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CONTROL OF PLANT VIRUS DISEASES IN SUB-SAHARAN AFRICA: THE POSSIBILITY AND FEASIBILITY OF AN INTEGRATED APPROACH

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ABSTRACT

Plant viruses and virus diseases have been studied for more than 100 years and much attention has been given to their control. However, this has been difficult to achieve because of the lack of any effective means of curing virus-infected plants. Chemotherapy, thermotherapy and meristem-tip culture can be successful, but they cannot be used on a large scale. Consequently, the main approach has been to prevent or delay virus infection or to ameliorate its effects. Various means have been used to achieve these objectives, including phytosanitation (involving quarantine measures, crop hygiene, use of virus-free planting material and eradication), changes in cropping practices, use of pesticides to control vectors, mild strain protection and the deployment of resistant or tolerant varieties. These measures can be used singly or in combination so as to exploit synergistic interactions. This paper considers the advantages of an integrated approach and provides selected examples from experience with several important African diseases, including cocoa swollen shoot, cassava mosaic and groundnut rosette. It is emphasised that much detailed research and a thorough knowledge of farming practices is required before an effective integrated programme can be developed and promoted. There are also formidable problems in ensuring adoption because of the generally limited education and resources of farmers in most parts of sub-Saharan Africa and the severe constraints imposed by the cropping practices adopted. Nevertheless, integrated control measures have evident benefits and should be fostered and promoted as a means of enhancing crop productivity to meet the increasing demands of a burgeoning human population.

Key Words: Cassava mosaic virus, pesticide, phytosanitation, quarantine

RÉSUMÉ

Les plantes agissant comme des virus et les maladies virales ont été étudiées pour plus de 100 ans et beaucoup d'attention a été donnée à leur contrôle. Cependant , ceci a été difficile à accomplir à cause du manque de moyens efficaces de contrôle. La chemothérapie, la thermothérapie et la culture en meristem-tip peuvent être utilisées avec succès, mais elles ne peuvent pas être utilisées à large échelle. En conséquence, la principale approche a été de prevenir ou retarder l'infection virale ou remedier à ces effets. Différents moyens ont été utilisés pour atteindre ces objectifs, incluant la phytosanitation (impliquant des mesures de quarantaine, l'hygiène des plantes, l'usage délibéré du virus sur le matériel de plantation et l'éradiation) ; les changements des pratiques agricoles, l'usage des pesticides pour contrôler les vecteurs, la protection de souches douces et le déployement des variétés résistantes ou tolérantes. Ces mesures peuvent être utilisées singulièrement ou en combinaison, pour exploiter les intéractions synergetiques. Cet article considère les avantage d'une approche intégrée et pourvoit des exemples sélectionnés à partir des expériences avec plusieures importantes maladies africaines, incluant le rejet du cacao gonflé, la mosaïque de manioc et la rosette d'arachide. Il a été souligné que des recherches détaillées et une bonne connaissance des practiques agricoles sont exigées avant de développer et promouvoir un programme effectif et intégré. Il y a aussi des problèmes énormes pour assurer l'adoption à cause de l'éducation et les resources souvent limitées des fermiers dans la plupart des pays de l'Afrique au sud du sahara, et la sévère contrainte imposée par les pratiques culturalles adoptées. Néanmoins, les mesures intégrées de contrôle ont des bénéfices évidentes et devront être encouragées et promises comme un moyen d'améliorer la productivité des plantes pour faire face aux demandes croissantes d'une population humaine en expansion.

Mots Clés: Mosaïque de manioc, pesticides, phytosanitation, quarantaine

INTRODUCTION

Higher plants provide the habitat for a wide range of pathogens, of which viruses are some of the most prevalent. They affect different crop species, including those of great importance in agriculture. The effects of viruses are sometimes benign but they usually decrease crop growth and yield and may cause serious losses. This has long been recognised and has provided an early incentive to study viruses of crop plants. One of the main objectives was to develop effective control measures that could be used on a large scale to increase crop productivity and make effective use of the land, labour and other resources under utilisation.

The main approaches to control are considered here, with the emphasis on virus diseases of crops in sub-Saharan Africa (SSA). The paper considers the constraints to adoption and the scope for developing and utilizing integrated control measures.

Control measures. Some viruses can be eliminated from infected plants by heat or meristem-tip therapy, or by the use of chemicals (Faccioli and Marani, 1998; Mink *et al*., 1998). These methods are used widely to develop virus-free plants of vegetatively-propagated crops for further propagation and release to growers. However, therapy cannot be used on a large scale and the lack of any feasible means of curing infected plants is an important constraint to control. Consequently, other approaches have been adopted. These are to:

(i) prevent plants from becoming infected;
(ii) delay infection to such a late stage of crop growth that yields are not seriously impaired; and
(iii) decrease the effects of infection.

These objectives can be achieved in different ways as discussed in the following sections under five main headings.

Phytosanitation. This term is applied to various approaches to control achieved by decreasing the number of foci of infection from which further virus spread can occur. There are five main ways of doing this, they include:

(i) quarantine measures to avoid introducing viruses and their vectors to areas free of them
(ii) sanitation involving the removal of all surviving plants, debris and self-sown 'volunteer' seedlings of previous crops;
(iii) removal from within and around crops of any weed or wild plants known to be alternative hosts;
(iv) use of virus-free stocks of seed or vegetative propagules for all new plantings; and
(v) removal ('roguing') of diseased plants from within plantings, especially those found during the early most vulnerable stages of crop growth.

Quarantine. The information available on the geographic distribution of viruses and their vectors is inadequate, especially in SSA, because of lack of facilities and trained personnel to conduct surveys and virus identifications. Nevertheless, it is apparent that some viruses and vectors are restricted to certain regions and are absent in others. Some of the most important of the potential threats to crops in SSA are:

(i) *Rice hoja blanca virus* (currently restricted to South and Central America);
(ii) Rice tungro viruses (South and SouthEast Asia)
(iii) *Indian cassava mosaic virus* (India/Sri Lanka)
(iv) *Sri Lanka cassava mosaic virus* (Sri Lanka)
(v) *Cassava common mosaic virus* (South America)
(vi) *Cassava vein mosaic virus* (South America)
(vii) *Maize rough dwarf virus* (Mediterranean)
(viii) *Maize rayado fino virus* (South/Central America)
(xi) *Groundnut bud necrosis virus* (Asia)

There are obvious advantages in adopting quarantine and other measures to maintain the current situation and to avoid introducing viruses or vectors to areas where they could become established and cause problems (Foster and Hadidi, 1998). This has long been recognised and there has been considerable expenditure on establishing and operating quarantine facilities at several centres in SSA, including Muguga in Kenya, Ibadan in Nigeria and Pretoria in Republic of South Africa. Current regulations are devised and co-ordinated by the Inter-African Phyto-sanitary

Council and the United Nations Food and Agriculture Organization, which has published a series of guidelines on the safe movement of germplasm (Frison and Putter, 1989). However, there are formidable difficulties in implementation and enforcement due to the continually increasing scale of international travel and traffic in plant material. There are also particular problems in controlling the movement across land borders and difficulties associated with the disruptions caused by natural disasters, insecurity and civil unrest. These problems have led to the suggestion that quarantine controls are of limited value because pests and pathogens will eventually become established in all the areas where agro-ecological conditions are suitable.

However, this 'inevitability concept' is unduly pessimistic and there are cogent arguments for enforcing quarantine controls to delay the introduction of pests and pathogens for as long as possible and to provide the opportunity to introduce resistant varieties and make other contingency arrangements for use should the need arise (Hewitt and Chiarappa, 1977; Kahn, 1989). This emphasises the importance of maintaining and improving quarantine procedures and of the need to develop new techniques to overcome currently intractable problems in virus detection. One of these is posed by *Banana streak virus*, which can be integrated within the host plant genome and activated in response to environmental stress factors that are as yet ill-defined (Ndowora *et al*., 1999). This has complicated quarantine procedures and has led to constraints on the movement of *Musa* germplasm to avoid the risk of introducing the virus to new areas. The effect has been to impede crop improvement and breeding programmes.

