Aphid and whitefly management in cotton growing: Review and challenges for the future

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ABSTRACT

In many cotton-growing regions in the world, the phytosanitary situation of cotton has been marked in the past two decades by, among other things, a renewed increase in the populations of certain piercing-sucking insects and especially the aphid Aphis gossypii *Glover and the whitefly* Bemisia tabaci *(Gennadius). These pests are polyphagous and display very special biological and ecological features causing damage with extremely serious economic consequences. The methods generally used to control these sucking insects were based mainly on the use of insecticides targeting aphids or whitefly, in most cases with the same spray procedures as for those used to control other major cotton pests such as bollworms. This chemical control has finally proved not very effective, it is expensive and forms a real danger for the conservation of biological diversity and for the environment as a whole. Alternative control methods that are better suited to the integrated management of aphid and whitefly populations are proposed within the framework of more rational and sustainable farming. They are based on the principle of seeking a return towards a balance between these pests and the various accompanying indigenous beneficial insects. For this, a break with past practices is first recommended in order to prevent an aggravation of the phytosanitary situation, followed by the application of a new strategy based on the integrated pest management concept. The role of preventive measures would thus become preponderant. These are based on a strategy enabling plants to escape attacks by these pests thanks to various procedures such as early sowing, choice of varieties with short cycles, limited vegetative development and vegetation with low appetency for the insects. Traditional agronomic techniques such as rotations and cropping patterns, rational combinations of crop plants, trap crops, etc., also have complementary effects by limiting pest outbreaks and enhancing populations of beneficial organisms. The prospects opened up by genetically modified varieties are discussed. The phytosanitary situations of the field are then monitored using population count techniques and economic thresholds are set. If it is then found to be essential to use curative control measures, priority should be awarded to alternative techniques and chemical spraying with active substances causing the least damage to the environment should be used only in the last resort. Appropriate agronomic techniques for the phytosanitary situations in cotton growing are mentioned. It is proposed that agronomists and crop protection specialists should adopt a concerted approach in following these new pathways and report the results obtained in the medium term.*

Introduction

In recent decades, the entomological problems experienced in agriculture have been marked by two major phenomena related to the intensification of production and, more particularly, it increased use of inputs (fertilizers and pesticides). Indeed, it has been observed on the one hand that certain pests have become resistant to insecticides and on the other that other insects that hitherto had a minor effect on yields and production quality rapidly gained major economic importance. In most cases, the control of outbreaks was not satisfactory using common control resources.

Cotton growing is no exception to this general observation. Phenomena of resistance to insecticides have thus been observed, and are widespread today in certain important lepidopteran pests of cotton fruit organs, including the noctuids *Helicoverpa armigera* (Hübner), *Heliothis virescens* F. and *Spodoptera* spp. This also applies to Hemiptera such as the aphid *Aphis gossypii* Glover and the whitefly *Bemisia tabaci* (Gennadius), which have recently become major cotton pests in various parts of the world. This new phytosanitary situation has alerted both farming community stakeholders and research scientists.

The present update is aimed at changing the status of these piercing-sucking pests in cotton growing. It covers first of all their biological characteristics and the damage that they cause to crops and briefly describes the evolution of the control techniques used. The reasons for the outbreaks of these new pests are described and an inventory drawn up of the main parameters to be taken into account to achieve sustainable management of pest populations. A phytosanitary approach - both technical and strategic - for solving this crop protection problem is then proposed. Although a great variety of agro-ecological situations are observed in cotton growing around the world, the information presented here is drawn in particular from small-scale cotton growing in Africa and has been used to make general recommendations that can be applied most, if not to all of these situations.

Pests that have gained major economic importance

Evolution of their status and geographical distribution

A. gossypii and *B. tabaci* have long been on the list of cotton pests (Hargreaves, 1948). But whereas they were still considered to be of minor importance until recently, they gained major importance at the end of the twentieth century in many parts of the world (Butler and Henneberry, 1994; Leclant and Deguine, 1994).

A. gossypii can be considered as the most important and most harmful aphid species in the world, especially on cotton and cucurbit crops in North America, Africa and Asia. A ubiquitous species, it flourishes in the tropics and subtropics but can also flourish in continental climates as in the Xin Jiang in China (Zhang *et al.*, 2000). It is the commonest and most polyphagous aphid in sub-Saharan Africa. It is found on all species of the genus *Gossypium,* and especially on *G. hirsutum* and *G. barbadense* (Mursal, 1993). Outbreaks have been particularly severe in the past two decades: in China since 1983 (Luo and Gan, 1986), in the Middle East since 1984 (Broza, 1986) and in the United States since 1986 (Akey and Butler, 1989; Grafton-Cardwell, 1991; Steinkraus *et al.*, 1991). In West Africa, Onu (1989), Silvie (1989). Renou and Deguine (1992) drew attention to the growth of the populations of this aphid in West Africa, in particular in Cameroon and Chad, where Couilloud (1965) had described them 25 years earlier as being of little importance or even practically non-existent. *A gossypii* thus suddenly became a key pest in cotton growing in many countries at the end of the twentieth century.

B. tabaci was described as a cotton pest in India in the early twentieth century (Husain and Trehan, 1933). Outbreaks were reported between 1970 and 1980 in the Sudan, Turkey and Israel (Gerling and Henneberry., 1998). It has been considered as a pest of economic importance in the United States, and particularly in California and Arizona, since 1981 (Toscano *et al.*, 1998). The losses caused are estimated at nearly two hundred million dollars in certain years (Henneberry and Faust, 1999). It is a cosmopolitan whitefly and found in the zone lying between the 40^{th} parallels, and even further north in Europe. *B. tabaci* is reported today in most countries in western, central and southern Africa and in the Indian Ocean islands (Cock, 1986).

The main biological characteristics of the 'new' pests

Numerous studies on whitefly and aphids have been published, including those on cotton. Recent bibliographical syntheses have been published concerning the latter plant, and we refer in particular to those of Leclant and Deguine (1994) on *A. gossypii* and of Butler and Henneberry (1994), Cock (1986) and Oliveira *et al.* (2001) on *B. tabaci*. In addition to their very broad distribution on a global scale, aphids and whitefly display remarkable intrinsic biological characteristics and in particular polyphagia and the capcity for multiplication and adaptation to a range of environmental conditions.

