 9 triangular)
** 280 g of copra/nut
*** 10.4 g K per harvested nut
**** Assuming 42 kg K/ha continuous supply from an 'average' soil and decreasing efficiency in utilisation of applied fertiliser K as replacement needs increase

3.3 Effects of potassium on young trees

As in the oil palm, vegetative production appears to have priority over dry matter storage in the inflorescence and nuts. A slight K shortage will therefore first affect nut size, then nut number and finally vegetative growth. With severe K deficiency the rate of new leaf production is reduced, leaves are smaller (fewer and shorter leaflets) and leaf duration is less. Young palms ill supplied with K take much longer to develop a trunk and to come into bearing.

The trunk of a palm grown under conditions of K deficiency is slender with the leaf scars close to each other, a sign of slow growth. Palms will never fully recover from early K deficiency even if it is corrected later. *Frémond* and *Ouvrier [1972]* in the Ivory Coast tested the effect of withholding potassium on the development of young palms (Table 8).

Table 8. Effects of time of first potash fertiliser application on the performance of young coconut palms *(Frémond* and *Ouvrier [1972])*

Year	Characteristics observed	Time of KCl application A from field planting	 B from bearing age only	B as % of A
1956	Number of fronds	8.89**	7.69	86.5
1958	Length of frond (cm)	256 **	223	87.1
1959	Circumference of trunk	124.1 **	105.4	69.9
1960	Number of fronds in one year	11.7 **	10.7	91.4
1962	Kg of copra/ha	944 ***	272	18.7
1966	Kg of copra/ha	2560 ***	2272	88.8
1970	Kg of copra/ha	2480 ***	2096	84.5
1961–1970	Cumulative yield, kg/ha	17344 ***	12704	73.2

Similar data were obtained in the Philippines, where the effect of fertilisers on vegetative growth and on early yield was tested (Table 9).

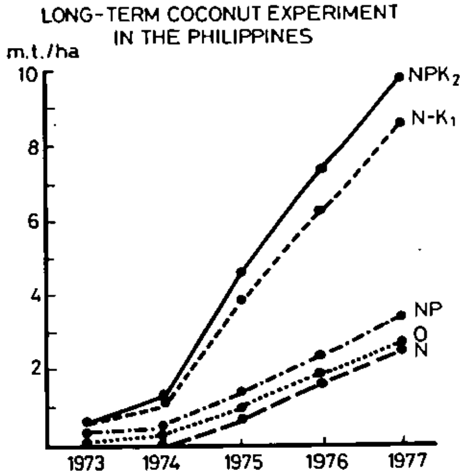
Table 9. Effect of different fertiliser treatments on vegetative growth and number and size of nuts

Grams of nutrient per tree and year:
N: 300 g. N as ammonium sulphate
P: 600 g. P_2O_5 as superphosphate
K_1: 500 g. K_2O as muriate of potash
K_2: 1000 g. K_2O as muriate of potash

Fertilizer treatment	Number of leaves in 4 years	Girth at 4 years	Height of trunk	Number of nuts in 5th year	Number of nuts in 9th year	Copra average weight/nut		Cumulative copra yield per tree, kg
						5th year	9th year	
Control	56	142	20.2	5.5	23.6	96	228	17.4
N	55	134	21.2	0.0	29.3	0	204	16.7
NP	58	142	31.7	5.3	30.7	65	217	20.7
NK	63	166	41.1	14.6	49.6	104	314	54.6
NPK	63	169	47.4	15.9	46.2	160	354	60.0

Source: Calculated from *Prudente et al. [1978]*

The effect of varying fertiliser treatment on cumulative yield is shown in Figure 5. Hybrid coconuts that commence bearing in the 4th year or even earlier should be 'loaded' with K (and other nutrients) before heavy fruiting starts. Leaf K dropped within one year from 1.8% K to 0.8% (frond No. 14) when hybrid coconuts came into bearing.



Fertiliser treatments (grams of nutrient per tree and year:
N: 300 g. N as ammonium sulphate
P: 600 g. P_2O_5 as superphosphate
K_1: 500 g. K_2O as muriate of potash
K_2: 1000 g. K_2O as muriate of potash

Fig.5. Cumulative copra yields per ha as affected by different fertiliser treatment (after *Mendoza et al. [1978]*)

3.4 'Critical' nutrient levels

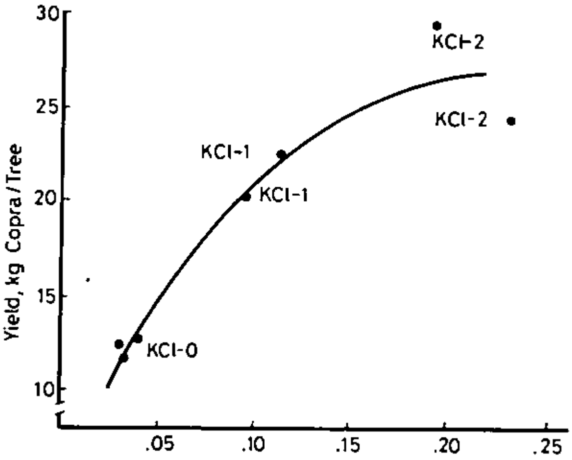
For adult trees the 'reference' leaf is the leaf or rank 14 and 'critical' levels currently used (IRHO) are:

N	P	K	Ca	Mg	Cl	Fe	Mn	B
		% in dry matter					ppm	
1.8–2.0	0.12	0.8–1.0	0.5	0.3	0.4	50	60	10

Similary to the oil palm, 'critical' K levels are higher for young than for old palms. It should be higher if the pool of available K is low and *vice versa.*

3.5 The role of chlorine

Ollagnier [1971], von Uexkull [1972], Mendoza and *Prudente [1972]* strongly suggest that chloride must be considered an essential *macro*-nutrient for coconuts. Chlorine deficiency appears to be widespread in many inland areas, especially on well-drained soils (volcanic soils). Many responses to applied potassium chloride may have been responses to both potassium and chloride. Chloride deficiency affects nut size, copra yield, nitrogen uptake and the water economy of the plant (Figure 6).



Fertiliser treatments (grams of nutrient per tree and year:
N: 300 g. N as ammonium sulphate
P: 600 g. P_2O_5 as superphosphate
K_1: 500 g. K_2O as muriate of potash
K_2: 1000 g. K_2O as muriate of potash

Fig. 6. Effect of three levels of potassium chloride on chlorine levels in frond No. 14 and on copra yield *(Uexkull [1972])*

3.6 The future

With the recent introduction of early maturing, high yielding hybrid coconuts, a new chapter in the production of vegetable oils has begun. Hybrid coconuts have the potential to produce 6 tons of oil/ha and plantation scale yields of 3–4 tons of oil/ha are within easy reach. Few other oil crops will be able to compete with the coconut and the oil palm and most of the future gains in vegetable oil production will come from these two crops. Potassium is the most important plant nutrient for both coconut and oil palm and for both, it is important to ensure good K nutrition in the early years.

4. Rubber

4.1 General

Latex is essentially a hydrocarbon compound containing only very small quantities of inorganic ingredients. The direct nutrient removal was therefore trifling in the early days of low-yielding seedling rubber. Early estimates put the nutrient removal at 3 kg/ha N, 0.5 kg P and 1.8 kg K/ha *(De Vries [1921])*.

As with most crops, potassium became a most important factor only when, as a result of a combination of breeding, agronomy (more intensive tapping) and crop physiology (stimulation), the potential and actual yields increased. They shot up from about 650 kg/ha dry rubber in the 1920's to over 5000 kg/ha today.

Early fertiliser trials showed little response to K and frequently even negative responses were reported *(Akhurst* and *Owen [1950], Owen et al. [1957])*.

On the basis of the low K removal in the latex and poor responses observed in the early experiments, it was concluded that:

a) rubber had a low K requirement *(Rhines et al. [1952])*; and
b) most mineral soils (in Malaysia) were adequately supplied with K *(Bolton [1966])*.

Early practice was to apply rock phosphate in the planting hole (and to the cover crop) and small dressings of N (ammonium sulphate) up to the early mature stage. Modern recommandations give the main emphasis to K.

Many factors have contributed to the rapid change in thinking about the proper potassium nutrition of the crop. They fall into 3 different groups:

Group 1. Those that increase yield and nutrient requirements.
  a) Changes from seedling to clonal rubber.
  b) Better clones.
  c) Better and more complex buddings.
  d) Better upkeep.
  e) More intensive tapping systems.
  f) Yield stimulation.

Group 2. Those that decrease soil K availability.
  a) Replanting.
  b) Rock phosphate and ammonium sulphate only applied in the past.

Group 3. The correction of other nutrient deficiencies.
- a) Mg deficiency.
- b) B deficiency.

The combined effect of the above is that, especially for wind-prone clones and for intensive exploitation with Ethrel stimulation, potassium has become the most critical element *(Chan et al. [1972], Puddy and Warrior [1960], Sivanadyan et al. [1972], Pushparajah et al. [1971])*.

The latest recommendations for smallholder's rubber in Malaysia range from 23–47 kg N, 0–57 kg P_2O_5 and 25–59 kg K_2O for wind-resistent clones and 15–22 kg N, 0–56 kg P_2O_5 and 30–70 kg K_2O for wind-prone clones *(Chan et al. [1972])*.

4.2 Sources of nutrient demand

Unless grown on very fertile soils (where normally more demanding crops like oil palm or cocoa are preferred), high-yielding rubber has a fertiliser demand that far exceeds the amount of nutrients removed with the latex. There are 4 reasons for this.

a. Nutrients immobilised in the trees

Very substantial quantities of nutrients are immobilised in the trunks and branches of rubber trees as shown below (Table 10):

Table 10. Nutrients immobilized in clone RRIM 600 *(Lim [1974])*

Age of trees month	Number of trees per ha	Nutrients immobilized			
		N	P	K	Mg
33	420	140	19	75	9
79	420	635	73	365	103
190	335	656	134	874	149

Large quantities are immobilised in the tree and less than 10% of the nutrients are contained in the green branches and leaves, *Shorrocks [1965]*, and this explains why potassium often becomes a critical factor on replanting.

b. Nutrients leached from leaves

Frequent heavy rains in the tropics leach considerable quantities of nutrients from the leaves. In Malaysia it has been found that with 2,540 mm of rain per annum, about 20 kg of K/ha can be leached out of the foliage of mature rubber *(Lim [1974])*.

c. Nutrients drained with the latex

Under 'normal' conditions the nutrient drain in the latex is small. Even with the yields of 2000 kg of dry rubber/ha, removal would be below 20 kg of K/ha, but nutrient removal increases steeply under yield stimulation. In extreme cases, where with stimulation yields of 5796 kg of dry rubber have been obtained in 10 months of tapping, removal in the latex reached 63 kg/ha *(Pushparajah et al. [1971])*. Stimulation decreases the D.R.C. (Dry Rubber Content) in the latex. As practically all potassium is contained in the serum, any yield increase as a result of stimulation will cause a very large increase in the removal of K as shown in Table 11.