Crop sanitation. The epidemiological literature contains numerous examples of the hazards posed by the debris of previous crops, and by regrowth from the tubers, roots, stems or other plant material left in the ground at harvest. There are also problems due to the growth of 'self-sown' seedling 'volunteers' of crops such as cereals, rice and groundnut. This facilitates the survival and perennation of viruses and their vectors, and can provide a 'green bridge' between successive growing seasons. An African example is provided by groundnut rosette disease and the main aphid vector *(Aphis craccivora)*. These are most prevalent in areas and in seasons when there is abundant growth of volunteer seedlings from previous crops that act as bridging hosts (Evans, 1954).

There are advantages to be gained by adopting husbandry practices that decrease the amount of crop debris and impede survival. This was appreciated at an early stage in studies on cotton leafcurl disease in the Sudan Gezira Irrigation Scheme. Special implements were devised to facilitate the removal and destruction of the cotton stumps remaining after harvest, that would otherwise survive and regenerate to become foci of infection in subsequent plantings (Tarr, 1951). Similar measures are also adopted to avoid the carryover of inoculum in sugarcane, tobacco and other commercial crops, and they have at times been enforced by legislation to help ensure the removal of all crop residues before new planting begins. A typical example is tobacco in what is now Zimbabwe (Hopkins, 1932; Shaw, 1976). Such measures are seldom adopted by peasant farmers although there are undoubtedly benefits to be gained.

Removal of weed or wild hosts. Many viruses have weed or wild hosts that act as foci of infection from which there is spread into or within crops (Bos, 1981; Thresh, 1981). For example, the initial distribution of maize dwarf mosaic disease is often associated with patches of the perennial grass weed, *Sorghum halepense,* that occur commonly within and around crop stands (Damsteegt, 1976). Similarly, the common composite weed *Tridax procumbens,* is the host of the aphid-borne virus or viruses that cause ringspot and leafcurl diseases of sunflower in eastern and southern Africa (Theuri *et al*., 1987). These examples emphasise the importance of adopting effective weed control measures, not only to avoid competition, but also to eliminate sources of inoculum. The advantages to be gained are also apparent from experience with *Cacao swollen shoot virus* in the Western Region of Ghana, where many of the outbreaks in cocoa are associated with the under-storey forest tree *Cola chlamydantha* (Attafuah, 1965). These trees are indigenous hosts of the virus from which spread occurs to nearby cocoa and the wild hosts are removed when outbreaks are treated during the eradication campaign discussed in more detail later (in this paper).

Elsewhere, there have been restrictions on cultivation of okra and Malvaceous ornamentals in the Gezira irrigation scheme in the Sudan, as these plants are known to be hosts of *Cotton leaf curl virus* and the whitefly vector *Bemisia tabaci* (Tarr, 1951). Such measures are likely to be more widely applicable, but they are difficult to enforce in SSA, where little attempt is made to control virus diseases by removing weed or alternative hosts.

Virus-free propagules. The use of virus-free propagules for all new plantings is a basic approach to control that is beneficial for several reasons:

(i) virus-free material establishes more readily and is more productive than infected;

(ii) if virus-free material is adopted there are no initial foci of infection within crops from the outset, during the early most vulnerable stages of crop growth. This delays and curtails the period over which any subsequent spread can occur;

(iii) plants not infected until a late stage of crop growth are affected less severely than those infected early; and

(iv) infected propagules are particularly dangerous sources of inoculum because they tend to be distributed randomly within crops. This facilitates virus spread from infected to neighbouring healthy plants, whether this is by contact or by vectors.

For these reasons, much attention has been given in technologically advanced countries to producing virus-free stocks of seed and of tubers, cuttings or other propagules of crops that are propagated vegetatively (Hollings, 1965). There are no major technical problems in obtaining stocks that are free or largely free of infection by careful selection from those already available, or by using some form of therapy as discussed previously (in this paper). When such stocks are obtained, they are multiplied at selected sites where little or no infection is likely to occur. The 'elite' stocks are then released to seed merchants, wholesale distributors or nurserymen, or direct to farmers. Official inspection and certification procedures are used to designate and maintain the health status of the stocks being distributed, and they are widely used in North America, Europe, Australia and elsewhere (Ebbels, 1979; Waterworth, 1998). Temperate crops that benefit from this approach include potato, deciduous fruits, hop and ornamentals that are propagated vegetatively. Others are crops grown from seed including lettuce, barley, *Phaseolus* bean, lupin and other legumes.

A similar approach would undoubtedly bring considerable benefits with many African crops and facilitate control of virus diseases including cassava mosaic, bean common mosaic, cowpea mosaic and others that are currently causing serious losses. However, little attempt has been made to produce and deploy virus-free stocks, except to meet quarantine requirements and so facilitate the movement of germplasm, commercial stocks and other plant material between SSA countries and from SSA to other regions. An exception to this generalization is in the Republic of South Africa where seed and stock certification schemes are available for potato, sweetpotato, citrus and a wide range of other crops. Banana is another crop of which selected stocks are available and micro-propagated material is currently being used widely in Kenya, Uganda and elsewhere in SSA. There has also been considerable use of virus-free stocks of potato in North Africa, Ethiopia, Sudan, Kenya and several other SSA countries, using 'seed' tubers produced locally or imported from Europe. In addition there have been imports to Africa of certified stocks of rose, chrysanthemum, carnation and other ornamentals and seed of horticultural crops including tomato, lettuce, *Phaseolus* bean and cucurbits.

These examples are few but indicate the scope for a generally increased use of virus-free material of a much wider range of African crops. However, this will not be achieved quickly or easily because of the need to develop appropriate seed production systems and to educate farmers and encourage a transition from traditional subsistence farming to commercial crop production utilizing certified stocks of improved quality and health status. Meanwhile, commercial seed production and distribution systems in SSA are poorly developed and the usual practice of farmers is to retain seed or other propagules from previous plantings or from neighbours; only limited attention is given to health status which is frequently unsatisfactory (DeVries and Toenniessen, 2001).

Roguing. The removal of diseased plants from within crop stands is usually termed roguing. This is a well-known means of virus disease control achieved by eliminating initial sources of infection from which further spread can occur. Roguing is widely applicable and has been used in attempts to control or at least contain diseases of diverse crops in both temperate and tropical regions (Thresh, 1988). The approach is most effective against viruses that do not spread quickly or far in any considerable amount (Putter, 1980). However, roguing is generally unpopular with farmers, who are seldom prepared to allocate the time and effort required to inspect crops with the thoroughness and frequency required to identify and remove diseased plants. There is also a reluctance to rogue any diseased plants that may contribute at least some yield and an even greater unwillingness to remove neighbouring symptomless plants, even though this may be necessary to eliminate latent infections.

For these reasons roguing has been most successful when adopted by government or commercial organizations, which take on the responsibility of employing and training staff to carry out the regular inspections and treatments required. This approach has been adopted in Australia against banana bunchy top and sugarcane Fiji diseases, and in parts of Europe and North America against citrus tristeza, plum pox and other diseases of fruit crops (Thresh, 1988). Roguing has also been used widely to maintain the health status of 'seed' potato stocks. The inspection and treatment procedures adopted in operating such schemes are based on epidemiological information and, where infection is prevalent, whole plantings may be removed as a means of safeguarding less severely affected plantings.

The eradication campaign against cocoa swollen shoot disease in Ghana has been the biggest and most ambitious ever undertaken in SSA or elsewhere, as described in the detailed case history (in this paper). There has, at times, been considerable opposition to the campaign from farmers and such measures are seldom appropriate or feasible in an African context. This explains why so little use has been made of roguing as a means of controlling cassava mosaic or other diseases that are likely to be amenable to this approach. However, roguing has been used to improve the health status of cassava or other crops being propagated by researchers or extentionists for distribution to farmers. There is also scope for roguing stands of sugarcane, banana, citrus, pineapple or other plantation crops and on large commercial farms. However, these circumstances are exceptional, individual small-scale farmers make little use of roguing and the situation is unlikely to change in the immediate future.

Decreasing the incidence of infection by changing cropping practices. There is abundant evidence from a wide range of crops of the importance of cultural practices in determining the prevalence of virus diseases and the losses they cause (Thresh, 1982). A further detailed consideration of the many husbandry practices that influence spread is beyond the scope of this review. Nevertheless, some of the most important are listed in Table 1 in which it is convenient to distinguish between practices adopted before or at planting and those adopted later.