Several hundred *A. gossypii* host plants have been counted in the world (Essig, 1947; Leonard *et al.*, 1971; Roy and Behura, 1983; Inaizumi, 1980; Millar, 1994; Deguine *et al.*, 1999). In addition to cotton, the cultivated plants of economic importance that suffer from infestation are both vegetable crops (aubergine (eggplant), cucurbits, gumbo, melon, peppers, etc.) and ornamental species (*Bougainvillea, Hibiscus, Lantana*, etc.) and a few perennials (*Theobroma*, *Citrus*, *Coffea*) are also attacked. *B. tabaci* is also well known for its polyphagia and Greathead (1986) mentions 506 host plants belonging to 74 different families: Asteraceae (56 species), Convolvulaceae (20 species), Cucurbitaceae (17 species), Euphorbiaceae (32 species), Fabaceae (96 species), Malvaceae (35 species) and Solanaceae (33 species).

The two insects also display strong reproductive capacities varying according to the climatic conditions. Parthenogenesis in *A. gossypii* in the tropics should be noted. This property enables residual populations to develop very rapidly, sometimes with an exponential pattern (Deguine and Leclant, 1997).

Both insects are also remarkable in their capacity for adaptation to the environment and their optimum exploitation of it. This feature goes a long way towards accounting for their harmfulness as it enables rapid exploitation of plants; no less rapid colonisation of new host-plants, adaptation to climatic conditions through modification of the biological and reproduction cycles and the ability of both aphids and whitefly to engender biotypes. The intraspecific morphological variability of *A. gossypii* is now clearly recognized (Wool and Hales, 1997; Komazaki and Osakabe, 1998; Vanlerberghe-Masutti and Chavigny, 1998; Zou *et al.*, 2001). The phytosanitary importance of this property is known for *B. tabaci*, with the appearance of the B-biotype in the United States in 1986. This biotype can spread more diseases and more easily acquire resistance to insecticides and is now widely distributed around the world (Peterschmitt *et al.*, 2001). The *B. tabaci* species complex was the subject of a synthesis and revision by Perring (2001). However, it should be remembered that certain characteristics of the *B. tabaci* species, such as polyphagia and strong reproductive capacity, are not found in certain biotypes (Peterschmitt, personal communication).

It is difficult to draw up the general characteristics of the population dynamics of aphid and whitefly populations in cotton because of the diversity of the agro-climatic conditions observed. However, in many cases, the outbreaks at the beginning of the vegetative cycle before flowering, like those observed at the end of the cycle after cut-out and during boll dehiscence when there is shortage of rainfall or moisture, are particularly harmful to crop yields and production quality (Deguine *et al.*, 1994 and 2000; Nibouche *et al.*, 1998).

Damage and economic consequences

For these various reasons, aphids and whitefly now have major economic effects in most cotton regions. Sucking-piercing insects are held to be responsible for both loss of seed cotton production and depreciation of cotton fiber quality. Three types of damage are caused: trophic damage by the withdrawal of sap from the plants, plant pathology effects by the spread of virus diseases and technological damage resulting from honeydew production that hinders cotton processing.

Production losses result from sap sucked by the insects (larvae and adults) during plant growth and the simultaneous injection of phytotoxic saliva. These attacks cause lateness in plant growth and the vegetative cycle, especially if they occur at the beginning of the season. In some cultivation situations today, the economic effects of such trophic damage can exceed those of bollworms (Deguine *et al.*, 1994; Nibouche *et al.*, 1998). A decrease in fiber quality results from the production and excretion of honeydew on seed cotton in open bolls ready for picking at the end of the season. In most countries, the sticky cotton phenomenon that may be observed in spinning is ascribed to the honeydew deposits that accompany late outbreaks of *A. gossypii* and *B. tabaci* (Hector and Hodkinson, 1989). Although there are some differences between aphid and whitefly honeydew with regard to the composition (Héquet and Wyatt, 1999) and the size and shape of the drops (Couilloud, 1986), the difficulties encountered in cotton processing are similar. Honeydew also forms a culture medium for various saprophytic fungi that cause sooty mould, hindering plant respiration and chlorophyll uptake when they affect leaves.

A. gossypii and *B. tabaci* are also well known for their ability to spread numerous plant diseases, and especially virus diseases. The aphid spreads blue disease of cotton in West Africa (Cauquil and Vaissayre, 1971), a disease that is doubtless very close to *Cotton Leaf Curl Virus* in South-East Asia and *mosaico da nevuras* in Brazil. It is also held to be responsible for the spread of another disease, anthocyanosis, in the South American continent (*vermelhao*) (Costa, 1956), and in India (Mali, 1978). Without control of the vector, damage to certain varieties can be considerable, as is shown by observations performed in Paraguay and Vietnam; this is why the thresholds for insecticide spraying are sometimes very low, as in the Mato Grosso in Brazil. *B. tabaci* is the vector of more than 70 virus diseases that affect numerous plants (Hunter and Polston, 2001). Although it has been confirmed that it can be the vector of at least seven virus groups (Duffus, 1987), the spread of geminiviruses is the most frequent. In cotton, these diseases are known as *Cotton Leaf Crumple Virus*, described in the United States in *G. hirsutum* (Brown and Nelson, 1984) and CLCuV, mentioned in the Sudan in *G. barbadense* and described more recently in Pakistan (Ahmad and Ali, 1998) and in India (Singh *et al.*, 1998) in *G. hirsutum*. Another type of virus disease is spread by *B. tabaci* causes mosaic diseases involving different pathogens, both in Africa (African Mosaic) and America (*mosaico* and *rugosidad*) (Cauquil and Follin, 1983). *B. tabaci* is also held responsible for other syndromes such as red cotton disease that appeared recently in Africa (Nibouche *et al.,* 1998).

Evolution of the control of sucking-piercing insects

The first steps in directed control

Until the last decade of the twentieth century, cotton crop protection in most regions generally consisted of chemical control applied according to a preset calendar and subsequently according to the pest population levels and the risks. The control techniques used were aimed essentially at pests of fruit organs (especially Noctuid lepidopterans) rightly considered at the time as the most dangerous pests for seed cotton production and hence as the most harmful for growers.