Table 11. Nutrients drained on stimulation, clone RRIM 605, pannel B *(Pushparajah et al. [1971])*

Treatment	Yield kg/ha	relative	Nutrients drained, kg/ha and relative							
			N		P		K		Mg	
No stimulation	1454	100	7.6	100	1.7	100	5.1	100	2.1	100
2,4, 5-T (1%)......	1716	118	12.7	167	2.4	141	8.7	171	3.6	171
Ethrel* (10%)	2269	156	19.3	254	4.7	276	15.8	310	4.8	229

* 2-chloro-ethylphosphoric acid

d. Inhibited feeder root proliferation as a result of exploitation (tapping)

Tapping interferes with the normal flow of assimilates to the roots and thus increases the nutrient drain and, at the same time, decreases the active absorbing root surface area. Feeder root proliferation is particularly inhibited by Ethrel stimulation *(Haridas et al. [1975])*. To compensate for the poorer efficiency of the root system caused by intensive tapping, the K concentration in the soil solution must be increased.

4.3 Roles of potassium

4.3.1 Effects on early growth

Lack of K during early growth limits the active leaf area and reduces the photosynthetic activity of the foliage. As a result girth increases slowly and it takes the tree much longer to reach tapping age. Good management and proper fertiliser use can reduce the time to come into tapping to less than 3 ½ years *(Sivanadyan et al. [1975])*. Properly fertilised trees can be opened up at a smaller diameter as they continue to put on girth, even under tapping (Table 12).

Table 12. Effect of tapping and fertiliser on girth increments *(Sivanadyan et al. [1975])*

Treatment	Girth increment in cm (Oct. 71–May 75)			
	Tapped		Untapped	
Manured	1.2	100	2.0	100
Unmanured	1.8	150	2.4	120

4.3.2 Effects on bark thickness and quality

As latex is produced in the bark, good bark 'quality' is most important for sustained high yield. Recent work by *Pushparajah [1969]*, *Pushparajah et al. [1974]* and *Samsidar Hamzah [1975]* have shown that K significantly improved bark thickness (bark regeneration), phloem thickness, cell size, latex vessel size and number of latex vessels per unit bark.

4.3.3 Effect of potassium on latex flow and latex stability (latex quality)

By improving bark quality K also increases the flow rate of latex on tapping. It has also been found that K helps to prevent pre-coagulation of latex in the cup or on the tapping cut. Improvements in latex stability could be a direct effect of K or might be caused by lower Ca^{++} and Mg^{++} levels and relatively higher P levels in the latex. High Ca^{++} and Mg^{++} values are closely associated with unstable latex. Where precoagulation of latex occurred due to excessive application of magnesium or due to high soil Mg content, application of potassium has been shown to overcome this and to increase the yield. Potassium together with phosphorus has also been shown to improve the stability of stored concentrated latex.

4.3.4 Potassium and wind damage

Rosenquist [1960] was the first to suggest that severe wind damage might be associated with K deficiency. He showed that:

a) Nitrogen increased losses and this effect was related to leaf N content.
b) Rock phosphate increased losses, but this effect was not correlated with leaf P content.
c) Low leaf K was correlated with heavy losses. This does not necessarily imply that low potash was the cause of the losses.

Middelton et al. [1965], on the other hand, found that potassium reduced wood strength. Today, it is an accepted field practice to reduce nitrogen and increase potash for wind-prone clones.

4.3.5 Potassium and seed production

Watson et al. [1965] found that, when K increased yield, less seed was produced. There was an indication that this was associated with widening of the N/K ratio in the leaves. Heavy fruiting is often triggered by a stress situation. Low K and high nitrogen could cause (temporary) moisture stress or a stress in available carbohydrates; both might induce more profuse flowering and fruiting.

K-deficient trees tend to shed their leaves later and the 'wintering' period is longer than when K is adequate. Refoliation of trees with a good K-status is faster and more uniform and this could possibly affect flowering and fruiting.

4.3.6 Potassium and latex yield

As K has a pronounced positive effect on bark quality and latex stability, it follows that it also affects yield. Table 13 shows the effect of nitrogen and potash on girth and yield of young mature rubber grown on a Rengam series soil in Malaysia *(Pushparajah [1969])*.

Increasing the leaf nitrogen level from 3.19% to 3.46 at a K level of 1.35 increased the yield. Increasing leaf N from 3.22 to 3.38 with a leaf K of 0.8% decreased yield.

Recent investigations of the nutrient requirements of ethrel stimulated hevea have shown the need for adequate manuring under such intensive exploitation. Figure 7 shows the effect of supplementing the regular maintenance estate manuring with extra K on the response to ethrel stimulation.

Table 13. Girth and yield response of young rubber to N and K in West Malaysia (Experiment Se 1/21)

Treatment	Girth increment (cm in 6 years)	% K in leaves	Mean yield/tree/tapping (g) 1st year	3rd year	6th year	6 year average
N_0K_0	17.7	0.83	26.3	47.4	53.8	49.4
N_0K_2	20.4	1.48	26.0	48.2	55.1	52.2
N_2K_0	15.8	0.79	26.2	40.3	40.4	42.0
N_2K_2	20.7	1.25	23.2	50.5	66.0	57.3
S.E.	1.22	0.006	1.51	4.48	5.32	
Min.sig.diff. ($P < 0.05$)	3.7	0.19	0.19	13.5	16.0	

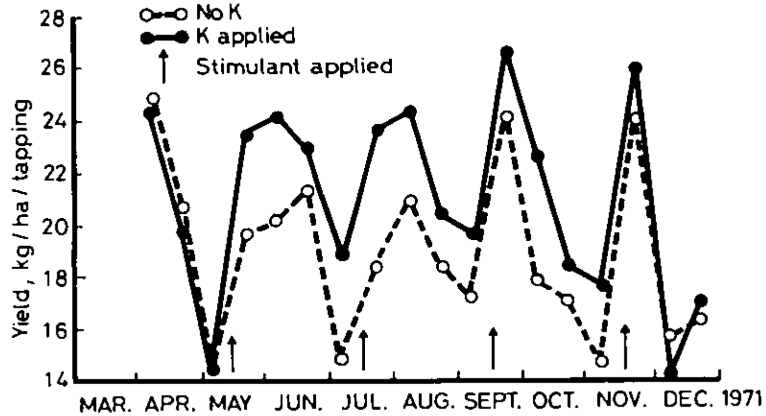


Fig. 7. Effect of potassium application on response to ethrel stimulation. (Expt. S 484/2, clone tjir 1, seedl. panel B) *(Sivanadyan et al. [1972])*

N and K are the main requirements of mature rubber which receives normal (NPKMg) maintenance fertiliser during the immature period. The effectiveness of N depends largely on adequacy of K and *vice versa.*

Current recommended maintenance dressings for young mature rubber on average Rengam series soil are 130 g N, 40 g P, 160 g K and 26 g Mg/tree and year. With a stand of 280 trees/ha, this would come to about 35 kg N, 11 kg P, 46 kg K and 7 kg Mg/ha.

4.4 Critical leaf – K levels

Leaf analysis is widely used to assess the nutritional status and fertiliser requirements of rubber *(Beaufils [1955], Cocci [1960], Shorrocks [1965], Guha [1969], Pushparajah et al. [1972]).*

The *Rubber Research Institute of Malaya [1963]* suggested the following 'critical' values for the major nutrients (Table 14).

Table 14. 'Critical' leaf nutrient contents of Hevea (expressed as percentage of oven-dry sample)

Nutrient	Nutrient level below which response likely		Nutrient level above which response unlikely	
	Leaves exposed to sunlight	Leaves in shade of canopy	Leaves exposed to sunlight	Leaves in shade of canopy
Nitrogen	3.20	3.30	3.60	3.70
Phosphorus	0.19	0.21	0.25	0.27
Potassium	1.00	1.30	1.40	1.50
Magnesium	0.23	0.25	–	0.28

Later, the above levels were found to be unsatisfactory for certain newer clones. PB 5/51, RRIM 600, GTI responded to K even when leaf K ranged from 1.5–1.8% (Table 15).

On the basis of such findings, fresh criteria have been adopted (Table 16).

Table 15. Response of clone PB5/51 to potassium in areas high in leaf potassium *(Pushparajah* and *Tan [1972])*

K-level kg K_2O/ha/year	% K in low shade leaves		5 year cumulative yield, dry rubber, kg/ha
	1967	1970	
0	1.71	1.90	6585
54	1.70	1.97	6890
102	1.76	2.15	7290
156	1.72	2.14	7780

Table 16. Range of K content in leaves at optimum age* in the shade of canopy (% K in dry matter)

Clone group**	Low	Medium	High	Very high
I	1.25	1.26–1.50	1.51–1.65	1.66
II	1.35	1.36–16.5	1.66–1.85	1.85

* About 100 days old

** Group I : 'Normal' clones
Group II: RRIM 600, PB 86, PB 5/51, GTI

4.5 Conclusion

The natural rubber industry has made tremendous advances in the past twenty years. These have made natural rubber more competitive. Over the same period, potassium has also become the most prominent major nutrient. Its importance will continue to grow as further progress is made in rubber breeding and agronomy.

5. Coffee

5.1 General

The need for potassium in coffee production was recognised as early as 1879 *(Hughes)* and fertilisers with high K content are used worldwide. *Anstead* and *Pittock [1913]* estimated that uptake appropriate to a crop of 5000 kg fresh cherries (about 1 tonne clean coffee) were about 100 kg N, 10.5 kg P and 125 kg K. *Mehlich [1966]* calculated the total nutrient requirements of 3 year old coffee (1330 trees/ha) yielding about 1250 kg dry beans/ha at 140 kg N, 14 kg P, 157 kg K and 20 kg Mg, and that about 35% of the K was contained in the fruit.

In contrast to the oil palm or the coconut, partition of assimilates is clearly in favour of the generative phase. Coffee tends to overbear, especially when grown without shade and with insufficient fertiliser. Such overbearing may cause patterns of alternate bearing, dieback or even death of the tree.

5.2 Potassium and physiological dieback

Heavy bearing branches carry a bundle of fruit of 30 cherries or more for every pair of leaves. *Roelofsen* and *Coolhaas [1940]* found that over 75% of all K, 60% of N, P and Mg of a fruit-bearing branch was accumulated in the ripening cherries.

Schweizer [1940] found that in non-bearing trees much of the K in the canopy moved into the branch tissue before the leaves became senile and were shed. Presence of fruits in healthy trees tended to increase K in the leaves of fruiting branches. During early ripening the fruit would draw heavily on the K contained in the leaves. On ripening some of the K would be returned to the leaves; the leaves would then remain green and healthy and would not be shed early. This is a precondition for a good following crop. In contrast, heavily laden branches with low leaf K would draw so much K from the leaves that photosynthesis and translocation of carbohydrates was impaired, causing early senescence and premature shedding of the older leaves and fruit. The drain of potassium into the fruits results in a narrowing of the K/Ca ratio in the leaves, causing them to age prematurely, to lose moisture, to develop marginal scorch and to drop. The rate of photosynthesis per unit leaf area decreases while the respiration rate increases, thus sharply reducing net assimilation *(von Uexkull [1968])*.

In extreme cases the carbohydrate exhaustion goes to the extent that the branch tissue collapses and dies. Before that happens, energy translocation into the roots will be impaired and parts of the roots may die. Trees whose root systems have been damaged as a result of overbearing (caused by potassium and nitrogen shortage) recover only slowly and often show as a secondary effect trace element deficiency symptoms (manganese, iron and zinc in particular) on their new flush.