Pre-planting factors include the choice of site, as based on previous cropping history, site suitability and availability and the selection of planting material. Factors at planting include the date chosen, the spacing adopted, the size and shape of the area planted and the choice of variety or varieties and any intercrop(s) grown. Post-planting factors include thinning and harvesting dates, the method, timing and frequency of any weed control measures, and applications of irrigation water, fertilisers or pesticides.

Virus spread is facilitated by some cropping practices and impeded by others. This provides an opportunity for farmers to adopt measures that are beneficial or at least 'neutral' in their effects, and to abandon any that are detrimental. Farmers can do so empirically their indigenous knowledge indicating that some practices usually lead to satisfactory and reliable yields, whereas others do not. However, it is more advantageous for decisions to be based on, or at least influenced by, a detailed knowledge of the epidemiology of the virus or viruses of concern. Such information is difficult to obtain and is seldom available for diseases of African crops. Moreover, even if the information is available, it is not easily disseminated to farmers, especially those with little or no awareness of even the most rudimentary plant pathological principles.

A further problem is that cropping practices known to be beneficial in decreasing disease incidences are not always feasible or appropriate in relation to other agricultural or horticultural requirements, or on socio-economic grounds. This is evident from experience with maize streak disease in the Democratic Republic of Congo. It is well known that the disease is more prevalent in late than in early plantings. However, the area of land that can be cleared and planted early depends on the amount of manual labour available within the community, which can be a serious constraint (Vogel *et al*., 1993). Other examples of the importance of cropping practices are provided in the 'case histories' of specific diseases (in this paper).

The benefits of close spacing in decreasing the proportion of infected plants within a stand have been demonstrated in experiments on groundnut rosette (A'Brook, 1964; Davies, 1976, Farrell, 1976a) and cassava mosaic diseases (Fargette *et al*., 1990; Egabu *et al*., 2002). It has also been shown that the incidence of *Tomato spotted wilt virus* in tobacco is decreased if thinning to the final spacing required is delayed until after the main influx of thrips vectors has occurred (Vanderplank, 1944; Vanderplank and Anderssen, 1944).

Several other cropping practices merit further discussion in relation to virus diseases in SSA. One relates to the sites used for new plantings. It may be advantageous to adopt fresh sites or suitable rotations to avoid any carry-over of inoculum from previous crops. There may also be advantages in planting in large compact blocks of uniform age to decrease the proportion of plants in the vulnerable peripheral areas where incoming insect vectors tend to alight preferentially and lead to a high incidence of infection (Hayes, 1932; Fargette *et al*., 1985; Colvin *et al*., 1998). Moreover, it is advantageous to provide at least some degree of isolation from known sources of inoculum and to consider the direction of the prevailing wind and plant upwind rather than downwind of major foci of infection (Thresh, 1976). These principles are utilized widely in temperate agriculture and, especially in producing virus-free stocks of seed or vegetative propagules. Comparable benefits could be gained in SSA, as apparent from studies on several diseases in which the incidence of infection decreased with increasing distance from the source. Such gradients tend to be curvilinear and of concave shape, which means that the decrease is usually more rapid over quite short distances near the source, as reported with cocoa swollen shoot (Thresh and Lister, 1960), cassava mosaic (Fargette *et al*., 1990), cotton leafcurl (Giha and Nour, 1959), maize streak (Gorter, 1953; Rose, 1973), okra mosaic (Atiri and Varma, 1991) and okra leaf curl diseases (Fargette *et al*., 1993). The advantages of isolation and siting in relation to wind direction and known sources of infection can be exploited to decrease the incidence of maize streak disease in South Africa (Gorter, 1953) and also with sugarcane and other tropical plantation crops. However, this is seldom feasible in subsistence agriculture, especially in the many areas where land is scarce, individual holdings are small and there is little or no separation between them; and it is difficult to ensure synchrony in planting date. This facilitates spread into and between plantings of a wide range of tropical crops, as exemplified in studies on cocoa swollen shoot disease (Thresh *et al*., 1988) and from experience with maize, rice and other crops that are commonly grown in overlapping sequence.

Genetic diversity is a marked feature of many crops in SSA. This is due to the cultivation of numerous local landraces of crops including *Phaseolus* bean, cassava, cowpea, maize, sorghum, sweetpotato and yams. Commonly, two or more landraces are grown in each field and the mixtures are sometimes complex. This is exemplified by data for cassava in northern areas of Mozambique where many landraces were recorded in each locality and up to five occurred in individual small plantings (Hillocks *et al*., 2002). Moreover, interplanting two or more different crops is a common practice and one that is facilitated by the frequent use of hand labour for planting and weeding.

Both varietal mixtures and inter-planting with other crops have received considerable attention from agronomists and other researchers. It is now recognized that both types of crop diversity are important in providing farmers with at least some degree of resilience and stability that contributes to reliable yields and avoids total crop failure (Smithson and Lenné, 1996). This is achieved if one or more constituents of the mixture are able to withstand adverse weather conditions or the damaging effects of pests and diseases, even though others succumb. Beneficial effects of this type are likely to occur with virus diseases through effects on vector populations and their movement within crop stands, or by providing physical barriers or camouflage and by increasing the separation between susceptible individuals within the mixture. However, little attention has been given to decreasing virus spread in this way and there is scope for much additional research. This is apparent from the few published results which show a decrease in the spread of cassava mosaic disease to a susceptible variety of cassava when grown together with resistant varieties (Sserubombwe *et al*., 2001) and also with maize or other crops (Ahohuendo and Sarkar, 1995; Fondong, Thresh and Zok, 2002). There is also an earlier report of a decrease in the spread of *Bean common mosaic virus* when bean was intercropped with maize (van Rheenan *et al*., 1981). However, the situation can be complex and inconsistent results have been reported in other intercropping trials with cassava (Fargette and Fauquet, 1998) and on the incidence of *Maize streak virus* when maize was intercropped with millet in comparisons with sole stands in Uganda (Page *et al*., 1999). There is also a report of the adverse effect of *Phaseolus* beans on the growth and yield of a groundnut intercrop in Malawi, even though the incidence of rosette disease was decreased (Farrell, 1976b). Additional studies of this type and cost/benefit analyses are required to elucidate the role of biodiversity and to assess the implication of the current trend away from crop and varietal mixtures. It may eventually be possible to devise cropping systems that combine the advantages of modern varieties and methods of cultivation with those of traditional practices.

Host plant resistance. At least some degree of genetic diversity is a feature of all crop species. It is one that is exploited by agriculturalists and horticulturalists to increase crop productivity and to avoid the most damaging effects of pests and pathogens. This is achieved by selecting and adopting genotypes that yield satisfactorily and avoid or in some way withstand biotic and abiotic constraints.

In considering host plant resistance to virus diseases, it is helpful to distinguish between *'positive'* and *'negative'* selection. *Negative selection* occurs when particularly vulnerable crop genotypes are discarded by farmers or researchers, either because they are recognized as being severely diseased, or simply because they do not grow or yield satisfactorily, even though the reasons for this are not fully understood. *Positive selection* is the outcome of a deliberate attempt to identify particularly resistant genotypes when heterogeneous populations are exposed to infection. Consequently, positive selection requires considerable scientific input and expertise, whereas negative selection is practised within even the most primitive cropping systems. Both approaches to selection have been widely used and intentionally or unintentionally host plant resistance has made a big contribution to virus disease control by decreasing the incidence and/or consequences of infection.

The use of disease-resistant genotypes has obvious advantages because it provides a convenient means of control that can be used alone, or to supplement or complement other measures. Moreover, there are no harmful side effects and no additional costs once resistant varieties are made available that are comparable or superior in performance to the susceptible ones being grown. This explains why breeding for host plant resistance has featured so prominently in research on many crops and especially in the tropics at the International Agricultural Research Centres in SSA and elsewhere.