As a result of the recent outbreaks of sucking-piercing insects, mainly at the end of the cycle, cotton crop protection in the past two decades has also incorporated features to control *A. gossypii* and *B. tabaci*. However, although spraying for control bollworms is justified and has proved effective, chemical control of aphids and whitefly is not as satisfactory and has even be considered to be ineffective.

The first measures taken to control aphids and whitefly in the 1980s consisted of incorporating aphicides and whitefly control products, whose active substances were mainly organophosphorus compounds and carbamates, into bollworm control programs based essentially on pyrethroids. The spraying program and the application techniques were not usually greatly modified.

The first setbacks and the evolution of chemical control in the 1990s

The failure to control sucking-piercing insects by leaf spraying (aerial or ground treatment using manual techniques) and a correlated increase in economic losses, led cotton sector stakeholders, and especially scientists, to revise their intervention strategy, taking the biological and ecological characteristics of the insects into account, but still using a chemical approach: increasing the volume of mixture applied to better contact the pests beneath the leaves, the development of insecticide treatments of seed, treatments triggered according to specific thresholds, etc.

However, in spite of the switch from directed control to supervised control, a glimpse of the limits of chemical control was preceded in the setbacks observed in the control of aphids and whitefly (Kuklinski and Borgmeiser, 2002), the appearance of phenomena of resistance to insecticides in both *A. gossypii* (Gubran *et al.*, 1992; Sun *et al.*, 1994; Deguine, 1996; Moores *et al.*, 1996; Herron *et al.*, 2001) and *B. tabaci* (Moores *et al.*, 1988; Dittrich *et al.*, 1990; Ahmad *et al.* 2000), the appearance of new diseases and the maintaining or even increase in population levels and damage. Meanwhile, the first integrated protection measures based on cultural, varietal and biological techniques were proposed and sometimes applied but without it being always possible to evaluate their efficacy (Butler and Henneberry, 1994; Leclant and Deguine, 1994).

The calling into question of chemical control

The initial recommendations for the chemical control of aphids and whitefly were often taken under emergency conditions. Use was made of the experience of protection against well-known cotton pests and especially bollworms, whose bio-ecological characteristics are nevertheless very different. The inappropriateness of these chemical control techniques for the management of these sucking-piercing insects lies above all in their bio-ecological properties that are clearly different from those of cotton bollworms.

A. gossypii and *B. tabaci* are insects that live and feed on the undersides of leaves. They are thus physically protected from applications of insecticides whose the micro-droplets fall on the upper faces of the leaves by gravity. The phenomenon is aggravated by the fact that spraying is often performed with small volumes of mixture per hectare, whether by ground or aerial techniques (ultra low volume and very low volume spraying). Furthermore, the systemic properties of some of the insecticides used are increasingly weakly expressed from the beginning of flowering and then reduce rapidly. The targets are then not contacted. In addition the strong multiplication capacity of these piercing-sucking insects can very rapidly compensate for the possible reduction of their numbers as a result of the action of insecticides. For example, it has been shown in central Africa that the progeny of a single aphid can attain several thousand individuals in only two weeks (Deguine and Leclant, 1997). Similar comments can be made concerning the speed of infestation of a field from host-plants or neighbouring crops. For example, even if it is supposed that a spray can totally annihilate the whitefly population of a field of cotton, only a few hours are required for massive infestation to high levels from populations along the edges or in neighboring fields, especially when a low persistence whitefly pesticide is used (Deguine *et al.*, 1998). Finally, it is essential to remember that both of these insect species have the capacity to develop insect-resistant populations, whether these consist of aphid clones or a whitefly biotype.

In addition to the limits of its efficacy, chemical protection against aphids and whitefly has other major disadvantages. Like many substances used in phytopharmacy, the active substances for controlling aphids and whitefly have toxic effects on non-target insects and especially beneficial parasitic or predatory insects. The role of indigenous beneficials is now well recognized. Even if it does not seem sufficient to control outbreaks of Homoptera pests it should be conserved as much as possible. The same active substances, which was often used for homopteran control (such as monocrotophos, omethoate, dimethoate or metamidophos) generally display high toxicity for man and the environment (ground water, wild fauna) and are increasingly subjected to restrictions, or even the withdrawal of registration, in many countries.

It is now clear that chemical control applied under the conditions described above is, if not totally unsuitable for these new pests, at least far from attaining the level of efficacy expected or acceptable. This situation has considerably disturbed cotton sector stakeholders, by calling into question well established habits and confidence in "all chemical" solutions.

The present phytosanitary situation: analysis, consequences and prospects

The reasons for the change in the status of these new pests

Populations of sucking-piercing insects in cotton depend directly on abiotic factors, such as climate, and they interact with the plant environment and ecosystems in the vicinity (Figure 1). Recent outbreaks of these insects result from the upsetting of the previous balance between them, their environment and their set of natural antagonists. The reasons for this imbalance are described below, although it is not easy to rank them or to be sure that they are exhaustive.

A reminder of the bio-ecological characteristics of these insects should first be made. The strong intraspecific variability of both species is important (aphid clones and whitefly biotypes) as a favorable factor for their adaptation to changed or different environmental conditions. The destruction of populations of their natural antagonists by pesticides also favors outbreaks. Abiotic environmental factors are important and in particular the shortage of rainfall observed in many tropical regions since the 1970s. It has been established that this climatic factor, combined with high temperatures, is favorable for the development of sucking-piercing insects.

The evolution of agricultural practices should also be taken into account. The increase in the areas under cotton and the development of other crops such as vegetables, have considerably increased the food resources available to aphids and whitefly. This evolution has had an effect at all levels - local, regional and continental.