K starvation in coffee can set in very quickly with a heavy crop and seemingly healthy trees may look miserable one month later. Because its effects on branches and roots are so severe, often causing death, severe K deficiency is not easily cured, will always cause severe crop losses and the trees may need two or more years to recover.

Potassium uptake consumes energy and the intensity of K uptake is closely related to the amount of 'available' carbohydrates in the plant. To be most beneficial, potash fertilisers should be applied when the leaf K is highest *(Busch [1956])*. According to *Wellman [1961]* 'the secret of coffee production is obviously related to the encouragement of absorption of potassium and nitrogen into the leaves aiding in photosynthetic activities and starch accumulation of the leaves...'

Beaumont [1939] found that the relative length of terminal growth was an accurate index of crop expectation in the following year and *Cooil et al. [1948]* showed that in Hawaii the length of terminal growth was highly positively correlated with leaf K concentration during August/September. Problems of overbearing and physiological dieback rarely occur where coffee is grown under shade – and where yields are much lower.

5.3 Potassium and yield

As with most other crops, potassium grows in importance as yields increase. Adequate K is essential not only to prevent dieback or alternate bearing patterns but also for sustained yield and here potassium is considered to be a dominant factor *(van Direndonk [1959])*.

A progressive plantation in Papua New Guinea, aiming at 3.7–4.9 t/ha made coffee, recently started a fertiliser programme consisting of 5 alternate applications of 16–0–24 and 12–12–17–2 compound fertiliser, supplying a total of about 685 kg N, 95 kg P and 790 kg K. Additional magnesium may be needed to balance the high levels of N and K input. In Papua New Guinea the most popular coffee 'mix' is a 10–3–20–4 (NPKMg fertiliser). Other common formulas used are 10–5–20, 12–12–17–2, 16–0–24, 15-10-20, 12–10–20 ($N:P_2O_5:K_2O:MgO$) etc.

High yields are only possible when coffee is grown unshaded or under very light shade. The combination of high photosynthetic activity and temporary moisture stress seems to stimulate fruiting to the extent of overbearing. Cultivation of coffee without shade requires skilful soil management (water conservation) and constant attention to nutrition. But the rewards are continued heavy crops.

5.4 Leaf potassium and yield

Leaf K level and yield have been found to be closely related, provided other factors are not limiting. Leaf K content can vary from below 0.3% to over 3%. The optimum cation balance for Robusta coffee appears to be between 46 : 42 : 12 and 50 : 38 : 12 (K : Ca : Mg) *(Loué [1958])*. The sum of the 3 cations is fairly constant at 3.8% dry matter so the optimum K concentration would be in the range of 1.75–1.90%. Similar figures were given by *Haag* and *Malavolta [1960]*, though many workers still consider K levels of 2.3–2.7 to be 'medium', 'normal' or 'desirable'.

K-deficiency symptoms may also show up when leaf K drops below 1.1% but the appearance of symptoms much depends on the presence of the other nutrients, on water stress and other factors. *Malavolta et al. [1962]* showed that when N was applied alone K-deficiency symptoms appeared at much higher leaf K values than with a N-P treatment (Table 17).

This shows that care is needed in establishing 'critical' leaf nutrient values. A coffee tree may look perfectly healthy and may not respond to potassium at leaf K levels of 1.2%. Under other conditions, responses may be obtained at leaf K levels of 2.5 or more (Figure 8) which many would consider excessive.

Table 17. K and Mg content of coffee leaves associated with deficiency symptoms under different fertiliser treatment

Treatment	Symptom	K	Mg
Nitrogen	None	1.38	0.28
	Slight marginal chlorosis	1.07	0.29
	Brownish rim	0.98	0.30
	Necrosis	0.88	0.31
Nitrogen + Phosphorus	None	0.63	0.37
	Slight marginal chlorosis	0.56	0.39
	Brownish rim	0.56	0.40
	Necrosis	0.29	0.44

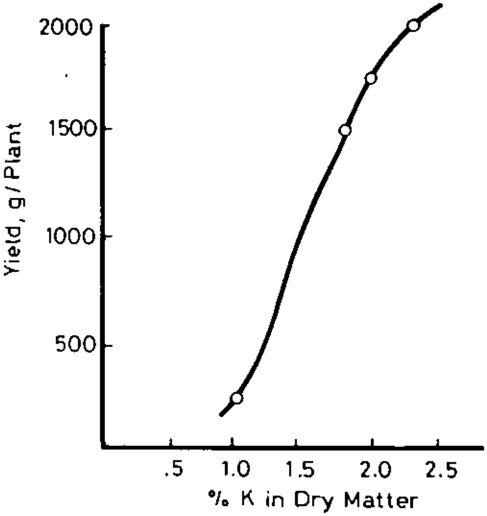


Fig. 8. Relationship between leaf K and yield of Arabica coffee (from *Medcalf et al. [1955]*)

5.5 Conclusion

Potassium (fertiliser) will become increasingly important in the future for a number of reasons. The following factors will contribute to the rapidly growing role of potassium in coffee production.

a) The rapid disappearance of fertile, virgin soils suitable for coffee cultivation.
b) Increasing land and labour costs that make coffee cultivation profitable only if high yields are obtained.
c) Changes from shaded to unshaded cultivation.
d) Introduction of high-yielding, fertiliser-demanding clones and hybrids (*arabica* × *robusta* for example).
e) A growing worldwide demand for coffee.

6. Cocoa

6.1 General

Cacao's natural habitat is the tropical rain forest of Central and South America where it grows along rivers under the canopy of taller trees. The tree is physiologically very fragile, having a shallow root system only moderately efficient in utilising soil moisture and nutrients, and leaves with a rather high transpiration quotient.
Lemée [1965] showed that photosynthesis, growth and transpiration are markedly reduced when the availability of soil moisture drops to 60—70%. If cocoa leaves lose about $^1/_6$ of their water content, necrotic areas resembling potassium deficiency develop *(Alvim [1965])*. According to *Murray* and *Maliphant [1965]* the tolerable range in nutrient levels is more restricted in cocoa than in other crops. Small imbalances may lead to premature leaf fall.

Cocoa leaves are also sensitive to high temperature and can tolerate leaf surface temperatures of 50° for only very short periods *(Mainstone [1972])*. To make use of sunlight, leaves must transpire water, not only for photosynthesis and uptake of nutrients, but also in order to remain cool.

6.2 Fertiliser and shade

Cocoa nutritional problems cannot be discussed without at the same time discussing shade. Shade is absolutely essential for young trees. As the trees grow taller and the canopy closes, there is often enough 'self-shading' and no additional 'overhead shade' may be required. The question whether and how much to shade depends on a number of factors, such as:

a) The amount of 'climatic shade'.
b) The relative humidity (when dry periods are long, shade may be needed).
c) Planting material. (Upper Amazon cocoas require less shade than Trinitarios, Amelanados or Criollos).
d) Soil fertility and the adequate and skilful application of fertiliser. The less shade the higher the demand on soil fertility and proper fertiliser.
e) The surrounding vegetation and insect fauna. (In certain cases a 'shade' vegetation is essential to reduce insect damage and to maintain an insect population needed for pollination).

Most of the world's cocoa is grown under rather heavy shade, sacrificing yield for health. Average yields of shade-grown cocoa range from 200–400 kg dry beans/ha. Shadeless cocoa may be able to produce yields of over 5000 kg of dry beans/ha. Like coffee, cocoa trees respond to the combination of moisture stress and increased rate of photosynthesis that follows the removal of shade with an impulse for generative reproduction. Unless the increased demand for water and nutrients is met, removal of shade usually results in a steep, short-lived increase in production followed by severe leaf-fall and dieback.

Under reduced light intensity, it is much easier to maintain a healthy balance between water uptake and transpiration and between nutrient uptake, dry matter production and nutrient removal *(von Uexkull [1968])*. Without fertiliser maximum yields are usually obtained at about 40–60% light intensity, whereas with fertilisers the best results are obtained at 75–100% light intensity (Figure 9).

Many of the early fertiliser esperiments with cocoa were conducted under heavy shade where fertilisers had little effect.

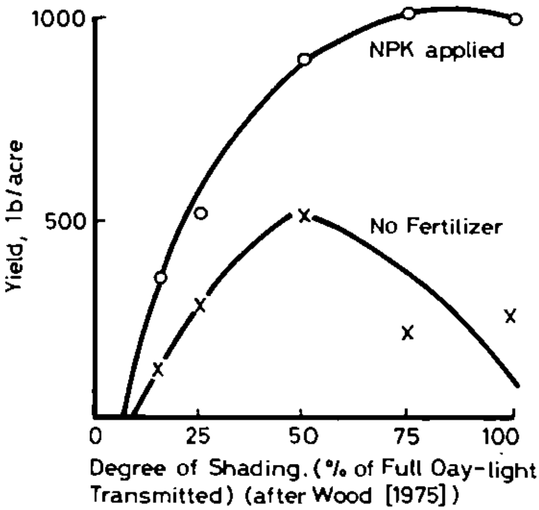


Fig. 9. Interaction between light intensity and fertiliser in cocoa

6.3 The role of potassium

In all crops potassium gains importance as yields increase. Cocoa is no exception. (Fertiliser) potassium is of little importance if cocoa is grown under heavy shade and yields are low. Cocoa pods contain 4.2–5.5% K in dry matter and cocoa beans contain usually 2.2–2.4% K, whereas healthy leaves contain about 1.2–2.2% K. This means that a heavy crop of cocoa drains much K from the leaves and branches. A good crop of 3 tons of dry beans would remove over 170 kg K/ha. Even good soils will not be able to supply K at such rates (plus the K immobilised in the living tree) for long (Figure 10).

Mainstone and *Thong [1978]* reviewed fertiliser responses over 6 years from planting of monocrop cocoa on a Bungor series soil in Malaysia. For the whole 6 year period reviewed potassium treatment had the largest effect among all nutrients (NPKMg). It increased the height of jorquetting, the lateral spread of the canopy and the cross-section area of the trunk. In the first year of harvest K boosted the crop yield by 53% but this boost fell to 14% in the 4th year. The response to applied nitrogen was largely dependent on adequate K.

K-deficient trees lose more moisture per unit leaf area, use up more carbohydrates for respiration and translocate less energy to the roots. Extended potassium deficiency therefore results in a weakened root system and poor water utilisation, which

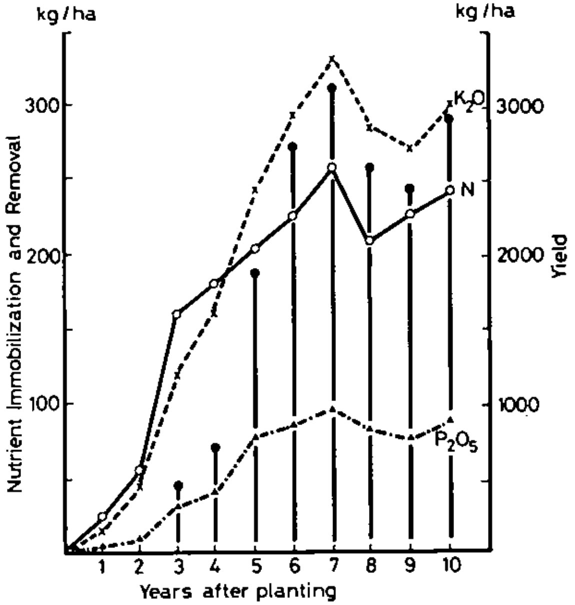


Fig. 10. Annual nutrient immobilization and removal of high-yielding cocoa over a period of 10 years

causes severe dieback or total exhaustion of the tree. Same as in coffee, advanced K deficiency is difficult to correct because of damage to the root system.