The scope for exploiting host plant resistance is apparent from experience with many African crops and diseases. For example, it has long been known that cassava varieties differ considerably in their response to cassava mosaic disease. Some of the many varieties being grown are more severely damaged by the disease than others, and farmers can alleviate the problem of mosaic by retaining the most productive varieties and discarding those that are particularly vulnerable. This occurred during the early epidemics reported in Ghana and elsewhere in West Africa (Dade, 1930) and later in Madagascar (Cours, 1951) and more recently during the severe pandemic in Uganda

(Otim-Nape *et al*., 2000; Otim-Nape *et al*., 2001). The 1990s pandemic in Uganda was most damaging in districts where few varieties were being grown; farmers in other districts were able to select somewhat resistant types from the wide range of varieties available. One of the reasons why farmers were able to adapt so quickly to the problem of mosaic is that cassava is propagated vegetatively from stem cuttings collected when previous plantings are harvested. Severely diseased plants produce few cuttings that are suitable for further propagation and so tend to be under-represented in subsequent crops, even if farmers do not discriminate in favour of vigorous unaffected plants or those that are only slightly affected.

Similar considerations apply with the many other vegetatively-propagated crops that are affected by virus diseases, including banana, yams, potato and sweetpotato. This provides farmers with an important 'coping strategy' and explains why these crops can usually be grown satisfactorily despite the often high incidence of infection. Affected plants tend to express inconspicuous symptoms that are not associated with obvious effects on growth or yield.

The scope for resistance breeding to avoid or alleviate the losses caused by viruses of tropical crops has long been evident from experience with sugarcane mosaic disease (Summers and Brandes, 1948). Resistant varieties were also sought in early studies on cassava mosaic, cocoa swollen shoot and groundnut rosette diseases, as discussed in the three 'case histories' (in this paper). Moreover, attention has been given to many other diseases including bean common mosaic, maize streak and rice yellow mottle. Considerable success has been achieved and various types of host plant resistance have been exploited. They include hypersensitivity, resistance to infection, tolerance of infection and resistance to the insect vector. These traits have been obtained by selection from amongst existing or introduced varieties, or by crosses to related species.

Resistant varieties are used widely in agriculture and horticulture and they could make an even greater contribution to disease control but for several constraints:

(i) A considerable research effort is needed to develop effective resistance breeding programmes, as these must also take account of other biotic and abiotic constraints and meet the often exacting requirements of farmers, consumers and processors. The necessary funds, personnel and resources are not always available for a sufficiently long period, or they may be inadequate.

(ii) There have been instances of resistant varieties being released without adequate on-farm testing to ensure that the varieties are suitable for adoption and that they meet the often stringent requirements of farmers and consumers. Some of the recent criticism of this so-called 'top down' approach and of the alleged lack of interaction between farmers and researchers is excessive and unjustified.
Nevertheless, there is undoubtedly scope for greater involvement of farmers in evaluation and selection and a participatory approach is now a requirement of many donors funding crop improvement programmes in SSA.

(iii) Even if resistant varieties are developed, they may not be available because of the lack of an effective seed multiplication and distribution system, or because farmers are unaware of the benefits to be gained from their adoption.

(iv) The resistance may be associated with undesirable traits as resistant varieties may lack some of the desirable attributes of the susceptible varieties being grown.

(v) The need to adopt resistant varieties is not necessarily compelling, especially if the disease occurs sporadically and attracts less attention than other factors decreasing yield.

(vi) Resistance may be overcome due to the emergence or increased prevalence of virus strains that damage previously unaffected varieties. Moreover, varieties that are resistant in some areas may be susceptible in others. Thus, it may be difficult to develop and exploit broad-based resistance that is also durable.

Collectively, these constraints are of great importance, as apparent from the three case histories (in this paper) and many other examples. Nevertheless, virus-resistant varieties of several African crops are already available through conventional plant breeding and this approach could make an even greater contribution to virus disease control if extended to other crops and diseases, and if improvements are made in the means by which resistant varieties are evaluated, selected, multiplied and made available to farmers. Moreover, progress will be facilitated by using modern technologies to improve conventional breeding programmes. These approaches are being used already to ensure viable crosses between hitherto recalcitrant parents or species and to locate resistance genes and so permit marker-assisted selection as now possible in breeding varieties resistant to cassava mosaic disease (Akano *et al*., 2002).

There will also be an opportunity to exploit the novel forms of resistance that have become possible since the seminal studies in the 1980s on pathogen-derived resistance to *Tobacco mosaic virus* (Powell Abel *et al*., 1986). Several viruses of tropical crops have featured in such studies and resistance to papaya ringspot disease achieved by incorporating the coat protein of the causal virus into the genome of papaya is being used successfully to control the disease in Hawaii (Gonsalves, 1998; Ferreira *et al*., 2002). A similar biotechnological approach is being considered with several viruses of crops in SSA, including *Rice yellow mottle virus,* cassava mosaic viruses, *Banana streak virus, Groundnut rosette virus* and *Sweetpotato feathery mottle virus*. Transgenic plants with putative resistance to these viruses are being tested in laboratory containment facilities in Europe and North America, and there have been field trials with a transgenic sweetpotato in Kenya. An advantage of the transgenic approach is that resistance can be introduced to improve widely-grown varieties that are popular because they have many of the attributes required by farmers and consumers, even though susceptible to virus infection. However, there is considerable opposition to the release of genetically modified organisms (GMOs) and formidable regulatory issues and public misconceptions will have to be overcome before GMOs can be released for general use. As for conventional resistance, effective methods of multiplication and distribution will be required if GMOs are to be widely adopted.

Chemical control. Many viruses have animal or fungal vectors that spread into, between and within crops. This has led to the use of pesticides or other chemicals to prevent such spread by decreasing vector populations or by impeding transmission (Satapathy, 1998; Perring *et al.*, 1999). Insecticides, acaricides, nematicides and fungicides have all been used successfully to prevent or at least decrease virus spread. Mineral oils and repellents have also been used to impede virus transmission by vectors. However, several difficulties have become apparent and the use of chemicals is not always applicable or appropriate.

One of the problems with the use of chemicals is that the relationships between viruses and their vectors are complex and a decrease in vector populations does not necessarily achieve a commensurate decrease in virus spread. This is apparent from the limited effectiveness of insecticides used in attempts to control the aphid vectors of non-persistent viruses. These are acquired and transmitted most effectively in brief probes and often by aphid species that visit but do not colonize the crop being sprayed. Moreover, there are problems due to the difficulty and cost of treating crops throughout the entire vulnerable period of growth. There may also be damage to the natural enemies of vectors and risks to the environment and to human health. Consequently, pesticides play only a limited role in plant virus control, even in developed countries where they are mainly used against the vectors of persistent viruses of sugarbeet, cereals, potato and a wide range of horticultural/vegetable crops. Mineral oils are also used to protect horticultural crops and ornamentals that are of sufficiently high value to justify the cost of repeated applications.

There is even less use of chemicals to control viruses in SSA, where the main use of pesticides is to control direct pests and pathogens of export crops including coffee, cocoa, tea, cotton, pineapple, sugarcane, tobacco and vegetable/horticultural crops. Otherwise, except on the relatively few large-scale commercial farms, only a small proportion of farmers has access to pesticides or means of application and the value of the crops being grown is seldom sufficient to justify or cover the cost of treatment. Moreover, it is inappropriate to promote the use of pesticides on subsistence crops, many of which are consumed fresh or after minimal processing.

The scope for using insecticides to control viruses in SSA is indicated by trials with maize streak (van Rensberg *et al*., 1991) and the three diseases discussed as case histories. However, such treatments are seldom cost-effective and they have not been recommended for general use. The main use of insecticides in SSA is currently in attempts to control viruses of tomato and vegetable crops and insecticides are likely to be increasingly important in horticulture as vector populations continue to become more prevalent on such crops. Whiteflies have already done so over the last decade and led to serious virus problems in other tropical and sub-tropical areas following the arrival of the damaging B-biotype of *Bemisia tabaci* (Brown, 1994; Morales and Anderson, 2001), which has also been reported in some parts of Africa (Bedford *et al*., 1993).

Mild strain protection. A possible means of alleviating the effects of virus infection on growth and yield is by prior inoculation with a mild strain of the same virus. The ability of mild strains to protect plants from the damaging effects of closely related virulent ones has long been recognized and the phenomenon has been used extensively by virologists to assess the relationships between viruses and virus strains (Bawden, 1950). However, there were several reasons for an initial reluctance to consider this approach to controlling virus diseases. There was concern that mild strains might mutate to more virulent forms, or that they would spread and cause damage to other and more virus-sensitive crops. It was also feared that mild strains might have synergistic effects in combination with other unrelated viruses. Moreover, the deliberate dissemination of mild strains was incompatible with control strategies based on phytosanitation.