The changes in crop management sequences, cultural practices and crop protection procedures have also contributed to upsetting the previous balance in entomofauna. The increase in inorganic fertilizer doses, especially nitrogen fertilizer, causes substantial foliar masses of excellent nutritive quality, favoring the establishment of large populations of piercing-sucking insects. Low-volume crop spraying techniques (ULV and VLV), whether aerial, ground-based or manual, do not cover the undersides of leaves sufficiently and are therefore not suited to the pests that live there (aphids and whitefly and also mites, bugs, etc.). Furthermore, some of the active substances used, such as pyrethroids, have only limited efficacy on these insects in the tropics. The choice of varieties grown is doubtless not the most favorable for the conservation of populations of beneficials. The hairiness of varieties, chosen for resistance to other pests such as jassids, affects the activity of the natural antagonists of aphids and whitefly, making these varieties more susceptible to the latter (Baloch *et al*., 1982). Conversely, smooth varieties enhance the establishment and growth of populations of the piercing-sucking insects themselves. In addition, some varieties have strong vegetative growth, in particular to enable the formation of quality lint in the bolls and therefore have a high leaf index, which is attractive to phyllophagous insects. The massive, sometimes anarchic, use of insecticides on vegetable crops that often adjoin or are intercropped with cotton, where the farmers are little supervised, aggravates the general imbalance observed between piercing-sucking insects and their natural antagonist. These practices are also such as to favor the appearance of resistance phenomena frequently induced by the intensification of insecticide spraying. Programs for resistance management are often proposed but they are also something of a constraint for users. Palumbo *et al*. (2001) give some examples for *B. tabaci*.

Breaking with past practices or habits to prevent a worsening of the situation

The crop health situation, already considered to be critical, may worsen unless appropriate control techniques are instigated rapidly. These piercing-sucking insects could become even more dangerous than they are today through both an increase in outbreak levels, a generalization of resistance to insecticides or by the selection of new biotypes, which are vectors for diseases or syndromes that are more damaging than those known today. Before the recent outbreaks, aphids and whitefly were in ecological balance with their natural enemies in various cropping systems. The changes in their environment, caused in particular by inappropriate farming practices, have destroyed this balance.

There should thus first be a break with the procedures and habits used for the past twenty years or so to control the damage caused by piercing-sucking insects to prevent an aggravation of the problem. Such a change requires a change in the mentalities of all the stakeholders in the cotton sectors, and especially those of research scientists (who should agree to re-orient their lines of research), extension agents (who should agree to favor long-term rather than short-term measures) and growers (who should accept the presence of a certain level of pests in their fields).

Adopting a new approach and practices that enable a return to a balanced situation

In the future, the aim of rational (supervised) management of agro-ecosystems should be that of reducing the populations of potential pests to levels that are economically bearable for the crops in question and also take environmental or social considerations into account (Figure 2). In the light of unfortunate past experience, it has become necessary to manage populations and no longer hope to eradicate them, discarding the easy chemical protection reflex and above all anticipating the appearance of risk by means of a set of agronomic techniques resulting in a sustainable procedure. Preventive measures thus gain a greater importance. This phytosanitary diagnosis is not specific to cotton growing, which is just one example among others. In all cases, consequences of practices that ignore the biological bases of the functioning of ecosystems can be disastrous for both the economics and sustainability of production and for the protection of human health and the environment as a whole. The attention paid to this particular example, because of the outbreaks of pests that are both the vectors of diseases of a major world-wide crop and also have the facility for acquiring resistance to insecticides, provides clear arguments for those who recommend a revision of the present phytosanitary strategy (Ferron, 1999).

As an example, we know the unfortunate consequences of the first green revolution on outbreaks of rice brown plant-hopper, *Nilaparvata lugens* (Stal), resulting from the secondary effects on beneficial fauna of the increased use of pesticides required by the cultivation of varieties selected for their high yields. This hopper suddenly became a pest of great economic importance in Indonesia when cropping intensification had been in progress for only half a dozen years (Oka, 1991; Teng, 1994). Today, a ‘doubly green revolution’ (Annex 1) is being launched on an ecological basis, which rehabilitates the determinant role of indigenous beneficials.

As rice growing is ancestral in the Asian regions concerned, it can reasonably be supposed that a balance gradually became established between populations specific to this particular agro-system and that the return to supervised agricultural practices has enabled a return to the initial state (Settle *et al.*, 1996). Comparable results have nevertheless been obtained in agro-systems that are *a priori* less favorable (orchard fruit crops and protected crops) (Blommers, 1994). The United Nations conference in Rio de Janeiro (1992) crystalized for the first time an awareness of the imperative that the biosphere be reserved for the future development of human activities. The impact of agriculture on the conservation of biological diversity, rightly considered to be the driving force of ecosystems, was stressed in particular and illustrated by the new sustainable development concept.

An evolution in crop protection is therefore essential and is the subject of forward-looking reflections that give a proper place to pesticides in an overall integrated production strategy (Ferron, 2003).

The bases of sustainable management of the populations of piercing-sucking insects

The procedure and the stages

These observations, experience and reflections are used to propose the basis for the sustainable management of these piercing-sucking insects. It is based on the integrated pest management concept in a context of sustainable agriculture with an attempt at reconciling the advantages of two different strategies. One of these is considered as a priority and favors an ecological approach to population regulation and thus considers the agro-system as the level for organization and preventive intervention. The other is based on the curative use at field level of varied techniques including the application of easy-to-use, relatively inexpensive, synthetic pesticides that are very effective but have low selectivity and should only be used as a last resort.

The success of such an approach can clearly only be assured by the strict respect of a single, truly integrated approach, every stage of which must be completed before starting the next, making it very difficult and restricting for farmers applying it. This, therefore require basic training, technical assistance and decision aids that are of high quality.

The initial stage of this integrated strategy is aimed at reducing phytosanitary risks as much as possible by means of a set of preventative agro-technical measures updated using the most recent knowledge of the dynamics and management of populations. The second stage is aimed at a diagnosis of the sanitary state of the field and its environment, and possibly of the whole farm or farms using the same cropping system and therefore requires knowledge of the phytosanitary risk in a given socio-economic context. The third and last stage is curative and aimed at performing the intervention measures that are the least harmful for the environment (for human health and biological diversity). It therefore forms as a whole, a true specification, aiming at ensuring the profitability and hence the sustainability of the farm, conservation of the agronomic potential of the land and the maintaining of indigenous biological systems in accordance with the sustainable development concept.

Account will be taken of the most varied experiences, taking account of their reliability, in the design of the approach in a real situation. Although not a reference or an objective, given the profitability constraints that it induces, organic farming in cotton growing displays in most cases a marked decrease in the severity of the problems raised by piercing-sucking insects and the damage that they cause (Myers and Stolton, 1999; Boguslawski and Basedow, 2001).