The relationship between cocoa yield, K-removal and K-fertiliser needs is shown in Figure 11.

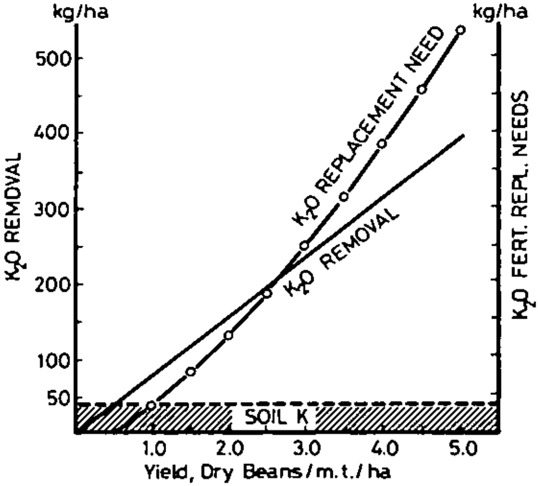


Fig. 11. Cocoa: K_2O removal and K_2O fertiliser needs at different yield levels

6.4 Leaf analysis

In contrast to other tropical tree crops, leaf analysis has not so far proved to be much help in determining fertiliser needs.

It is very difficult to get representative and reproducible leaf samples. Leaf nutrient values are influenced by position on the tree, the amount of shading, the number of flushes and ripening pods on a branch, etc.

'Critical' values may also vary widely, depending on nutrient capacity/intensity factors, soil moisture, eva-transpiration, the amount of climatic and artificial shade, etc. The more favourable the conditions in the rhizosphere, the lower the tolerable 'critical' levels will be. As a general guideline, the following levels are currently considered as 'deficient' (associated with symptoms), 'low' and 'normal' (Table 18).

Table 18. Content of nutrients for normal cocoa leaves, leaves without definite deficiency symptoms and leaves showing deficiency symptoms

Nutrient	Deficient	Low	Normal
	Percent dry matter		
N	<1.80	1.80–2.00	>2.00
P	<0.13	0.13–0.20	>0.20
K	<1.20	1.20–2.00	>2.00
Ca	<0.30	0.30–0.40	>0.40
Mg	<0.20	0.20–0.45	>0.45

6.5 Rates of fertiliser used for cocoa

Current cocoa yields rarely exceed 1 t/ha dry beans and fertiliser rates are correspondingly low. Rates recommended by different authors are shown in Table 19. On the basis of our current knowledge we would estimate the following fertiliser rates for young, mature, unshaded cocoa (Table 20).

Table 19. Rates of application of nutrients to cocoa (after *Wirley-Birch [1972]*)

Author	Nutrient rates (kg/ha) N	P	K	Remarks
Wirley-Birch [1972]	37	41	100	Light shade, yield 450 kg of dry beans. East Malaysia
Maliphant [1965]	105	30	167	Unshaded cocoa
Cunningham and *Smith [1963]*	–	50	–	Shaded Upper Amazon cocoa
Quartey-Papafio and *Edwards [1963]*	58	33	–	Smallholder cocoa in Ghana
Cunningham [1963]	115	26	198	Unshaded cocoa producing 2.5 t/ha dry beans
Verliere [1967]	–	37	133	P applied as rock phosphate
Wessel [1967]	132	13	–	Smallholder cocoa in Nigeria

Table 19. Rates of application of nutrients to cocoa (after *Wirley-Birch [1972]*)

Author	Nutrient rates (kg/ha) N	P	K	Remarks
Jacob and *von Uexkull [1963]*	22–34	18–22	28–37	Cocoa up to 3 years old
	34–68	13–26	56–84	Mature cocoa over 3 years old
	100–156 or 150–233	44–68	83–129	Planting density 1100 trees/ha
	97	25	61	Young trees Trinidad
	195	50	123	Old trees Trinidad
van Dierendonck [1959]	16	68	69	Bahia, Brazil, Shaded cocoa
	23	6	19	1st and 2nd years Jamaica shaded cocoa
	47	12	37	3rd year Jamaica shaded cocoa
	31	12	75	4th year Jamaica shaded cocoa
	16–37	5–11	11–28	Ivory Coast. Young trees 2–6 years. P as rock phosphate

* In addition to these recommendations, magnesium as dolomite or kieserite is applied where magnesium deficiency is likely. Where high rates of potassium are used, application of magnesium should always be recommended.

Table 20

Targeted yield, dry beans, ha	kg/ha N	P_2O_5	K_2O	MgO
1.0	40	40	40	10
2.0	80	60	120	30
3.0	130	80	250	60
4.0	190	110	385	100

7. Discussion – Tree crops

Most early work with tropical tree crops did not produce spectacular fertiliser response. Responses to potassium in particular were rare and limited to soils of lowest fertility (coastal sands and peats). Today, potassium plays a central role in the nutrition of tropical tree crops and the importance of potassium in absolute terms as well as relative to other nutrients is going to grow considerably in the future.
The main factors that are responsible for this trend are:

a) A rapid improvement of the genetic base.
b) A better understanding of crop physiology.
c) Better agronomic techniques from raising the seedlings to upkeep in the field.
d) Depletion of accumulated fertility through continuous intensive cropping.
e) The need to obtain high yield in order to keep production costs per unit as low as possible.

The future trend will be towards:

a) Smaller trees.
b) Higher densities/unit area.

c) Earlier maturity.
d) Shorter lifetime of the tree (faster turnover).
e) Higher yield.
f) Higher fertiliser rates.
g) Higher rates of K in fertiliser.

High yield invariably means partition of assimilates (and nutrients) in favour of the harvested (and removed) portion of the total dry matter production. This in turn means that less nutrients (and carbohydrates) will be available for vegetative growth and for root expansion. This in turn means that a higher nutrient concentration must be offered to meet the higher needs of high-yielding tree crops.

Absorption of potassium is an energy-requiring process and, at the same time potassium is essential for energy transformation and transfer in the plant. To be effectively absorbed and metabolised, potassium should never be permitted to become deficient in high-yielding tropical tree crops where dangers of exhaustion are much larger than in temperate tree crops.

8. Cotton

(by: *A. Cohen)*

8.1 General

Cotton does not appear to be an exhaustive crop *(Bassett et al. [1970], Brand* and *Dubernard [1971], Christidis* and *Harrison [1955]),* since only the lint and seeds which contain small amounts of mineral nutrients are removed, while the rest of the plant (roots, stems, leaves and burrs) remains in the field. However, when grown intensively, high-yielding crops need abundant supplies of available nutrients over a relatively short period.

8.2 Nutrient uptake and dry matter production

Nitrogen, phosphorus, potassium and magnesium are the major nutrients essential for cotton, while sulphur, zinc and other minor element deficiencies have been reported. Results relating dry matter production to nutrient uptake have accumulated since the beginnung of the century but early studies referred to yields low in comparison to those obtainable today with improved cultivars, more precise management and irrigation.

Basset et al. [1970] measured dry matter production and nutrient uptake by cotton at various places in the irrigated San Joaquin Valley of California. Lint yield was relatively high, ranging from 1178 to 1628 kg/ha with average total dry matter production from 6900 to 8900 kg/ha. In Israel, *Halevy [1965]* studied dry matter production and nutrient uptake of two cultivars which differ in their response to K fertiliser under irrigation. The results, summarised in Table 21, show that irrigated cotton makes a higher proportion of its total growth in the later stages than does the raingrown crop.

Table 21. Dry matter production by cotton at different stages

	% of total dry matter						
Stage	Seeding	Early square		Early boll		Maturity	
Georgia	3.1	8.0		37		51	
California	2.0	7.0		66			
Israel:							
Acala 15–176.....		5.6	13.3	25.5	26.5	22.3	6.8
Acala 4–42......		3.4	11.3	21.4	24.6	28.8	10.5
Days from emergence		0–57	57–72	72–84	84–98	98–112	112–15

8.2.1 Potassium uptake

In general, nutrient uptake by cotton proceeds more rapidly than dry matter production. Cotton grown in humid areas *(Olsen* and *Bledsoe [1942])* absorbed 22% and 30% of the total N and K respectively by the time only about 11% of total dry matter had accumulated, while in California, under irrigation *(Basset et al. [1970])* the crop took up about 15% of the total N, P and K before 10% of total dry matter production. Seasonal uptakes of N, P and K by cotton and their partition among plant organs was reported in detail by *Basset et al. [1970]* and *Halevy [1965].*

Potassium uptake continues up to 120 days from planting (Figure 12) after which the amount of K in the plant diminishes.

According to *Halevy* (Figure 13) the shape of the K uptake curve is similar to those for dry matter production and N and P uptake, but there are two differences:

a) Maximum K accumulation in the plant was reached at 112 days, after which the K content diminished.

b) There were changes within the plant due to translocation of K from leaves and stems to the reproductive organs. The decrease in total plant K content after 112 days may be due to the movement of K back to the soil, as has been reported for other plants *(Eaton* and *Engle [1957], Halevy [1976]).*

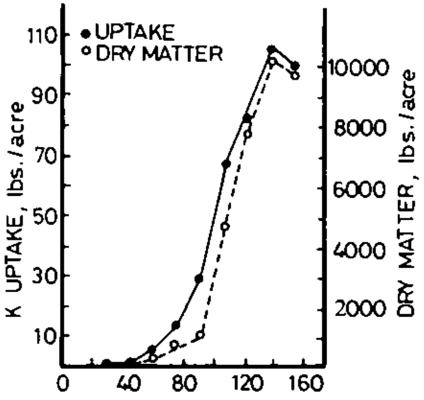


Fig. 12. K uptake and dry matter accumulation (after *Kamprath* and *Welch [1968])*

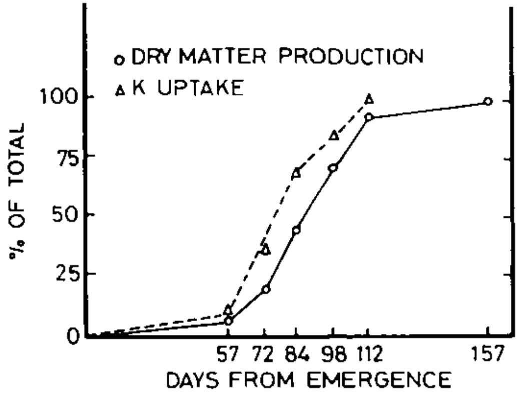


Fig. 13. Rates of dry matter production and K uptake in cotton *cv* Acala 1517 C *(Halevy [1976])*

8.2.2 Rate of K uptake

Table 22 summarises results obtained in Georgia, California and Israel.