Despite these reservations, mild strains have in recent decades been disseminated widely and successfully to control *Tomato mosaic virus* and several other viruses that are so prevalent and difficult to control by other means that the deliberate dissemination of mild strains was considered to pose no additional hazards (Fulton, 1986). This is the situation in tropical areas of Asia that are severely affected by *Papaya ringspot virus* (Yeh *et al*., 1988).

However, mild strain protection has not been used in SAA except against *Citrus tristeza virus* in the Republic of South Africa (van Vuuren*et al*., 1993; Garnsey *et al*., 1998). There have also been trials on the scope for using mild strain protection against *Cacao swollen shoot virus* (in this paper). The approach was promising, but far more research is required on this and other pathosystems before mild strain protection can be recommended.

The integration and uptake of control measures. In considering the effectiveness of control measures and their integration, it is convenient to follow the approach of Zadoks and Schein (1979) and distinguish between measures that decrease the initial amount of inoculum from which spread occurs (Xo) and those that decrease the rate of disease progress (r). Clearly, phytosanitation decreases Xo, whereas resistant varieties, pesticides, intercrops and several other measures decrease r.

There are obvious advantages in combining two or more approaches to decrease both Xo and r. An example is the use of virus-free seed together with intercropping to achieve partial control of *Bean common mosaic virus*. Failure to use virus-free propagules or other means of decreasing Xo can undermine the otherwise beneficial effects of isolation and other measures. This is evident from the case histories presented (in this paper), which also indicate the benefits of adopting a selected combination of measures. The problem is to devise an integrated approach of this type that is not only effective but also one that farmers are able and prepared to adopt. Herein lie the difficulties, as there are serious obstacles to developing and adopting an appropriate and effective combination of control recommendations. This is due to the inadequate information on the range of options available, or to the failure of farmers to utilize the measures proposed, either because they are inappropriate or they have not been adequately promoted. For example:

(i) Virus-free propagules are not generally available and other phytosanitary measures are unpopular and seldom adopted;
(ii) There are limitations on the extent to which site selection and other cropping practices can be adapted to avoid or alleviate virus disease problems. Moreover, some of the changes associated with modern practices are likely to undermine the effectiveness and resilience of traditional cropping systems;
(iii) Resistant varieties have been identified for only some of the many diseases encountered and they are not always readily available, or they are not durable and may have undesirable features which limit their adoption by farmers;
(iv) There has been little use of chemicals to control vectors or to impede virus transmission and the use of pesticides is seldom justified because of socio- economic considerations and the risks to human health, natural enemies and to the environment;
(v) There has been inadequate research on mild strain protection and there are likely to be few situations in which this approach to control is likely to be appropriate and effective;
(vi) There are continuing delays in the development and use of transgenic forms of resistance, in part due to the lack of regulatory procedures and public concern over the use of genetically modified organisms.

Collectively, these are powerful constraints and explain why such limited progress has been made in controlling virus diseases in SSA that continue to cause very serious losses. These comments and conclusions apply generally and they are illustrated by the following ‘case histories’.

The control of three important African diseases. Three African diseases of particular importance are discussed here to illustrate how the general principles presented in the foregoing sections have been used in developing control measures. The examples selected are three of the most important and widely studied diseases of African crops (Thresh, 1991).

Cocoa swollen shoot disease. Cocoa swollen shoot disease was first reported in what is now Ghana in 1936, although there is anecdotal evidence that it occurred in the 1920s, when large patches of dead and dying trees were seen in one of the main cocoa-growing areas (Posnette, 1947). The disease was soon shown to be caused by a mealybug-transmitted pathogen that was assumed to be a virus, but it was not possible to implement control measures on a large scale until after the Second World War (1939-1945). An official eradication campaign was then introduced and enforced by staff of the Department of Agriculture, despite considerable opposition from farmers. The eradication procedure adopted was based on field studies which established that outbreaks could be brought under control by regular inspections and treatments so as to find and remove all trees with the stem or leaf symptoms of swollen shoot disease (Posnette, 1943). This approach was shown to be most effective in treating small outbreaks and when all neighbouring symptomless ‘contact’ trees were also removed in attempts to eliminate latently infected trees that could be foci of infection (Thresh and Owusu, 1986).

Based on these findings, eradication measures have been used on a large scale in Ghana for more than fifty years and they still continue. There has been no recent assessment of the campaign but by 1988, a total of 187 million cocoa trees had been removed, which is equivalent to 187,000 ha at conventional spacings, or *c.* 9% of the total area of cocoa recorded in the 1970s (Thresh, 1988; Ollennu *et al.*, 1989). Many other trees have been killed by the disease and there have at times been millions more awaiting removal because of delays in implementation. Moreover, there have been periods of little or no activity due to opposition from the farmers or to a lack of funds. A major problem has been the huge scale and expense of the undertaking which has necessitated a huge allocation of national resources. This was justified by the importance of cocoa as the main export crop and source of 'hard' currency, but inevitably there has been a major diversion of funds that otherwise could have been spent on other aspects of cocoa production or on agricultural improvement projects.

Despite the massive allocation of budget and resources in Ghana, it has seldom been possible to inspect and treat the worst affected *'areas of mass infection'*. Consequently, the main emphasis has been on treating the immediately adjoining areas to form a *'cordon sanitaire'* and on the less affected *'areas of scattered outbreaks*'. A similar eradication policy was adopted in Nigeria, where the swollen shoot problem was less than in Ghana. Accordingly, it was possible to adopt more drastic cutting out procedures and initially all trees with symptoms were removed and also all symptomless trees within a distance of 30 metres around each outbreak (Lister and Thresh, 1957). The measures were revised later on the basis of experimental results and outbreaks were then treated less drastically according to the size of the outbreak found (Thresh and Lister, 1960).

The extensive areas of mass infection in Ghana have been left largely untreated and virulent strains of swollen shoot virus have become prevalent. In these circumstances the deliberate dissemination of mild strains of virus to protect plants from the damaging effects of virulent strains poses no additional hazards. The scope for using mild strains in this way was suggested from the results of early studies (Posnette and Todd, 1955). However, these were not pursued because the intention at the time was to implement the eradication campaign in all areas and the two approaches of phytosanitation and mild strain protection were not compatible. It was later realized that eradication was not feasible and research on mild strain protection was resumed (Hughes and Ollennu, 1994). Promising results were obtained but the approach has not been adopted widely.

Various attempts have been made to improve the effectiveness of the eradication campaign in Ghana by applying an insecticide to the symptomless trees around the outbreaks being treated so as to prevent any further spread. A decrease in mealybug vector populations and in rate of virus spread were apparent in an early trial with a systemic organo-phosphorus insecticide applied to the soil or injected into the trunk (Hanna and Heatherington, 1957). However, these benefits were only achieved by repeated applications, which was expensive and caused an undesirable taint of the cocoa beans harvested from the treated trees.

Other problems were encountered when the chlorinated hydrocarbon insecticides, endrin and dieldrin, were used to decrease vector populations by controlling the crematogasterine ants that protect and tend mealybug colonies (Entwistle, 1972). This led to undesirable side effects and to the emergence of secondary insect pests of cocoa that had hitherto caused little or no damage to the shoots and pods. It has also been difficult to decrease vector populations by introducing or augmenting natural enemies, and currently vector control plays no part in the routine measures adopted against swollen shoot disease in Ghana or elsewhere in West Africa.

There is obvious scope for using virus-resistant cocoa varieties to help overcome the swollen shoot problem by decreasing the risk of infection and so enhancing the effectiveness of eradication measures. This was appreciated at an early stage of the investigations, but the range of varieties available in West Africa was limited at the outset and initial attempts to identify resistant genotypes were unsuccessful (Posnette and Todd, 1951). Accordingly, seed was obtained from trees held in a collection of cocoa in Trinidad that originated in the Amazon region of South America. Genotypes from the upper Amazon region of Ecuador were identified that are infected less readily and develop less severe symptoms than the Amelonado cocoa that predominated at the time in Ghana and elsewhere in West Africa. Seed or seedlings of selected Upper Amazon types have been widely distributed to farmers and for official replanting schemes to replace trees removed during cutting out operations. Moreover, selected Upper Amazon trees have been intercrossed or crossed with Amelonado trees to produce vigorous hybrids that yield well and begin to bear pods earlier than Amelonado trees. Some of the hybrids are also resistant to virus infection and seed gardens have been established to provide progeny for use in the worst affected areas (Thresh *et al*., 1988).