Preventive measures

As the object is the avoiding of phytosanitary risks, control measures therefore aim at preventing populations of organisms that are potentially harmful for crops from causing economically significant damage. They are based on proved agronomic techniques that have generally been abandoned in favor of the systematic use of inputs. Crop rotation, cropping plans, choice of resistant varieties, tillage operations, prophylaxis, rational fertilization, trap crops and intercrops, etc. are all techniques aimed at the simultaneous creation of unfavorable conditions for crop pests and favorable conditions for their antagonists. They have recently been rehabilitated both by the International Organization for Biological Control (Boller *et al.*, 1998) and by the Global Crop Protection Federation (GCPF, 1997). Recent knowledge of the dynamics and genetics of fragmented populations (very common in farming systems) and the recent momentum given to research on biological diversity, strengthen these aims by awarding them scope for application broader than the boundaries of the cultivated field, with consideration of the farm as a whole, surroundings included, or even different farms with the same cropping systems within a given territory (Dron and Ferron, 2002).

In the particular case of aphids and whitefly on cotton crops, preventive strategies can be envisaged at field and cropping system level and for the farm as a whole.

First, we will consider a strategy enabling the plant to escape attacks by its piercing-sucking pests at the scale of the field and the annual cycle, in particular by limiting their incidence at both the beginning and the end of the season by means of the following techniques:

- **Installing the crop as rapidly as possible** by early sowing in order to limit in time the coinciding of the physiological stages of the plant that are the most attractive and the most susceptible on the one hand and of these insect populations of the other (Slosser *et al.*, 1992; Parajulee *et al.*, 2002). The techniques enhancing the rapid installation of the crop are direct drilling on plant cover (DMC) (Séguy *et al.*,

1998) or after limited tillage. This reduces the time required for preparation and installation of the crop (Torrey *et al.*, 2000). These procedures are increasingly successful around the world, especially in cotton growing (Séguy *et al.*, 2003).

- **Shortening the sowing to fruiting period** in the same way using techniques such as the choice of varieties with shorter cycles; limited vegetative growth; synchronous fruiting lasting for a short time; judicious choice of sowing density; coating seed with systemic insecticides;, use of growth regulators, etc. Such solutions have already been adopted in varied agro-ecological situations. In addition to the DMC cropping systems in the Mato Grosso in Brazil mentioned above, those of the Ultra Narrow Row Cotton (ULNR) type in the United States (Heitholt *et al.*, 1993) optimize interaction between high sowing density and plant architecture and size by favoring fast mechanical harvesting. In sub-Saharan Africa (Deguine *et al.*, 2000; Lançon *et al.*, 2003), the rapid installation of the crop under rainfall conditions that are nonetheless limiting is inspired by the same principles.
- **Shortening the period during which dehiscent bolls are exposed to honeydew** excreted by aphids and whitefly, if necessary by means of the curative techniques described below but also by early or fragmented harvesting or by the choice of varieties; or rapid defoliation facilitating and speeding up manual picking (large bolls making picking easier) or by mechanical harvesting (plant architecture and grouped fruiting required).
- **Limiting the food resources available to pests at all times during the cotton season** by the selection of varieties whose foliage is less palatable and less nutritive both in terms of quality (e.g. leaf color or texture and high amino acid and sugar contents) and quality (leaf area index, leaf shape and size) and by appropriate management of organic fertilization (Balasubramanian and Mulibaskaran, 2000) and inorganic fertilizer, especially nitrogen (Bi *et al.*, 2001; Nevo and Coll, 2001; Cisneros and Godfrey, 2001; Crafts Brandner, 2002) and of water supply. Good management of crop residues that may harbor piercing-sucking insects for several days is also recommended.

Preventive strategies can also be recommended at the different scale of cropping system, or even farm. These are aimed at limiting pest outbreaks while favoring the populations of beneficials through choice of rotations and cropping plans; rational combinations of crops (Gabr and Sourial, 2001); the introduction of trap crops for pests and refuge plants for beneficials; 'push-pull systems' (Nielsen, 2001) and the management of reservoir plants between seasons, are all pathways to be explored. It is doubtless still premature to encourage farmers to reconsider the shape and area of their fields to enable the optimum regulation of pest populations by their indigenous beneficials in a natural biological control approach. It is noted nevertheless that this pathway has already been explored in Mali to reduce the damage caused to sorghum by head bugs (Ratnadass *et al.*, 2002). However, cotton growing is perhaps suitable study material for such investigations, given the diversity of the insect fauna associated with it and its different forms in smallholding agriculture on the one hand and industrial farming on the other (Mensah, 1999; Parajulee and Slosser, 1999). In the latter case, the juxtaposition of vegetable crops and cotton is certainly an example that is particularly difficult to manage but that holds rich lessons.

Finally, such preventive measures for aphids and whitefly only make sense if they are applied for a long period of time in a given situation.

The use of cotton plants genetically engineered to express genes for resistance to pests forms a logical part of this preventive approach. Indeed, with the reservation that the preliminary results obtained in the United States with varieties expressing the entomopathogen toxin of *Bacillus thuringiensis* be confirmed (Carriere *et al.*, 2001; Shelton *et al*. 2002), the use of cotton varieties genetically modified for resistance to certain pests ('Bt' against Lepidoptera for example) could bring a substantial decrease in insecticide sprays. Questions about possible outbreaks of mirids and pentatomids induced by the removal of insecticidal application might thus be answered (Greene and Turnipseed, 1998). Under these conditions, we might expect a decrease in the selection pressure exerted on beneficials that control piercing-sucking insects. However, appropriate research programs would be necessary to reveal this property and it would be necessary to demonstrate that the overall biological diversity of the agro-ecosystem considered is not affected by this new agronomic practice. Certain recent observations should nevertheless be taken into account; these show that piercing-sucking pest populations can increase substantially and become dominant in transgenic (Bt gene) cotton growing; this concerns both *B. tabaci* (Wilson *et al*., 1992) and *A. gossypii* (Cui and Xia, 1999 and 2000).