The rate of K uptake, slow at the beginning, increases rapidly at flowering, reaching its maximum of 4.6 kg K per day between 72 and 84 days *(Halevy [1969])* and 2.1–3.4 kg K/day between day 90 and day 127 *(Basset et al. [1970])*. In Israel more than 30% of the K was taken up in 12 days.

Table 22. K uptake in various experiments

	Olson and *Bledsoe [1942]*	*Basset et al. [1970]*	*Halevy [1976]*
Cultivar	Upland cotton	Acala 4–42	Acala 1517 C 4–42
Location	Georgia (humid)	California (irrigated)	Israel (irrigated)
Lint yield (kg/ha)	2250 seed cotton = 750 lint	1178–1628	1700
D.M. production (kg/ha)	10 900	6900–8900	12 200–13 500
Total K uptake (kg/ha)	111	127	164–185
Max. K uptake rate (kg/ha/day)	2.8 day 90–105 (15)	2.6 day 90–105 (15)	4.6 day 72–84 (12)
	1.9 day 90–135 (45)	2.1–3.4 day 90–125 (35)	3.0–3.4 day 57–98 (41)
Max. D.M. production rate (kg/ha/day)	260 day 90–105 (15)		260–280 A. 1517 C day 72–84 (12) A. 4–42 day 98–112 (14)
	220 day 90–135 (45)	110–140 day 90–136 (46)	230–250 day 72–112 (40)
K removed in seed cotton (kg/ha)	22.5	16–24	47–43

8.3 K requirements in relation to other factors

8.3.1 Management

Compared with early studies in humid climates, the results of *Basset* and *Halevy* generally showed a greater proportion of dry matter production and K uptake in mid- to late season (80–120 days from emergence). The differences may be mainly due to the marked increase in total boll set resulting from a combination of better water control through irrigation, better pest control and other improved practices.

These findings explain the differences in the response of cotton to K status of the soil and to K fertiliser under different growing conditions. When conditions are suitable for early and rapid flowering with reduced shedding of bolls, there is a heavy demand for K over a very short period during which K relase from soil minerals may be too slow. If the soil is low in available K, this demand will not be fulfilled and early leaf browning (cotton rust) will appear, with a decrease in photosynthesis and reduced yield. If the prevailing conditions lead to more extended boll setting, the demand for K will be slower and will also extend over a longer period so that the crop may yield well even if leaf browning appears at a later stage.

8.3.2 Other nutrients

K requirements are closely correlated with the availability of other nutrients, especially nitrogen. A field experiment *(Halevy [1970])*, in a region where K deficiency occurred, was conducted to determine the relationships between potassium, nitrogen and phosphorus. Two varieties, Acala 1517 C and Acala 4-42 were compared at two levels of each of the nutrients:

N: 0 and 180 kg/ha
P: 0 and 60 kg/ha
K: 0 and 300 kg/ha

Both varieties responded in lint yield to nitrogen and Acala 4-42 to phosphorus. There was a large and positive N × K interaction in Acala 1517 C, K slightly reducing yield at N_0 and increasing it at N_1 (Figure 14).

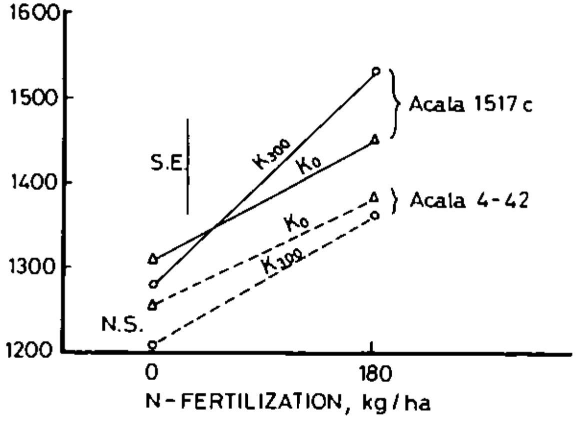


Fig. 14. N × K interaction effect on lint yield *(Halevy [1970])*

8.3.3 Irrigation

The relation between potassium, other nutrients and water use of crops has been studied by many authors. In the Upper Volta, ***Braud [1975]*** found that the K level in the plant was positively related to the water supply when complete (NPKS) fertiliser was applied. *Halevy [1965]* compared the K uptakes by cotton plants grown in pots at four irrigation levels and found a positive interaction between medium to high irrigation levels and high and very high K applications (Figure 15).

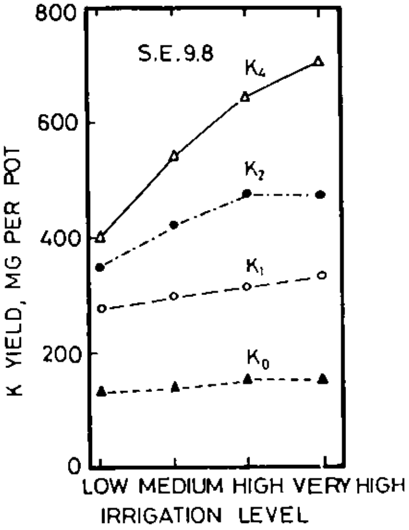


Fig. 15. Effect of irrigation on K uptake in pot experiment *(Halevy [1965])*

8.4 Discussion

K uptake by the cotton plant is closely related to the growth rate. Maximum K rate requirements occur over a period of six weeks, ranging from day 90–135 to day 72–112 from planting, according to cultural conditions, climate and cultivar.

Response to K fertiliser will be obtained if, during the critical period, the rate of K uptake demand exceeds the rate at which K can be released by the soil.

The total K requirements of cotton are closely related to N supply and to the water regime, maximum K rate requirements being found at high rates of N and under intensive cropping with irrigation.

Response to potassium fertiliser differs between cultivars, which have varying potential to exploit soil K because of differences in root system development and K uptake rate at critical periods of growth.

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The Potassium Requirements of Crops Harvested Green, with Special Reference to Grassland

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1. Introduction

The crops discussed in this paper are those whose useful produce is in the form of vegetative material (leaves and stems). Such vegetative material has a lower content of useful material (carbohydrate, lipids and protein) than the storage organs or fruits of the crops dealt with elsewhere in this volume. Some of the plants falling within this general definition form an accessory part of the human diet as appetisers and suppliers of vitamins – salads, spinaches, etc. – but they supply only a negligible proportion of our calorie requirement. More important in the present context are the following two categories of crops:

Forage crops: Herbivorous animals, in particular the ruminants, have digestive systems which enable them to use such low concentrate foods.

Certain industrial crops: Among these, sugar cane, stimulants such as tea and tobacco, and fibres (flax, hemp, etc.) should be mentioned.

2. The distribution of potassium in the plant

Potassium is extremely mobile in plant tissue. It has important functions in metabolism and this as well as its mobility results in its being found in particulary high concentration in the young tissues. This can be demonstrated in two ways:

a) By determining the composition of entire plants of different ages. This was done, for example by *Mengel [1972]* using oat seedlings; whole plants were analysed every three to six days. The highest concentration of K in dry matter was found one or two weeks after germination; later K concentration in the plant (still in terms of dry matter) decreased rapidly eventually reaching a value only one third of the maximum. Figure 1 shows change in K content in relative values; in absolute values, the young seedlings have K contents above 4.5 to 5.0% in D.M. for almost a month, with a maximum of 6.2% then the value falls due to dilution by rapid growth *(Mengel [1972]; Scharrer* and *Mengel [1959])*.

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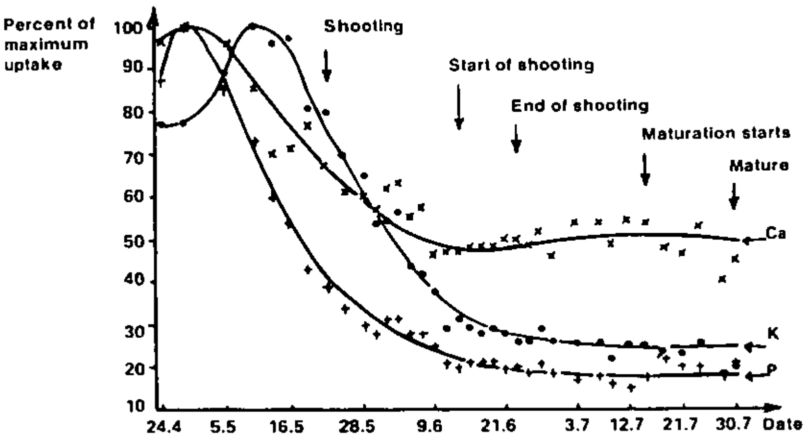


Fig. 1. Changes in concentration of oats seedlings with age. Percent of maximum uptake

Generally, plants have taken up their total potassium requirements by the time dry matter production by the plant has reached 50–70% of its maximum and 50% of the total K by the time 10–20% of dry matter has been formed. This means that K uptake must proceed very rapidly at critical stages of growth. Thus, for example, a crop of maize which takes up a total of 125 kg K/ha has a peak rate of uptake, just before shooting of 6 kg K/ha/day.

b) By comparing, at any given stage of growth, the composition of tissues of varying age as in the following two examples:

A model of this kind of analysis was carried out by *Ayres [1935]* using sugar cane. He showed how K content varied with age and variety and gave exact figures for composition of each part of the plant. He showed that K content varied between 0.3% in the base of the stem (reserve and mechanical tissue) to over 6% in the growing point. This led the author to write 'With regard to the large amounts of potassium which one usually finds in meristems and active plant organs, it is not particulary surprising to find this one element accounting for more than 6% of the total dry matter weight (or 45% of total ash) in this region of intense cellular activity.' Such extreme variation (1 to 20) in K content between different parts of the same plant is perhaps a little exceptional but serves well to illustrate the general point. Even comparing the same organs of different ages, the differences in K content can be very large – the youngest leaves are always the richest in K. *Malavolta [1962]* found that the K content of individual leaves on the same stem increased steadily from the oldest to the youngest leaf and that the K content of dry matter was at a maximum in the terminal leaf. To take another example, as is well known, tobacco leaves are harvested and graded according to their height on the plant (in other words their age) since quality depends upon this. The higher, younger leaves always have the highest K content. As an example *Loué*'s *[1970]* results are given in Table 1. It is clear from Table 1 that when the supply of K is low, the younger leaves have priority for the limited K supply.

Table 1. Effect of K fertiliser on K content of tobacco leaves of varying age

	No K applied	150 kg K_2O/ha	300 kg K_2O/ha
Upper leaves	2.40	3.55	4.73
Middle leaves	2.25	3.48	4.78
Lower leaves	1.75	3.28	4.78

The above general principles are of importance in relation to the potassium requirements of leafy crops.

3. Grassland

3.1 Economic importance

Grassland is by far the most widespread crop in the World. This is shown by the fact that it occupies very large areas, but its importance as a source of agricultural revenue is similary large. Grassland comprises about 50% of the 32 million hectares of agricultural land in France, 50% of 520 million hectares in the USA and 60% of 2.2 million hectares agricultural land in the Netherlands. But it is New Zealand which holds the record with 20 million hectares more or less intensively managed grassland alongside only 4 million hectares of arable land, of which more than half grows forage crops!