Inter-Amazon hybrids are now widely grown in Ghana and elsewhere in West Africa and they make a substantial contribution to cocoa production, which has continued despite the prevalence of swollen shoot disease. The contribution of the resistant varieties would have been even greater and reinfection would have been lessened if all new plantings had been made in large compact blocks that were separated from other cocoa by clear alleys or stands of non-host barrier crops. The scope for adopting such practices has long been recognized (Cornwell, 1958; Thresh, 1958; Ollennu *et al*., 1989). However, there has been little attempt to demonstrate or exploit the benefits, mainly because of the limitations imposed by the patterns of land use and land tenure.

Cocoa production in Ghana and Nigeria is largely by peasant farmers who establish mainly small plots of irregular shape. There is seldom any separation between plantings of different age or under different ownership and collectively these may form large contiguous stands (Thresh *et al.*, 1988). The spread of swollen shoot disease is greatly facilitated in these circumstances. Moreover, the work of the inspection and treatment teams is hampered by the need to identify individual farm boundaries and ownership, for compensation to be paid, or for replanting to begin. Cutting out and replanting may have to be delayed until all the owners are traced, or the operations are discontinued and untreated farms are left within partially treated areas. Consequently, there is little opportunity to establish the large isolated blocks of compact shape that would decrease the proportion of trees in the vulnerable peripheral areas and so decrease the risk of infection, especially if sub-divided into smaller separate units each surrounded by rows of a non-susceptible barrier crop.

Cocoa swollen shoot disease is exceptional in several respects. For example, it has received far more attention from researchers than any other virus disease of an African crop (Thresh, 1991). Moreover, the control of swollen shoot has been largely the responsibility of Government or quasi-Government organizations and farmers play only a very limited role. They do not carry out the inspections or cutting out treatments and at times the subsequent replacement of trees removed or replanting of treated farms has also been done on behalf of and not by the farmers concerned. This largely circumvented the need to educate and train farmers in disease control and replanting methods. It also facilitated the adoption of resistant varieties and enabled the authorities to enforce measures that would, otherwise, have been unacceptable. However, there were big financial implications and for years, the high cost of disease control measures dominated the budget of the Ghana Department of Agriculture. Responsibility for the eradication campaign later passed to the Ghana Cocoa Marketing Board and, recently part of the cost of cutting out operations has been borne by the European Community. Nevertheless, there has been little evident scrutiny of the effectiveness of the measures adopted and no cost/benefit analysis of the operation. This emphasizes the exceptional nature of the swollen shoot disease problem and the approach used is not one that can be applied to other virus diseases in SSA.

Cassava mosaic disease. The disease now known as cassava mosaic, was first reported in 1894 in what is now Tanzania. Mosaic has since been recorded in all the cassava-growing areas of Africa including the off-shore islands of Cape Verde, Zanzibar Madagascar and Seychelles (Calvert and Thresh, 2002). It has long been known that the disease is prevalent in some areas of SSA and relatively unimportant in others, and that the incidence of infection can change markedly within only a few years. This makes it difficult to assess the importance of mosaic and the benefits to be gained from adopting control measures. These are likely to be substantial, as apparent from recent surveys of the prevalence of the disease in several important cassava-growing countries (Calvert and Thresh, 2002), and from studies in several countries on the effects of the disease on representative varieties (Thresh *et al*., 1994a). Based on these findings, it has been estimated that total production in Africa would be increased by 15-24%. However, the effects of mosaic are becoming more and more apparent and this target may be averted (Thresh *et al*., 1997). This emphasizes the scope for adopting control measures to enhance production, or to increase productivity and so release land for other purposes, or to permit longer recovery periods of fallow.

Although the prevalence and importance of cassava mosaic disease has long been recognised, there have been only limited attempts to control the disease except at times and places when losses have been so severe as to threaten food security. This is partly because cassava has, until recent years, been somewhat neglected and it has received inadequate attention from researchers and extensionists, as well as those who were promoting more nutritious food crops. Moreover, cassava is grown mainly by small-scale farmers. Originally the productivity per unit of land was largely unimportant, because much of the crop is grown for local consumption, or for food security to be used in times of drought. The status of cassava is now changing as it becomes increasingly important because of its ability to grow and yield in poor soils and under adverse conditions, and as a substantial source of income through sales to urban areas and for processing into chips, flour, alcohol, starch or other products (Nweke *et al*., 2002).

In considering the different approaches to controlling cassava mosaic disease, it is helpful to distinguish between the measures used to some extent inadvertently by farmers and even by researchers from the specific control recommendations of pathologists. The important role played by farmers in overcoming the mosaic problem is apparent from early experience in West Africa soon after the disease was first reported there. It was then realised that some of the many varieties being used in what is now Ghana were growing much more satisfactorily than others and the least productive varieties were discarded (Dade, 1930). Whether this was done because of the severity of the mosaic symptoms expressed, or because of the poor growth and yield of the plants is unclear. Nevertheless, the outcome would have been similar in that it has led to the selection of varieties that are to some extent resistant to or tolerant of infection.

There is much additional evidence of the ability of farmers to cope in this way and to continue producing cassava satisfactorily by adopting suitable landraces. For example, the 1990s pandemic of a particularly severe form of mosaic in Uganda led to big changes in the main varieties being grown (Otim-Nape *et al.*, 2001). At the outset the locally selected variety *Ebwanateraka* predominated in several districts. It proved to be extremely vulnerable to infection with the severe form of mosaic and was soon largely displaced by other varieties, only some of which were introduced and distributed officially because of their resistance to infection. Local varieties that are somewhat tolerant of infection have undoubtedly made a big contribution to the recovery in production that has occurred since the peak of the recent pandemic in the mid-1990s (Otim-Nape *et al.*, 2000).

Currently, in Uganda and in many other African countries, mosaic undoubtedly decreases yields, but not to an unacceptably low level. Farmers may even be unaware or unconcerned that the disease is present, or they regard it as less important than other factors influencing productivity. This accounts for the observation that it is not uncommon for mosaic-infected plants of some varieties to out-yield healthy plants of others. Moreover, the ability of farmers to 'live with' mosaic also explains why the disease attracts so little attention in Ghana and other West African countries, where infection is prevalent in many of the varieties being grown (Calvert and Thresh, 2002). There is much use of infected cuttings as planting materials, and seldom any attempt to select healthy stocks. The failure of farmers and even researchers to practise selection is not readily explained, especially in areas where circumstances are propitious, i.e., enough healthy plants are available to provide the cuttings required for new plantings, the symptoms of mosaic are conspicuous and there is an obvious difference in the growth and yield of diseased and healthy plants. This emphasises the extent of 'the information gap' between farmers and researchers that must be bridged if progress is to be made in utilising the knowledge that is already available to improve the health status and productivity of cassava and other crops in SSA.

There were periods in the 20th century when cassava mosaic was in some areas so damaging that farmers were no longer able to 'live with' the disease and there was an urgent need for varieties that were more resistant and better able to withstand infection than those being grown. This occurred in Madagascar soon after the first reports of mosaic on the island in the 1930s (Cours, 1951; Cours *et al.*, 1997), and in what is now Tanzania in the 1940s. Severe epidemics were also reported later in Cape Verdé (Anon., 1992), Akwa Ibom State of Nigeria (Anon., 1993) and in Uganda during the 1950s (Jameson, 1964) and most recently in the 1990s (Otim-Nape *et al.*, 2000). The severe losses encountered and the threat to food security led to Government-funded resistance breeding programmes in Madagascar, Tanzania and later in Nigeria and Uganda. There were also efforts to introduce mosaic-resistant varieties from elsewhere for local evaluation so that the most promising could be multiplied and distributed to farmers.