With regard to work on transgenic plants expressing a gene of interest for resistance to aphids or whitefly, it is probable that some of the research undertaken is still confidential, not known, not yet published and insufficiently confirmed *in situ*. Much research has been performed in Bt strains effective on bollworms but none was found to have great direct efficacy on piercing-sucking insects. Today, research on the transfer of genes of interest in aphid control mainly concerns lectins (Rabhé *et al.*, 1995), especially GNA (*Glanthus nivalis* agglutinin), that causes a certain delay in growth and a decrease in the fertility of several aphid species (Hilder *et al.*, 1994; Stoger *et al.*, 1999). There is also Vat gene in melon (Pitrat *et al*., 1982), but this has yet to be transferred to other plant species or to cotton. Other lines of research include work on the OC-I gene (protease inhibitor) conducted on *A. gossypii* and other aphids (Rabhé *et al.*, in press), and the Mi gene envisaged in the control of *Macrosiphum euphorbiae* (Rossi *et al.*, 1998). In all cases, a rational strategy for the use of aphid-resistant transgenic cotton plants should be set out and adopted before its application in the production environment (Gatehouse *et al.*, 2000). Little information on whitefly is available. Few trials on transgenic plants such as tobacco are of relevance to *B. tabaci*. There is work on the use of protease inhibitors for *Manduca sexta* (Thomas *et al.*, 1995a and 1995b).

Among the other research pathways using biotechnologies, selection assisted by molecular markers from a resistance donor deserves mention, even though few results on cotton whitefly and aphids have been published. Certain work has been undertaken indirectly with a view to preventing virus diseases, for example blue disease spread by *A. gossypii* or leaf curl virus and geminiviruses spread by *B. tabaci* (Lacape, personal communication; Liu *et al.*, 1998; Lapidot and Friedmann, 2002). Genes of resistance to the viruses are identified and marked in both cases and introgressed by marker-assisted selection. The challenge for the future in this domain is the screening of variability in the genus *Gossypium*, in wild species and tetraploid types, many of which are reported to be 'resistant' to different insects. Molecular markers will in any case enable easier interspecific genetic transfers.

The same approach can be envisaged for other resistance characters that can be introgressed from cotton species other than *Gossypium hirsutum*, such as *G. barbadense* or *G. arboreum* (Reed *et al.*, 1999; Deguine and Hau, 2001). Cultivars harboring smaller aphid populations have thus been identified; this can be related to a lower amino acid and sugar content in plant tissue.

In conclusion, the importance to be awarded to the space-time dimension of the biological factors studied for rational (supervised) management of populations should be stressed. It is obvious that the preponderant, determinant role thus awarded to preventive measures in this new crop protection strategy implies the integration of approaches by pesticide specialists and agronomists. This has doubtless not been sought sufficiently to date (Papy, 2001; Ferron, 2003). These considerations conform perfectly with the recommendations of Hilje *et al.* (2001), who award a major position to agronomic methods in the prospects for successful management of *B. tabaci* populations on several crops.

The revised management of weeds which may be considered positively as habitats for beneficials, would doubtless be a complementary future approach (Norris and Kogan, 2000).

Diagnosis and decision aid

Population monitoring has a special position in such a context, as it makes it possible to determine the risk of crop damage and, if this is such as to compromise the revenue expected from the harvest, the need for curative interventions. In countries with intensive agriculture, warning systems alert stakeholders when such risks are forecastable on the basis of data supplied by a local observation network. It is then up to the farmers themselves to monitor the sanitary state of each of their fields to validate the warning or not. This individual approach requires the provision of simple diagnosis criteria for both the identification of insect pests and for the evaluation of their numbers. These observations should therefore be related to the economic thresholds established in principle for each region according to market conditions and biological and technical parameters and beyond which direct control or curative measures must be triggered. This is considered to be a fundamental approach by both users of supervised protection and those of integrated pest management (Audemard, 2003). It implies the training and supervision of farmers. A recent study in Thailand on the obstacles to be overcome to promote an IPM strategy for cotton is a good example of this (Castella *et al.*, 1999).

The design and development of techniques for estimating aphid and whitefly populations has been the subject of much research work. The solutions proposed concern the winged forms of whitefly (Munir and Muhammad, 2002) and aphids (Moericke, 1957; Byrne *et al.*, 1986; Deguine and Leclant, 1996; Chu and Henneberry, 1998), the mobile or fixed apterous forms and larvae of aphids (Slosser *et al.*, 2002) and whitefly larvae and nymphs. The implementation of these techniques has improved our knowledge of the monitoring in space and time of the populations studied. Understanding their dynamics according to relevant biotic and abiotic factors has been made easier in both space and time, thus enhancing the development of integrated pest management for these insects. In particular, the demonstration of the mechanisms of their movements at different scales—from crop field to continent—has been important for the management of their populations.

The design and development of a technique for trapping winged forms of *A. gossypii* in sub-Saharan Africa provided two levels of decision aid. Firstly, the dynamics of the first captures in the immediate proximity of a crop field makes it possible to predict an outbreak at the beginning of the vegetative cycle two or three weeks ahead (a good length of time for the choice of a management method appropriate to the local situation). Secondly, trapping on a countrywide scale in Cameroon revealed that the populations in a crop fields are partly indigenous and descend from local clones and partly of southern origins several hundred kilometers away (Deguine and Leclant, 1996). This information can then be usefully incorporated in strategies to prevent the development of possible resistance to insecticides.

The development of cotton tolerance thresholds makes it possible to make an objective diagnosis of the phytosanitary state of the crop and therefore to decide whether or not supervised curative interventions are necessary, for both *B. tabaci* (Chu *et al*., 1994) and *A. gossypii* (Gozé and Deguine, 1998). *In situ* counts of populations and also of the relative proportions of plants or vegetative organs infested are used for this. However, this diagnosis is little used in practice because of the small impact of supervised chemical control of the populations of these piercing-sucking insect pests of cotton. Certain decision-aid models nevertheless attempt to take these pests into account in an overall approach to the handling of crop management sequences, but their use is still limited.