The general term 'grassland' covers a very wide range from both the botanical and management points of view so that it is not easy to generalise on management or fertiliser treatment, or on the economics of the enterprise. For most arable crops there is a lower threshold below which it is not worth growing the crop, all arable entreprises are to some, albeit low, degree intensive and it is comparatively easy to arrive at fertiliser recommendations suited to the agricultural system and the region. This is not the case with grassland where, in practice, production may vary from a few hundred kg dry matter per hectare per year in a subsistence system to very intensive production with high yields obtainable under suitable climatic and soil conditions, with adequate water and fertiliser. Maximum yield levels attainable are of the order of 20 tonnes dry matter at 45° latitude and around 50 tonnes in the tropics. This extreme variability is illustrated in Table 2 taken from *Burton [1972]*.

Table 2. Sward productivity on sandy soils in S. Georgia after *Burton [1972]*

Year	Sward type	Liveweight gain (kg/ha/year)
1860	Natural prairie	9
1900	Carpet grass *(Axonopus officinis)*	34
1930	Bermuda grass	90
1948	Coastal Bermuda grass + 157 kg N + P + K/ha	543
1972	Coastcross + 673 kg N + P + K/ha	2240

3.2 Composition

In discussing the potassium nutrition of herbage plants, it is best to proceed from the particular to the general. We are essentially concerned with two groups of plants: legumes exemplified by lucerne (*Medicago* spp.) and grasses exemplified by ryegrasses (*Lolium perenne* and *Lolium italicum*). In both cases the principles discussed in Section 2 apply, that the younger the tissues the richer they are in mineral elements and this is particulary the case for N and K, concentration of both of which decreases very rapidly with increasing age. In cells which are actively multiplying K concentration can reach 8% of dry matter while in mature tissue (*e.g.* straw or grass hay after flowering) it will be of the order of only 0.6–1.2%. As the plant matures the proportion of juvenile tissue diminishes in favour of older tissues in which carbohydrates have accumulated. Total ash content decreases with time, K content decreases more rapidly (Table 3).

Table 3. Effect of age on K content of lucerne and ryegrass after *Thomas et al. [1952]*, % K in dry matter

Stage	Lucerne	Ryegrass	Stage
Early vegetative	4.0	3.00	Young herbage
Late vegetative	3.3	2.60	Ear emergence
Flowering	2.3	2.08	Anthesis
Mature................	2.0	1.80	End of flowering
Decline	1.5	1.20	Hay

Total nitrogen and protein content decline similarly and since protein is an important and costly item in the animal diet the tendency over the past thirty years has been to cut earlier and earlier. However, earliness of cutting is limited in two ways. The first is nutritional in that if cut too early the carbohydrate content of the herbage is too low, because the plant has not had time to accumulate sufficiently, and the energy needs of the animal will not be met, while in extreme cases the low energy content of the diet can lead to animal disorders (grass tetany). Secondly, there is a technical limit because the younger the grass the higher the water content and content of non-protein nitrogen and the lower the cellulose content, making conservation difficult. Developments in pre-wilting, ensiling technique and grass drying have made it possible to cut at the optimum stage.

A consequence of early cutting is that the herbage has a higher K content so that potassium removal per unit weight of herbage harvested is greatly increased.

3.3 Potassium uptake

It is very difficult to study the pattern of potassium uptake in plants which are harvested green. Uptake is the product of two factors: production of dry matter and its K content (and variation of the latter) over the period under consideration. As we have seen, the pattern of dry matter production is very variable, while K content at the time of harvesting may vary widely according to age. In contrast, crops harvested at the mature stage have a relatively constant composition. The pattern of potassium uptake is most importantly influenced by soil conditions affecting potassium availability.

3.3.1. Soil reserves

The inherent potassium supply of the soil greatly affects the K content of herbage at any particular stage of growth. For example in France, analyses of ryegrass herbage cut at the shooting stage showed a range of values from 1.2 to 5% K in dry matter, which reflected soil differences. *Rochet [1978]* surveyed mineral composition of Italian ryegrass in Normandy and found a mean value of 3.51% K at the shooting stage with a maximum of 6.61. The K content of the grass was correlated ($p = 0.05$) with the exchangeable K content of the soils.

The capacity of the *graminae* to exploit soil potassium has been used to measure the level of potassium which soils can deliver from non-exchangeable sources, for example Italian ryegrass *(Chaminade [1960]; Garaudeaux et al. [1965])* and barley *(de Ment et al. [1959]; Quémener* and *Roland [1970])*. Though the grasses are very efficient in extracting soil potassium, soil potassium supplies are only very exceptionally sufficient to provide sufficient potassium for full growth, when other conditions are favourable, over a period of several years, and potash fertiliser must be applied. Thus *Vicente-Chandler [1972]* used Pangola grass *(Digitaria decumbens)* to measure the potassium reserves of Puerto-Rican soils. There was a five-fold variation between soils in the quantity of K extracted in the first year and even in the richest soils available K reserves were very much reduced by one year's growth of grass.

Natural soil fertility is never sufficient to provide sufficient potassium for unrestricted growth of grass under intensive management.

3.3.2. Effect of potassium fertiliser

Applying potash fertiliser to herbage has a dual effect. It increases yield and also increases herbage K content. Consequently under intensive conditions, very high potash dressings are required to make up for K removal in crops. Figure 2 illustrates results obtained with lucerne. The hatched area represents conditions generally applying in temperate regions without irrigation and shows that under such conditions from 170 to 300 kg K per hectare annually are required to compensate for crop removal of K.

The situation with grasses is more complex because K uptake and removal is much affected by the level of N fertiliser applied and it would be necessary to construct a similar figure for each level of N. Further, the cumulative effects of K removals and additions in previous years must be taken into account.

Cutting and removing grass from the field greatly lowers soil potassium, especially under intensive management. The problem is difficult because when high levels of potassium are given, to compensate for removal, such a large proportion of the added potassium goes to increasing the K content of the herbage. This effect is illustrated by the results of *Hopper* and *Clement [1966]* which are quoted in Table 4. Even when high levels of potassium are given to intensively managed cut grass (for silage or drying) the soil is depleted of K and, in alternate husbandry systems this can have serious consequences for the following arable crop. Indeed, the rational use of potash fertiliser under such, not uncommon, conditions poses a very difficult problem.

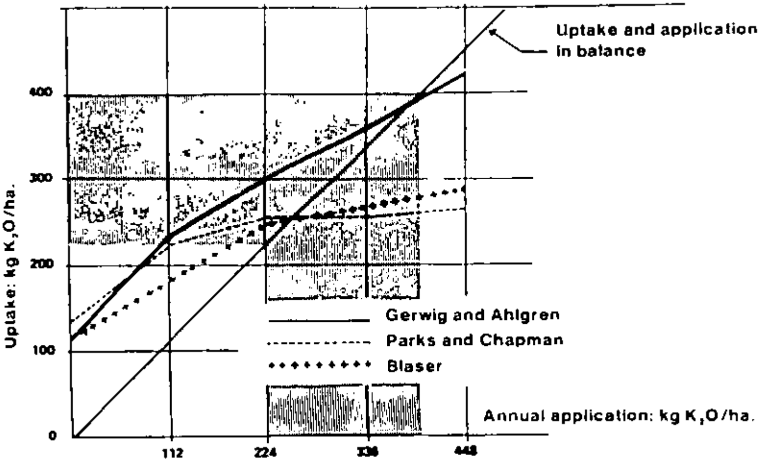


Fig. 2. Potassium uptake by lucerne in relation to K fertiliser application

Table 4. Output of potassium harvested in herbage from a cut grass sward receiving 314 kg N/ha/year and varying rates of K, 4 year totals

Input kg K/ha	Output kg K/ha	Balance kg K/ha	Yield ton dry matter/ha	% K in dry matter
0	660	660	36	1.9
250	840	590	38	2.2
500	1030	530	39	2.6
1000	1290	290	40	3.2
	±41.6		±1.02	

(After *Clement* and *Hopper [1966]*)

3.3.3. The relationship between plant composition, yield and potassium balance in the soil

It will be readily appreciated that the factors discussed above will have cumulative effects on soil potassium. It is well known that the potassium content of herbage will decrease from year to year if sufficient potash is not applied to compensate for that removed in crops. *Chevalier* and *Quémener [1977]* studied over eight years yield and composition of cocksfoot and the effects on K balance in the soil in a 4 × 2 × 4 (N × P × K) experiment at the Aspach Station (France). The grass was cut on a system to simulate grazing management. They found that, in general, herbage K content reflected soil K supply as indicated by the K balance of the soil (Figure 3). They also found a relation between dry matter yield and the mean annual K content of the herbage at each of the four levels of N applied. The more the soils were impoverished the higher the correlation and r attained values of from 0.90 to 0.96 in the three last years of the trial at the higher N levels (Figure 4). This indicated that at that stage potassium had become limiting. Similar results were obtained with rye-grass *(Chevalier [1978])*.

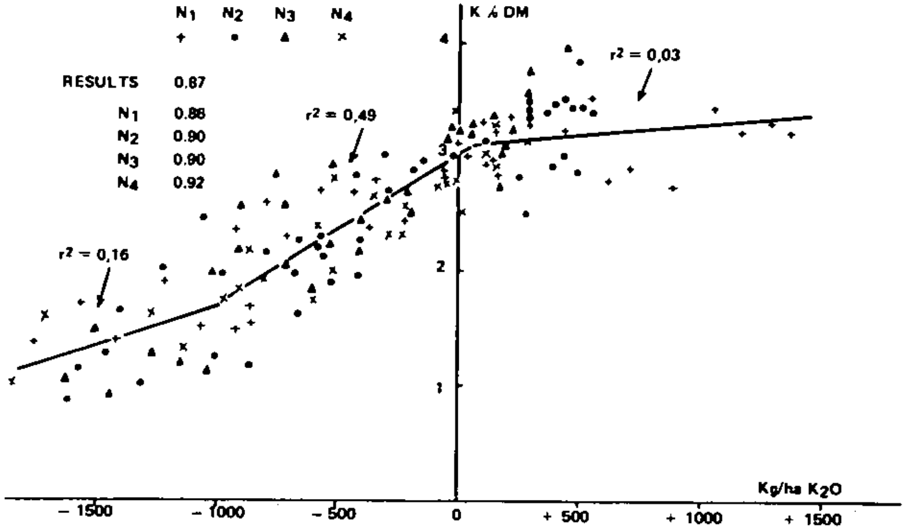
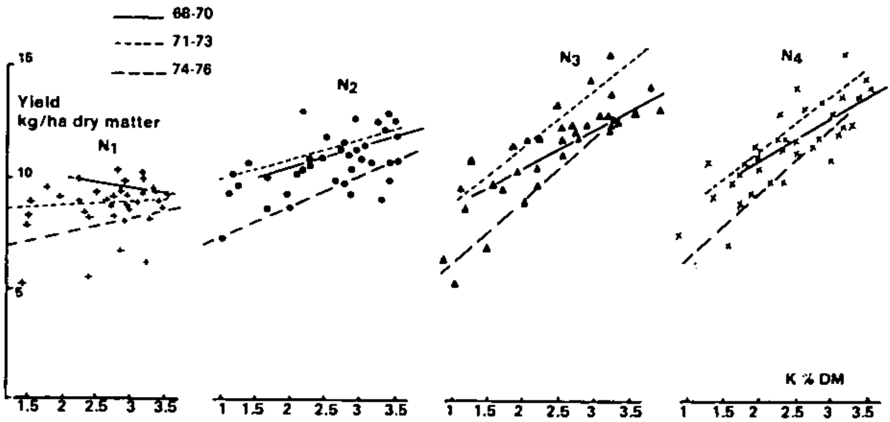


Fig. 3. Relation between soil K balance and mean annual herbage K content



Correlation coefficients

	N$_1$	N$_2$	N$_3$	N$_4$
1968-70	– 0.51	– 0.32	0.89	0.89
1971-73	0.13	0.64	0.90	0.82
1974-76	0.30	0.73	0.86	0.90

Fig. 4. Relation between mean annual herbage K content and dry matter yield at varying N levels

3.4 Grass-legume mixtures

Grass legume mixtures are much used particulary in temperate areas. Natural grassland usually contains both grasses and legumes. Such mixtures have several advantages.