Initially, there was little success using varieties introduced from Asia or South America or by inter-crossing African varieties. However, working independently the programmes in Madagascar (Cours, 1951) and Tanzania (Nichols, 1947; Jennings, 1994) produced highly resistant varieties from hybrids between cassava *(Manihot esculenta)* and ceara rubber *(M. glaziovii)* that were then back-crossed to cassava to produce progeny with satisfactory yields of tuberous roots. The varieties so produced were used successfully in Madagascar and parts of mainland East Africa. Seed from the Tanzania programme was also introduced to Nigeria and selections were used as parents in the national cassava breeding programme, and later at the International Institute of Tropical Agriculture to produce the Tropical Manihot Series of varieties (Beck, 1982).

The selection of these TMS varieties was based on their overall performance, including at least some degree of resistance to mosaic that enables them to yield satisfactorily, even in conditions of high inoculum pressure. This is because the varieties are not readily infectible, and when infected, they develop generally mild symptoms that become even less conspicuous as the plants mature. Moreover, infection is not fully systemic and some of the cuttings collected from infected plants are not infected and grow into healthy plants (Fargette *et al.*, 1996; Thresh *et al.*, 1998a). These features explain why the selection of healthy planting material has not been regarded as necessary and it is seldom practised, even in official multiplication and distribution schemes. Consequently, there is a generally high incidence of mosaic in some TMS varieties, although not in the most resistant ones.

The implication on yield of adopting or not adopting phytosanitation with TMS varieties is not known because of the limited amount of information available on the effects of mosaic on the growth and yield of resistant varieties. Consequently, there is continuing uncertainty on the most appropriate method of utilizing them. Some argue that sanitation and host plant resistance are complementary and should be used together; whereas others hold that sanitation is unnecessary if the varieties grown are sufficiently resistant. Thresh *et al.* (1998b) discuss the main issues involved in the continuing debate.

Despite the divergent views and uncertainties, TMS varieties and others derived from them have been adopted widely in Nigeria and elsewhere. They have also been used as parents in several National Breeding Programmes to provide varieties that are suitably adapted to local conditions. The methods used for multiplying and distributing TMS varieties to farmers in Nigeria and Uganda are particularly well-documented. In Nigeria, the uptake of virus-resistant material was facilitated by the demand for improved varieties to meet the requirements of processors who were supplying the rapidly expanding urban markets (Nweke *et al*., 1996). By comparison, the main incentive in Uganda was for varieties that could withstand mosaic during the recent epidemic (Thresh *et al*., 1994b; Otim-Nape *et al*., 2000). This created an enormous demand for planting material of resistant varieties to replace the vulnerable genotypes being grown and this was supplied with considerable financial assistance from the Gatsby Charitable Foundation and many other Non-Governmental Organizations (Otim-Nape *et al*., 1994).

Virus-resistant varieties accounted for *c*. 25% of all plantings recorded in surveys between 1997 and 2001 in representative districts of Uganda, and they made an even greater contribution to yield because of their superior performance compared with the local landraces being grown (Legg *et al*., 2002). However, some of the introduced varieties do not have all the flavour or other desirable attributes required by farmers, and it is likely that some of the landraces will be retained, at least until other resistant varieties are introduced which have superior taste and other attributes compared with those released originally.

This accounts for the current interest in the new 'TME' sources of resistance identified in some of the landraces collected in Nigeria and elsewhere in West Africa; and attributed to a dominant major gene designated CMD-2 (Mignouna and Dixon, 1997; Akano *et al*., 2002). Some of the landraces and their progeny have the upright growth habit and other characteristics sought by farmers. They are being intercrossed with TMS varieties to produce hybrids that are both high-yielding and highly resistant. These are now being assessed in on-station and on-farm trials in Uganda, Kenya, Rwanda and elsewhere, and eventually they are likely to make a big contribution in further decreasing the losses due to mosaic.

Another outcome of the recent damaging pandemic in Uganda and elsewhere in East Africa and of the recognition of the merits of the widely-grown landraces, is that there has been increased research on other approaches to controlling mosaic disease. This could lead to means of deploying resistant varieties more effectively than at present, and also avoid the current undue reliance on such varieties. For example, it may be possible to develop methods of safeguarding the health status of landraces through the use of varietal mixtures, intercropping or by an appropriate deployment of plantings to provide some degree of isolation and so decrease the risk of serious infection. Moreover, it may eventually be possible to utilize the transgenic forms of resistance now being developed. This was one of the objectives of the original 'cassava trans' project at the Scripps Institute in California (Fauquet and Beachy, undated). Studies have continued in the USA and Europe and some success has been achieved in engineering resistance to cassava mosaic geminiviruses in herbaceous host plants and, more recently, in cassava (Fregene and Puonti-Kaerlas, 2002). However, this approach has yet to be evaluated in the field and there are formidable problems to be overcome before it can be advocated for use on a large scale.

Groundnut rosette disease. Groundnut rosette disease was first described in 1907 and has since been reported in many countries of eastern, western and southern Africa (Naidu *et al*., 1999). The disease has received considerable attention from researchers because of its importance in decreasing the productivity of crops grown for local consumption or for export. Very damaging epidemics have been reported and farmers are well aware of the need for control measures, especially in areas that are particularly prone to infection.

Groundnuts are usually produced under rain-fed conditions in areas subject to a prolonged dry season and it has long been known that rosette disease tends to be more prevalent in crops that are sown late in the growing season, some weeks after the beginning of the rains (Hayes, 1932). By that time, there has been a considerable build-up of the main aphid vector (*Aphis craccivora*) on crops sown early and also on weeds and wild host plants. It was also recognized by farmers and researchers that rosette tends to be particularly severe in groundnut stands that are sown at wide spacings, or in which there are many gaps due to poor establishment. Other early observations were that rosette is particularly prevalent at the margins of plantings and in crops that have been weeded early to leave open stands having a discontinous canopy of foliage (Hayes, 1932). These observations led to the view that vector colonization and virus spread are facilitated where the crop canopy is open, and not at close spacings, or where a cereal or other non-host intercrop is grown. Based on these observations and the supporting evidence of field trials in Nigeria, Malawi, Tanzania and Uganda, farmers were advised to sow early and at close spacing to avoid serious losses due to rosette (A'Brook, 1964; Davies, 1975; Farrell, 1976a). However, they were not advised to delay weeding because it was considered that this 'might encourage indolence' (Hayes, 1932). Moreover, intercropping did not feature in the recommendations. It is considered to be beneficial in decreasing spread, but there is little evidence from field trials on the most suitable crop combination to adopt and a bean intercrop was shown to impede the growth of groundnut and decreased yields substantially (Farrell, 1976b).

The recommendations on planting date and spacing have been difficult to implement in many areas because of constraints on the availability of labour for land preparation and planting, and farmers tend to give priority to sowing maize or other cereals; groundnuts are planted later. Moreover, groundnut seed is often scarce and expensive, especially after a previous season of serious disease and low yields, and so there is a general reluctance to retain sufficient seed to adopt close spacings. There are also constraints on the use of large compact fields to decrease edge effects. Such sites are seldom available and socio-economic considerations also restrict the use of insecticides, although these have been shown to be effective in decreasing the spread of rosette into and within field trials (Evans, 1954; Davies, 1975).

In these circumstances, there are obvious advantages to be gained from adopting rosette-resistant varieties. These were first obtained from landraces of the Virginia type in West Africa (Sauger and Catherinet, 1954.) and were used later in breeding programmes in Nigeria and elsewhere. Some of these varieties have been adopted by farmers, but a serious obstacle to their use more widely is that they have an inherently long growth period. Consequently, they are not suitable for use in the many areas where short-duration varieties are required to decrease the risk of losses due to drought, especially during the late stages of crop growth.

Repeated attempts were made over many years to transfer the resistance from long-duration to short-duration types, but initially these were unsuccessful. However, short-duration rosette-resistant varieties have been obtained from other groundnut accessions introduced from Asia (van der Merwe and Subrahmanyam, 1997). These varieties seldom express rosette symptoms as they are highly resistant to *Groundnut rosette virus* and the associated RNA satellite. However, they are not resistant to *Groundnut rosette assistor virus* which does not cause obvious symptoms but may become prevalent and decrease growth under conditions of high inoculum pressure (Subrahmanyam *et al*., 2002).