Curative measures

Although it is indeed necessary to use curative techniques, the upholders of supervised protection recommend the choice of methods from the range of non-chemical procedures available and then, if necessary, choice among the range of active substances authorized for spraying. In the latter case, it is strongly recommended to choose an active substance reputed to be the least harmful for the environment. It is known, unfortunately, that farmers in most countries do not really have the choice, even in the so-called developed countries, and this reduces the scope of this strategy. Supporters of IPM should give priority to the alternative control measures available to them. Some award an increasingly large role to physical control measures: Orozco-Santos *et al*. (2002) for *A. gossypii* and *B. tabaci*, and Vincent *et al*. (2003) in a more general manner for insects. These practitioners aim at the maximum conservation of indigenous beneficial fauna and the use of chemicals is only tolerated as a last resort! There are few alternative measures (biological control, biotechnological and ethological methods, autocidal control) suited to particular biological and agronomic conditions and these are too seldom available (Blum, 2002).

Cotton is no exception. Most of the techniques for protection against aphids and whitefly are chemical. The use of entomopathogenic fungi, predators and parasitoids found suitable for greenhouse crops or special production systems are rarely successful in field cotton crops. This is clearly illustrated by recent syntheses of examples of the control of *B. tabaci* by fungi (Raria and Wraight, 2001), predators and parasitoids (Gerling *et al*., 2001) and of *A. gossypii* in Australia (Waterhouse and Sands, 2001). Aphids and whitefly have a great number of natural antagonists, whether entomopathogenic fungi, predators and parasitoids (Deguine and Leclant, 1997; Butler and Henneberry, 1994), but their impact becomes negligible if aerial chemical treatments are applied in a non-supervised approach (Naranjo, 2001; Kuklinski and Borgmeister, 2002).

The priority awarded to preventive measures is therefore all the more justified and it is recommended that maximum efforts should be made in this field. Provided that population levels are forecast objectively by trapping alates or counting individuals, the basis of supervised curative interventions can be predicted from the beginning of the season. Such interventions include the use of suitable pesticides for a significant reduction in the populations of aphids and whitefly and of the damage that they cause; treatments based on natural or synthetic oils or detergents to reduce the risk of viral infection or the use of formulations based on plant extracts (such as neem (*Azadirachta indica*) for example) (Kaadeh *et al*., 2001; Mann *et al*., 2001). If the preventive measures recommended are found to have been insufficiently effective at the end of the season, the following techniques can be planned according to thresholds and the risk of sticky cotton: early harvesting or staggered harvesting; manual or mechanical defoliation or topping of the plants; the application of large quantities of water (Arnold *et al.*, 2002) [washing with water is sometimes envisaged to control *A. gossypii* on ornamental plants (Stoyenhoff, 2001)] or, as a last resort, supervised chemical defoliation. Chemical control is unsuitable at in the end of the season as farmers are little inclined to make the outlay when the harvest is assured. It is also often ineffective. During this period, the easing up of chemical control is also very favorable for enhancing the regulating role of indigenous beneficials whose numbers increase.

Several initiatives for the integrated management of piercing-sucking insect populations on cotton have been made in recent years on the basis of the observations mentioned above (Hardee *et al*., 1994; Kogan, 1995; Butter and Kular, 1999; Ellsworth and Martinez-Carillo, 2001; Sharma *et al*., 2001; Deguine *et al*., in preparation).

All the stages in the approach and the measures proposed are summarised in Table 1. One of the major difficulties of the integrated management strategy is that of taking ensuring the compatibility of the different control techniques used for each of the major pests, bearing in mind the obligation to conserve biological diversity and the environment as a whole. This integrated approach concerns all the sectors of crop protection from entomology to plant pathology and weed science. It is thus necessary to be informed not only of the nature of the secondary effects of commercial active substances but also to possess accurate knowledge of the precise functioning of the ecosystems in question to achieve truly rational supervised management. Mastery of the situation in the case of crops like cotton, that are subjected to particularly strong and varied pest pressure, is very difficult and requires not only farmer training but also the provision of a decision aid system that is independent of commercial channels.

Conclusion and Prospects

The intrinsic characteristics of aphids and whitefly and their capacity for adaptation and reaction to cropping conditions have made these insects major pests - often poorly mastered - in cotton farming systems. The change in their status results from a biological imbalance between the insects, their environment and beneficials, and analysis of the reasons for this change in status makes it possible to envisage what can eventually provided sustainable supervised, management of these pests.

A new approach clearly favoring preventive methods is proposed after observation of the failure of the spraying of foliage with insecticides. This is aimed at a return to a biological balance and can only be evaluated on large time and spatial scales. It also requires an overall management view of populations of both potential pests and beneficials in an overall approach in line with the sustainable development concept. The corresponding techniques are being implemented only very gradually in a context in which immediate profitability often outweighs management of the future. These techniques certainly very difficult to apply as they concern agronomic decisions above all and require a change in the mentalities of users whose reflex is often that of using the chemical solution only. In the approach described, which is coherent with the principles of IPM, the use of chemical insecticides is the very last resort. They are only acceptable on a limited case-by-case basis, after evaluation of populations and of the objective chances of success of the treatment envisaged, with regard to both the size of the populations targeted and the economic, environmental and social risks.

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Annex 1.

Several definitions and details of concepts

Integrated control: Pest management system that in the context of the associated environment and the population dynamics of the pest species, utilizes all suitable techniques and methods in as compatible manner as possible and marinating the pest populations at levels below those causing economic injury. (FAO, 1967).

Integrated Production (Integrated Farming): Farming system which integrates natural resources and regulation mechanisms into farming activities to achieve maximum replacement of off-farm inputs, secures sustainable production of high quality food and other products through ecologically preferred technologies, sustains farm income, eliminates or reduces sources of present environmental pollution generated by agriculture and sustains the multiple functions of agriculture. (OILB/SROP, 1993).

Green Revolution: The Green Revolution has tried to fight against poverty and food shortages by selecting varieties and improved production systems, by the massive use of fertilizers and pesticides. Its impact was very important but only in countries with high production capacity, water surpluses and high population density. Griffon (1995).

Doubly-Green Revolution: The aim of the Doubly-Green Revolution consists of changing the agricultural development rationale based on the control of the environment to another based on the harmony with the ecosystems: working with and not against the variability of systems and making agriculture profit from the knowledge acquired by the ecological sciences. It aims to increase production without depleting the environment or affecting the bio-diversity for future generations. It also seeks to alleviate poverty and decrease food insecurity guaranteeing economic viability and social equity. Thus, the Doubly-Green Revolution requires an interdisciplinary, intersectorial and spatial approach Griffon (1995).