Form the point of view of animal nutrition, the legumes have much higher Ca content than grasses and often also of Mg. It is preferable to supply the minerals in the herbage rather than in the form of mineral supplements. Seasonal production of the mixtures is more even than that of either pure grasses or pure legumes. Finally, in comparison with pure grass, the mixtures enable savings to be made in nitrogen fertiliser.

It is always difficult to maintain the proper balance between legume and grass in such mixtures and apart from a number of other factors (level and pattern of N fertiliser, stage of cutting [or grazing], soil moisture, etc.) potash fertiliser plays an important part. Grasses are more efficient in exploiting soil potassium than legumes and when grown in association the latter will often be unable to obtain sufficient K in competition with the grass. Generous use of nitrogen which stimulates growth and K uptake by the grass, worsens the position. When grown in pure stands, legumes have K contents comparable with those of grasses but when they are associated the legumes always have lower K contents. This is demonstrated in Table 5 after *Balser* and *Kimbrough [1968]*.

Table 5. Herbage K content in a grass-legume mixture

K applied kg K_2O/ha	% K in dry matter grass	 legume	K in legume/ K in grass, %
0	2.71	0.70	26
46.5	3.46	1.21	35
93	4.01	1.78	42
372	3.85	3.53	92

(After *Blaser* and *Kimbrough [1968]*)

This behaviour is partly explained by the difference in cation exchange capacity of the roots of grasses and legumes, that of the latter often being as much as double the former. Various workers have explained the difference and the fact that legumes take up monovalent cations such as potassium only with difficulty on the basis of a 'membrane' theory or the *Donnan* equilibrium.

In practical terms the result of this behaviour is that adequate potassium fertiliser is more important for a mixed sward than for a pure stand of grass and there is an advantage in applying the potash fertiliser in repeated small dressings. Slow acting potassium fertiliser such as sulphur coated KCl would be useful.

3.5 Grass in the tropics and sub-tropics

As compared with the temperate zones, the manuring of grass has received little attention in the tropics, and if fertiliser is used at all, the rates applied are nowhere near those which the grass could utilise profitably. Provided there are no other nutrient deficiencies and there is sufficient water dry matter production increases linearly with increasing nitrogen fertiliser up to as much as 800 kg/ha N. According to *Salette [1971]* the average response by tropical grass is 20–30 kg dry matter per kg N applied but it can be as high as 80 kg. The response to applied N is linear up to a yield of 20–30 tons DM/ha above which the rate of response falls off, and nitrogen may be applied at up to 1500 kg N/ha. The most demanding and most productive grasses are *Cynodon* (Bermuda grass), *Paspalum* (Bahia) and particulary elephant grass *(Pennisetum purpureum)* which has yielded over 50 tons DM/ha when N was applied at 1500–2000 kg/ha. Normally the K content of such herbage would be between 1.5 and 2.5% resulting in the removal of 500–700 kg K_2O/ha at 30 tons DM. Thus heavy K applications are needed to maintain soil K status.

Tropical grass responds to K fertiliser whenever it is intensively managed. Response naturally varies according to soil fertility, rate of N and P applied and type of grass. Under the most intensive management, response normally continues up to a level of 500 kg K_2O/ha and experience shows that there will be a marked response to K whenever K content of the herbage at cutting is below 1% in dry matter. In most cases response will continue until herbage K content reaches 1.5% K. As was done above (Figure 2) a curve can be constructed showing K removal against K application and it will found that for tropical grasses removal and application will be in balance at about 500 kg K_2O/ha. Obviously at such high rates, divided dressings must be used *(Adams et al. [1967])*.

3.6 Effect of potassium on herbage composition

Potassium content has no direct influence on animal health. Animals fed on rations composed solely of grain may suffer K deficiency when the K content is below 0.5% K, but no grass would grow under such conditions so that the animals' potassium requirement (even of very high yielding dairy cows) will be satisfied if grass is included in the ration. Conversely there is no evidence that high K level in the herbage adversely affects the animal. *Kemp [1970]* showed that K excreted is proportional to K ingested. Even when intake exceeds 600 g K/day there are no ill effects on cattle *(Hendriks [1964])*.

However, potassium has indirect effects on both mineral and organic composition of the herbage. In both cases the effects on pure stands are discussed, the effects on grass legume balance having been briefly treated in section 3.4 above.

3.6.1. Mineral composition

Both K^+ and Cl^- ions are very easily taken up by the plant and they significantly affect mineral composition. Increased K uptake is necessarily accompanied by decreased uptake of other cations. In fact one can only speak of true antagonism in the case of sodium. Apart from evidence from experiments, *Nielsen [1969]* has studied Na content of herbage throughout Denmark. The depression of Na content is not practically important as salt is normally included in the ration of dairy cows, even when no potash is applied to the grass. Additionally, while Na content is affected by potassium, it also depends on species and cultivar *(ap Griffith* and *Walters [1966]; Garaudeaux [1959])*.

Potash fertiliser slightly decreases the Mg content of herbage and this has led to statements that potash fertiliser is responsible for herbage tetany. A number of experiments were reported showing that this is not a simple problem and that it is bound up in a complex way with the assimilation by the animal of ingested Mg and that potassium has no effect on this *(Werk* and *Rosenberger [1969])*.

3.6.2. Organic composition

Nitrogen is found in plants in three forms: mineral N, soluble N compounds (amines) and insoluble compounds (proteins). It is now well established that potassium fertiliser in general increases protein N content and reduces soluble N content *(Nowakowski [1964]; Demarquilly [1977])*. Potassium usually decreases the content of mineral N but in a less regular manner (Figure 5).

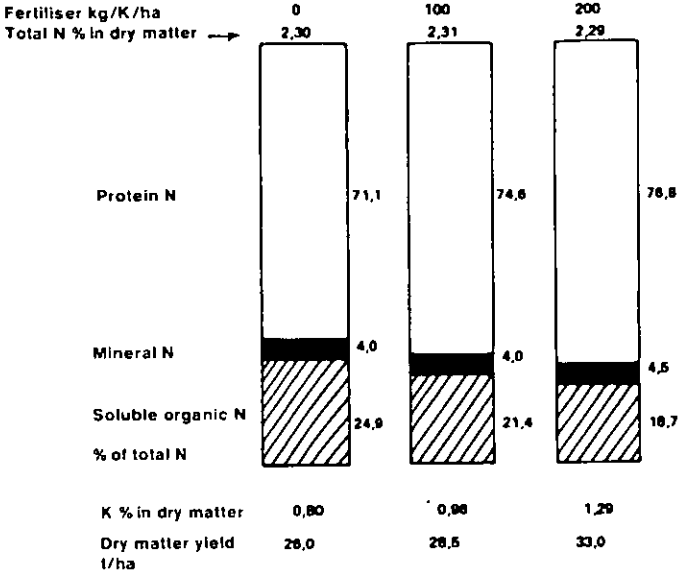


Fig.5. Variation in composition of Italian ryegrass with potassium manuring (2nd cut). After *Nowakowski [1964]*

It is well known that potassium has important functions in photosynthesis and glucoside metabolism. Lowering of leaf K content always results in the accumulation of soluble glucosides to the detriment of the higher polysaccharides *(Evans* and *Sorger [1966])*.

These analytical studies show that while potassium fertiliser can influence the quality of herbage the tendency is usually favourable and generally speaking it has little effect on the nutritive value. In most cases the effects of potash fertiliser can be completely described in terms of the effect on dry matter and digestible protein production. It has been shown that potassium has little influence on digestibility even when applied at high rates *(Martz et al. [1967]; Reid* and *Jung [1965]; Calder* and *McLeod [1968])*.

3.7 Effect on vigour

Adams and *Twersky [1959]* have shown that potassium fertiliser reduces winter kill, and *Evans* and *Sorger [1966]* showed that it had a favourable effect on disease resistance.

3.8 Conclusion

It has been shown that the potassium requirements of herbage plants are very high and that large amounts of K are involved in the nutrient cycle, that potash fertiliser produces large increases in yield which are of benefit to the animal. Experience shows that, under intensive management. in grass drying for example, yields can only be maintained if potassium removed is made good by fertiliser.

The problem of the potash fertilisation of grazed grass is difficult and is discussed in chapter 5 of this volume, suffice it to say here that the recycling of potassium is often over-estimated.

4. Sugar cane

The area planted to this crop has almost doubled (to nearly 13 million hectares) during the past twenty five years. During the same period average yield has moved up from 42 to 54 t/ha cane. Sugar cane production has kept up with the increase in World population. But, compared with the yields of 120 or 150 tons which are obtained in some countries the 54 tons average is still very low. The three largest producers together representing half the cultivated area in the World had, in 1975, only the following average yields: India 51.2 t/ha on 2.79 million ha, Brazil 46.1 tons on 2.24 million ha, and Cuba 44.3 tons on 1.15 m/ha. Because in most countries there is little possibility to increase the area planted with cane for lack of suitable land and sufficient water, further production increase can only be achieved by the improvement of cultural methods, improved varieties and the use of more fertiliser. *Humbert [1958]* has illustrated in classic fashion the relationship between usage of potash fertiliser and sugar yield (Figure 6).