Groundnut breeding programmes have made use of accessions that are resistant to the aphid vector (Padgham *et al*., 1990). These are susceptible to rosette but largely escape infection in the field. Short-duration varieties, with resistance to rosette and/or *A. craccivora,* are now being released by the International Centre for Research in the Semi-Arid Tropics sub-station at Chitedze to Governmental and Non-Governmental Organizations in Malawi, Mozambique and elsewhere in the region (Subrahmanyam *et al*., 2002). The varieties have also been introduced to Uganda, where they are being evaluated in comparisons with the susceptible local varieties being used (Chancellor, 2002). This is being done in on-station and on-farm trials involving close collaboration with farmers. The most successful varieties are resistant to rosette and crop at least as well as the locals, even in seasons when there is little or no rosette in the locality. Rosette-resistant material is now being multiplied in quantity for release to farmers. However, a general experience with groundnut is that rates of seed multiplication are low and various approaches are being adopted in attempts to expedite progress. The demand for the new varieties is high and they are likely to have a big impact in both enhancing and stabilizing production, especially in areas that are particularly prone to rosette attack and where farmers are unable or unwilling to adopt the cropping practices recommended to control the disease.

DISCUSSION

It is apparent from the foregoing that there are many approaches to controlling plant virus diseases and there is little doubt that many of the diseases now causing serious losses in SSA or elsewhere in the tropics could be controlled through the application of existing knowledge. There are also likely to be important contributions from the new techniques and approaches to control being developed by the biotechnologists. The challenge to researchers and extensionists is to ensure that this information is utilized in developing and promoting suitably large scale control measures that are not only effective, but also appropriate for use by the farmers concerned. The measures should also avoid harmful effects on human health or on the environment and should complement and be fully compatible with those being used against other pathogens and pests. There are many reasons why these are formidable and exacting requirements that are seldom met in SSA. An obvious technical problem is that it is difficult to evaluate the different options for control when used singly or in different combinations. Such studies are very demanding in terms of personnel and resources required for field experiments. This is, especially if these are to be done on a suitably large scale and over a sufficiently long period to provide a reliable indication of the cost-effectiveness of the measures when adopted widely by farmers. This is evident from experience with cereal yellow dwarf, potato leafroll, sugarbeet yellows, plum pox and other virus diseases that continue to cause problems in temperate regions, even though they have been studied extensively in many countries over a prolonged period.

Cocoa swollen shoot, maize streak, groundnut rosette and cassava mosaic are prime examples of some of the few African virus diseases that have been studied intensively over many years and yet it is apparent from the three ‘case histories’ (in this paper) that many uncertainties remain concerning their control and they continue to cause serious losses. Much less information is available on the many other virus diseases of African crops, some of which have been largely ignored. This is an unsatisfactory situation and a serious impediment to increased crop production and to the development of effective control measures. However, there is little prospect of any immediate improvement because of the limited allocation of personnel and resources to plant virology in Africa. The problem was discussed at a recent conference at the International Institute of Tropical Agriculture (Ibadan, 2001) when recommendations were made on ways of improving the current situation, although it was agreed that this will not be achieved quickly or easily, or without considerable expenditure.

An even more intractable problem is that even if researchers are successful in developing effective control measures, it will be difficult to ensure their adoption on a sufficiently large scale. This is because of the serious limitations of the extension services in the many parts of SSA and the limited ability of farmers to respond and adopt the technical advice and recommendations available. Extension services lack personnel, resources and funding, and the various attempts made to improve the situation in different countries of SSA have been largely unsatisfactory and not sustainable. One outcome has been for researchers to become directly involved in technology transfer, which is a current trend at the International Agricultural Research Centres, even though they have a limited capacity to undertake this rôle. National researchers also became involved in technology transfer in Uganda in the 1990s, following the onset of the severe pandemic of cassava mosaic disease (Otim-Nape *et al*., 2000). The Ugandan researchers who identified and evaluated mosaic-resistant varieties of cassava in on-station and on-farm trials undertook responsibility for disseminating the new varieties to farmers (Otim-Nape *et al*., 1994). This was done in collaboration with extension staff, local authorities and Non-Governmental Organizations. The outcome was very successful and contributed greatly to the recovery in cassava production that has occurred, although there was an inevitable diversion of the overall research effort.

In developing and deploying control measures in Africa, it is essential to consider the requirements and capacity of the farmers involved and their ability to utilize research findings. It is difficult to generalize because of the many different agro-ecologies that are exploited and the wide range of cropping systems adopted. At one extreme, there are large commercial farms or plantations, many of which are under strong central management. There is ready access to inputs and new technology, which have been adopted to enhance productivity and profitability. Examples of crops produced in this way include sugarcane, citrus, coconut, oil palm and banana plantations in several regions of Africa, the Gezira (Sudan) and other major cotton-producing schemes and large commercial farms growing food or export crops including rice, maize, wheat, barley, cassava, groundnut, pineapple and tobacco. However, such cropping systems are exceptional and typical landholdings are small, farmers have had little or no formal education. They also lack resources and ready access to new varieties and other technological innovations.

These are very powerful constraints to the adoption of control measures as farmers are likely to be aware of only the most obvious and damaging of the diseases present. They are also largely unaware of the benefits to be gained from controlling diseases, or the options available for them to do so. This creates a particular difficulty because currently much of the funding available for agricultural research is allocated by donors in response to the perceived needs of farmers, who are seldom able to articulate their requirements and so inevitably continue to be neglected.

In these circumstances, it is not surprising that farmers make little use of specific control measures against virus diseases, although they do adopt traditional practices that are believed to avoid or alleviate disease problems. This was apparent in Uganda during the recent pandemic of cassava mosaic disease, when farmers removed the shoot tips of newly infected plants as a naïve form of phytosanitation and applied wood ash and urine in attempts to control the whitefly vector. There is no evidence that this was beneficial, but similar 'indigenous' practices are also adopted against other diseases and merit further study to determine their effectiveness. Meanwhile, it is apparent that peasant farmers who have little or no knowledge of crop science or plant pathology can avoid serious losses due to disease, even though they do so unwittingly by adopting varieties and cropping practices that provide yields that are satisfactory, consistent and sustainable. This is unlikely to occur by retaining varieties that are particularly vulnerable, or practices that predispose plants to serious risk of infection.

The ability of African farmers to produce yields that are usually adequate, despite the occurrence of viruses and other pathogens, is an important feature of traditional agriculture that is associated with biodiversity. It is one that should be retained in any attempt to enhance yields by introducing higher-yielding varieties and more intensive methods of crop production including mechanization, irrigation, use of fertilisers and the adoption of specially bred varieties having a short growing season. Such developments are required so as to increase exports and also to feed the burgeoning human population in Africa, of which an increasing proportion will be in urban areas and not directly involved in agriculture. This will decrease the availability of farm labour and a further constraint will be the increasing impact of the HIV epidemic in decreasing the numbers and productivity of the rural work force.

As long ago as 1955, the eminent virologist F.C. Bawden (1955) considered some of the ways in which modern agricultural practices facilitate the spread of pests and diseases and concluded that the full benefits of improved technology would only be attained by developing more effective methods of controlling pests and diseases. This remains a crucial challenge to researchers, extensionists and farmers in the 21st century, as they must develop methods that are effective and sustainable and, also benign in their effects on human health and the environment. Improved methods of virus control have an important role to play in enhancing productivity and it will be possible to utilize the experience gained already in developed countries and also the new biotechnological approaches being introduced. It will also be important to integrate virus disease control measures with those being developed against other pathogens and pests. To date, little attempt has been made to develop or promote an holistic ecological approach along these lines and major research efforts that are well-funded and sustained will be required in the whole range of different agro-ecologies if success is to be achieved. However, the need is great and the benefits to be gained provide a powerful incentive to such undertakings.

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TABLE1. Cropping practices that influence virus spread

Practice	Details
Pre-planting	
Site selection	cropping history/isolation field size/shape/orientation/aspect
Crop/cultivar selection	single/multiple crops single/multiple cultivars seed/vegetative propagules source of propagules
Planting	
Sowing/planting	direct planted/transplanted planting/transplanting dates
Crop spacing/ arrangement	plant population in-row/between row spacing
Pesticide/fertiliser application	at or before planting, amount/type
Post-planting	
Weed control/tillage	method/frequency/effectiveness
Fertiliser	amount/type/timing/method of application
Thinning/Pruning	crop growth stage/extent/method
Roguing	intensity/timing/frequency/extent
Irrigation	amount/mode/frequency