Table 1. Integrated management of populations of piercing-sucking insects (aphids and whitefly) in cotton growing.

Preventive (indirect) measures	
Strategies • Enable the susceptible stages of cotton to escape infestation by piercing-sucking insects • Reduce or 'dilute' piercing-sucking insect populations • Enhance or conserve natural antagonists	
Scale: cotton field	Scale: cropping system, farm, 'terroir' (local area)
Rapid crop installation • Early sowing • Systems reducing installation time (direct sowing, minimum tillage)	• Cropping systems that can be favorable • (DMC, UNRC, etc.) • The case of genetically modified crops • Rotations • Cropping patterns • Field shape and size • Prophylaxis • Supervised (rational) fertilization • Crop residues • Inter-season reservoir plants • Rational associations • Trap crops • Refuge plants • Juxtaposition of crops
Shortening of sowing to fruiting time • Choice of variety (short cycle, limited vegetative development, synchronous, short fruiting) • Sowing density • Growth regulators • Seed coating • Optimization of interactions (UNRC, etc.)	
Shortening period of boll exposure to honeydew • Early harvesting • Several picking runs • Choice of variety (large bolls, plant architecture, synchronous fruiting)	
Limiting food resources • Choice of variety (foliage: color, texture, shape, size, leaf area index, sugar and amino acid contents) • Fertilization management (organic and inorganic) • Water supply management • Crop residue management • Other crop management features • Genetically modified cotton plants • Weed growth management	
Risk evaluation • Crop surveillance (field or groups of fields) • Forecasting and decision aid tools • Economic, social and environmental threshold	

Table 1. *Contd.*

Curative (direct) measures • Use of natural oils and detergents • Use of plant extracts (e.g. neem) • Watering or plant washing with water • Supplementary staggered picking operations • Defoliation, manual topping • Supervised chemical control (as the last resort) using synthetic insecticides, oils or detergents, synthetic defoliants for defoliating or topping (with products chosen according to the criterion of the least ecological incidence: specificity, toxicity, selectivity, secondary effects and respect of the environment)

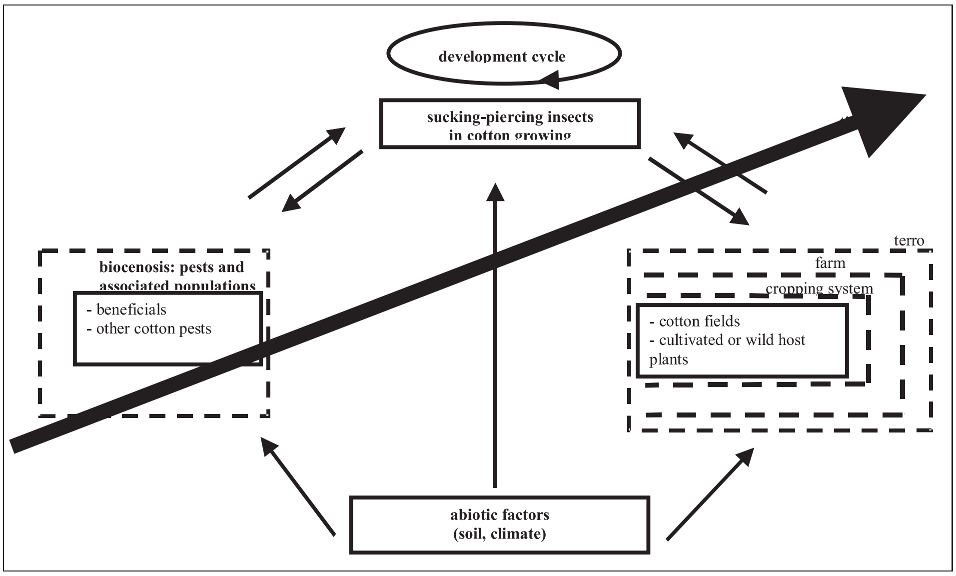

Figure 1. *Spatio-temporal relations between piercing-sucking insects (aphids and whitefly) and their environment (modified, after Audemard, 2003).*

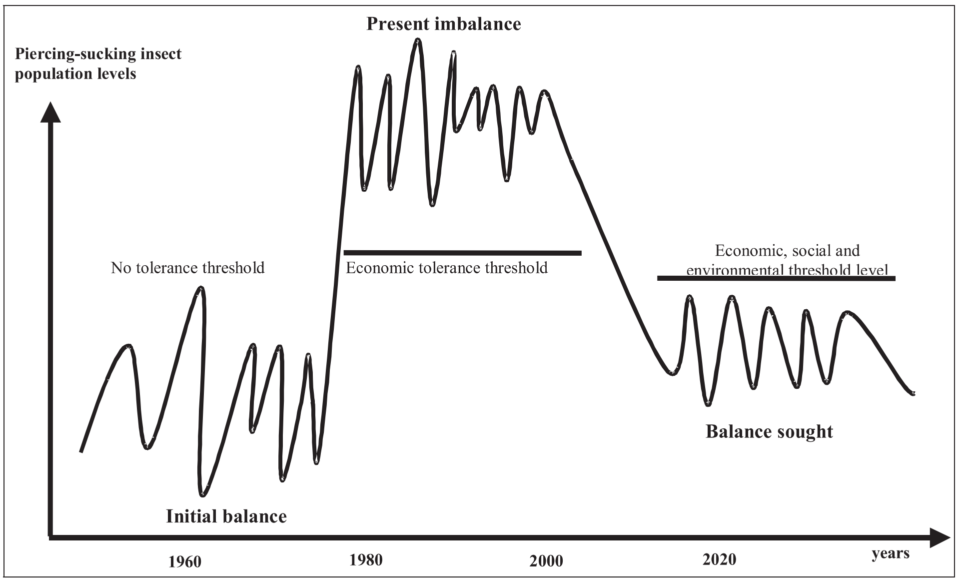

Figure 2. *Schematic representation of the evolution of situations of balance or imbalance between populations of piercing-sucking pests in cotton growing and their environment and the evolution of tolerance thresholds for the farmer.*