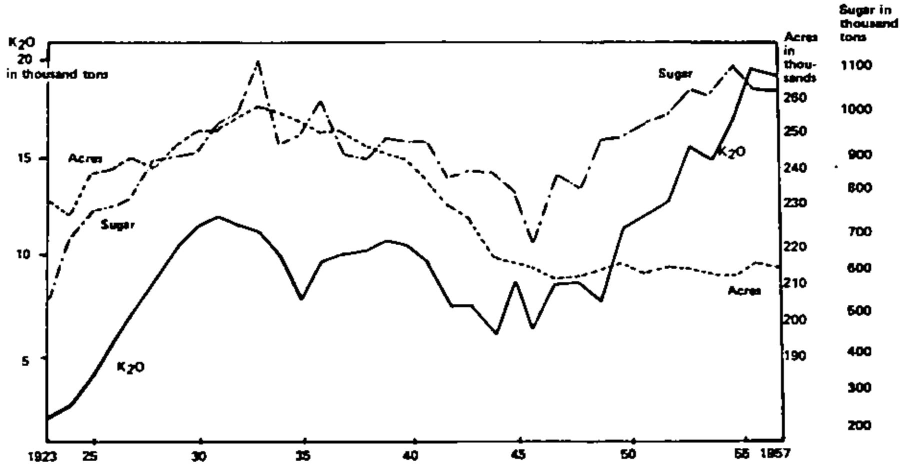


Fig. 6. Relation between sugar production and purchases of potash fertiliser by the Hawaiian sugar industry, 1923 to 1957 *(Humbert [1958])*

4.1 Uptake of nutrients

As a converter of solar energy into food calories the sugar cane is unequalled, so it is not surprising that its nutrient requirements, for the realisation of full yield, are very large. High yields can only be obtained on fertile soils which will satisfy these needs. This was shown many years ago in measurements of nutrient uptake made in Java on seven plantations with yields ranging from 107 to 174 tonnes/ha *(Honig [1934])* results are summarised in Table 6 which also summarises more recent results obtained in Argentina *(Fogliata [1975])* in which total removal over three years (new cane *cv* N.A. 56–79/129 t/ha, ratoon of the same *cv* (84 t/ha and ratoon of *cv* N.A. 56–30 [75 t/ha]) was measured.

Table 6. Nutrient uptake by sugar cane after *Honig [1934]** and *Fogliata [1975]***

Mean cane yield (ton/ha)	Uptake kg/ha/year						
	N	K_2O	P_2O_5	S	MgO	CaO	SiO_2
148*	–	365	59	56	39	34	708
96**	71	178	11	–	11	53	–

4.2 Fertilizer use

Because of its enormous potential for growth – a world record yield of 424 tons has been quoted! – sugar cane needs generous supplies of nutrients and water throughout growth right up to maturity. The harvest, which is a most demanding time can be extended by late application of nitrogen and potassium during the days immediately preceding cutting which favours translocation of sugar from leaf to stem. As with other intensive crops, supplementary application of N should always be balanced with potash fertiliser – potassium deficiency reduces cane yield and sugar content. According to Hawaiian experiments leaf K content below 1.25 to 1.7 % causes the accumulation of low molecular weight N compounds, delaying maturity and adversely affecting sugar extraction in the factory. An example of the effects of increasing potassium levels on yield and the main quality factors in Taiwan with the cultivar P.O.J. 28–83 receiving uniform N and P at 160 kg N/ha and 100 kg P_2O_5/ha is shown in Figure 7.

Potash was applied at rates up to 200 kg K_2O. This is only one of many cases were potassium improved yield, sugar percentage and juice purity. K response is variable but always positive as regards all these factors. Very often, sugar content and juice purity are further improved when potash is applied at rates above that which gives maximum cane yield.

The following is a brief summary of some world-wide results:

Réunion: Work is reported in 'L'Agronomie Tropicale', Vol. *29* (1975), showing that cane yield and sugar content were increased by potash applied at up to 200 kg/ha K_2O.

Thailand: The Annual Report of the *Department of Agriculture*, Bangkok for 1966 reports that cane yields were much increased by potash at 500 kg/ha K_2O and that

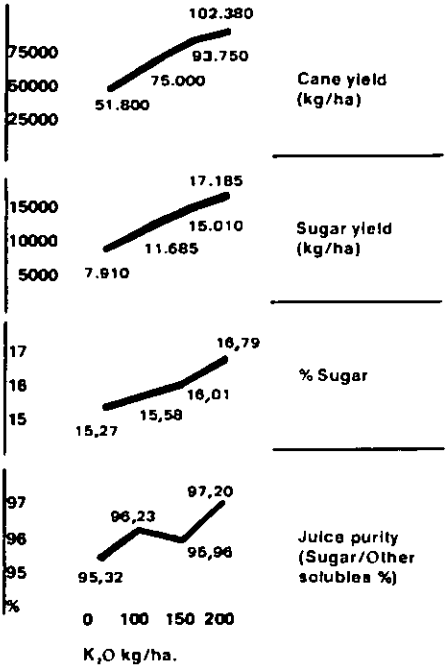


Fig.7. Effect of potassium on cane yield, sugar yield and quality

efficiency was improved by applying the potash in three equal dressings at planting, after 45 and 90 days.

India: Under optimum conditions sugar yield increases at as much as 20 kg sugar per kg K_2O applied; the optimum rate is about 200 kg K_2O/ha. *Gupta* and *Shukla [1973]* showed the crucial importance of N : K ratio in the fertiliser – increase of the former must be accompanied by increased potash.

Venezuela: Segura [1971] recommends a base dressing of NPK with additional top-dressings of N and K.

Philippines: Kunarajah [1971] reviewed a large number of experimental results which indicate average optimum fertilisation at 220 kg N, 100 kg P_2O_5 and 200 kg K_2O per hectare, with additional amounts to compensate for soil deficiencies.

South Africa: Meyer [1975] showed in factorial trials that yield is strongly influenced by each of the major elements (N, P, K). These factorial experiments showed interaction between K and the other elements in that potassium was particulary effective as regards both yield and quality at high rates of N and P, which tended to affect quality adversely.

5. Tea

Tea has been cultivated in S.E. Asia since ancient times. World production has more than doubled in the past twenty five years to 1.6 million tonnes in 1976. During the same period the planted area increased by 54% to 1.545 million ha. There has thus been a great increase in production per unit area through improved planting material, better plant protection and mostly through increased fertiliser use. Fertilisers are more important when tea is grown at low altitude under high rainfall, the soils often being acid and with a low content of exchangeable bases.

5.1 Special aspects of potassium fertilisation

In comparison with many other crops, and particulary with other crops grown in the tropics, mineral uptake by tea is relatively low as shown by *Dierendonck*'s *[1959]* figures quoted in Table 7.

Table 7. Tea. Nutrients removed in 6 tonne fresh leaves (1 tonne made tea)

Country	N	kg P_2O_5	K_2O
Sri Lanka	45	8	21
Indonesia	47.5	9.5	26
East Africa	42	6.8	24

The young shoots have quite high contents of N, P and K, particulary of N. Growth is stimulated by N but its one sided use adversely affects soil fertility. Potassium is important in promoting the translocation of carbohydrate to the young shoots which are harvested. The best quality teas are produced at high altitude and under these conditions potassium is valuable in preventing frost injury.

Yield is mainly stimulated by N fertiliser and the N × K interaction is often positive as we shall see in reviewing results obtained in some of the producing countries.

Soviet Union: Nitrogen fertiliser levels depend upon yield potential of the locality that is about 150 kg N/ha for a yield of 1000 kg leaf and 300 kg for a yield of 2000 kg. P and K recommendations are based on soil analysis. No potash is recommended when soil exchangeable K_2O is over 25 mg per cent and on poor soils annual application of 250 kg K_2O is recommended. Potassium deficiency is often seen when soil potassium is low (less than 15 mg per cent exchangeable). *Oniani [1971, 1972]* has evaluated and published the results of many NPK experiments studying effects on yield and quality. Very high rates of nitrogen (500 kg N and above) cause quality to deteriorate and such effects can be partially counterbalanced by increasing potassium application (Table 8).

Sri Lanka: A long term experiment was started in 1938 by the *Tea Research Institute of Ceylon*. This was a 3 × 3 × 3 factorial NPK experiment and showed that lack of potassium produced spectacular results. Mean yields in the last years of the experiment at the highest N level were:

K_0	761 kg tea
K_{84}	1667 kg tea
K_{168}	1929 kg tea

Table 8. Effect of potassium on yield and quality of tea

Fertiliser, kg/ha N	P_2O_5	K_2O	Crude leaf yield kg/ha	% in dry matter tannin	extracts
0	0	0	2050	22.4	44.0
300	150	0	4483	20.0	43.1
300	150	60	6034	21.9	44.2
300	150	120	7409	22.3	45.4

Under these conditions, the cost of K fertiliser was repaid more than 20 fold. Standard recommendations in Sri Lanka are for potash dressings from 60–200 kg K_2O/ha depending on the productivity of the plantation.

Similar results have been obtained in the other main producing countries – India, Japan, East Africa, etc., and usual recommendations vary between 60 and 160 kg K_2O/ha/year.

6. Tobacco

This crop grows rapidly and most of the useful yield is formed in the last two months of growth. *Chouteau [1969]* estimated the daily uptake rate at about 1.8 kg K_2O/ha. Consequently yields are always higher on soils well supplied with K or where K fertiliser has been applied. K does not only affect yield. It is well known that high leaf K content improves quality and that high Cl content has the reverse effect. These effects have been known since long ago and nowadays most of the tobacco treated in Europe has leaf content of over 5% K_2O. This would indicate that they have been grown on soils properly supplied with potassium. *Chouteau [1969]* found a relationship between soil K and leaf K content.

Cl content should be kept as low as possible. In practice up to 1% Cl in dry matter can be tolerated, quality falls rapidly between 1 and 2% above which level the leaf is useless. Chloride uptake is almost proportional to the Cl concentration in the soil. The main sources of Cl are fertiliser and irrigation water. Potash should always be applied either as sulphate or nitrate with the highest degree of purity practically obtainable. The use of chloride should also be avoided on the preceding crop and care should be taken that Cl is not recycled in farmyard manure. Where tobacco occurs frequently in the rotation it is best to avoid Cl containing fertiliser altogether. Water for irrigation should contain less than 25 ppm Cl.

The influence of potassium is not only seen on yield and burning properties but also on other quality criteria such as leaf size, specific weight, colour, texture, etc. Table 9 shows effects on leaf size measured by *Bowling et al. [1947]*.

Research workers in Maryland conclude that moderate K dressings are needed for maximum yield but that the value of the product is greatly increased by applying much higher rates. In a long term experiment it was found that while 80 kg K_2O/ha was sufficient for maximum yield, three times this rate was justified to attain optimum quality, greatly improving the price received by the grower. *Loué [1978]* gives results of French experiments where the optimum return (a combination of yield and price) was obtained at 300 kg/ha K_2O applied as sulphate (Table 10).

Table 9. Effect of potassium on leaf area in tobacco (Maryland Medium Broadleaf) *(Bowling et al. [1947])*

K$_2$O applied kg/ha	Mean leaf area (cm^2)			
	Upper leaves	Middle leaves	Lower leaves	Mean
0	97.3	147.4	162.5	135.7
34	94.4	150.3	171.0	171.0
135	116.8	182.9	204.5	204.5
270	113.4	183.0	220.0	220.0

Table 10. Effect of rate and source of K fertiliser on yield and crop value in tobacco

Rate kg K$_2$O/ha	Source	Yield kg/ha	$/ha	Price cents/kg
0	–	889	161	18
27	sulphate	1002	291	29
54	sulphate	1014	395	40
81	sulphate	1081	492	46
134	sulphate	1056	536	51
188	sulphate	1045	546	53
296	sulphate	1070	586	55
403	sulphate	1033	563	55
27	chloride	1079	333	31
188	chloride	1085	287	26

7. General conclusions

The list of plants treated here could easily be enlarged by including fibres, forages, other grasses and legumes and leafy vegetables and one would arrive at the same general conclusion, namely that the leafy crops take up and remove from the soil large amounts of potassium. Potassium therefore needs particular attention not only to see that the needs of the crop under consideration are met but also to see that fertility is maintained for the rotation as a whole.

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