1284 Agroecology and Ecological Engineering for Pest Management. Cotton Protection as a Case Study.

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This synthesis provides an annotated guide to the thinking and publications behind the evolution of concepts in cotton pest management over the last fifty years. The first movement was from the concepts of *Pest Contro*l to those of I*ntegrated Pest Management (IPM)*. It was soon appreciated that advantage needed to be taken of the beneficial aspects of agro-ecological biodiversity, leading to concepts of *Agro-Ecological Engineering*. This required action beyond the immediate cotton field and of many players other than the recommending scientist. *Area-wide* and C*ommunity-based* management, incorporating the lessons learnt from *Farmer Field Schools (FFS)* made this a more genuinely participatory process. It soon became apparent that biodiversity in itself does not deliver improved pest management and the practice of *Landscape Farming* came to involve the manipulation of spatio-temporal crop geometries, in turn leading to *Better Cotton Management Practices* (BMPs) aiming to capitalise on functionally useful biocomplexity rather than simple biodiversity as such and explicitly incorporating wider environmental concerns. More recent developments along this pest management continuum include the idea of *New Cotton Cultivation* (NCC) emphasising the interactions between the plant, the technical context and the natural and sociological environment of particular cultivators. With improvements in our understanding of the scale and complexity of the practices required to optimise cotton production systems we will continue to move towards more genuinely sustainable and lower physical-input systems.

Keywords: *Agroecology, Cotton, Pest Management*

Introduction

Since the widespread employment of synthetic pesticides against plant pests from the middle of last century, the crop protection community has been searching for guiding principles, capable of responding both to the requirements of agricultural production and the constraints imposed by the need for sustainable development of the planet (Lewis et al., 1997). Chemical control rapidly revealed its limitations, as well as its possibilities, and alternative solutions to pest management problems have been recommended since at least the 1960s. A new strategy was developed under the rubric 'integrated control', envisaging the employment of a range of different control measures, constrained by their compatibility and the requirement for minimising noxious effects on the wider environment.

Experience has shown that putting in place effective biological control procedures has required a significant reduction in chemical treatments, a condition which producers have found difficult to accept. In their defense, it must be said that the alternative solutions proposed have often been difficult to put into practice and frequently insufficiently or unreliably effective. These problems arise in large part from our still inadequate understanding of the mechanisms which determine the dynamics of pest populations in their agro-ecosystems (Geier, 1966). Since the mid 1960s we have passed through a number of significant stages in the thinking on crop protection, of which the first, under the term 'Integrated Pest Management' or IPM, abandoned the idea of comprehensive pest control and replaced it with the concept of the management of pest populations. In retrospect, this realisation of the importance of the interactions between populations within agro-ecosystems came late. It is now considered as a necessary precursor to the true management of pest populations within the global functioning of ecosystems (Altieri and Nicholls 1999).

Despite these difficulties, a biological, then ecological, orientation has underlain the development of crop protection over the last 50 years (Pimentel, 1995; Walter, 2003). This process has been marked by multiple and diverse interpretations of the concept of IPM (Kogan, 1998). Numerous technical innovations have been proposed, without, however, bringing any really significant change in the management of pests in major crops (Lewis et al., 1997), due no doubt to an unrealistic approach to the complexities of the phenomena concerned. The debate has been re-animated recently, both by the spectacular success of the recent advances in biotechnology and by genuinely taking into account the need to preserve biological diversity. As much for socio-economic as for ecological reasons, this has given rise to a re-examination of farming systems as traditionally practiced, through an innovative agro-ecological approach (Dalgaard et al., 2003).

In this context, cotton production offers the potential to analyse the fruits of rich and frequently controversial pest management experiences in a range of agro-ecological situations, from subsistence farming to industrial production systems. Cotton trading is today the object of a socio-economic investigation by the World Trade Organisation, whose conclusions may disrupt current production practices. For these various reasons, cotton production can be taken here as a case study illustrating the development of the concepts of crop protection and their strengths and weaknesses.

In this review, we have grouped theoretical and applied papers to produce a synthesis illustrated by concrete examples and have then attempted to draw lessons from this experience, with a view to supporting the adoption of a new strategy for cotton crop protection. We could have taken this approach for the different phases and concepts of crop protection: chemical control; IPM; biologically based integrated management (biotech and conservation biological control). But we have focused our review on the most recent agro-ecological approaches. The particular richness of the literature on this theme reflects the importance that it is given today.

Characteristics of agroecology and ecological engineering for cotton pest control

Since the 1970s, the evolution of plant protection has been driven by an improved understanding of the functioning of ecosystems (Botrell, 1980). At this time, the desire to explore these issues favoured the development of computer-based simulation models for risk assessment. The approach to these problems was considerably improved; taking into consideration the development of the plants in the particular soil/ moisture/ nutrient content and insolation context and considering the suite of pests present in the same crop – the development of an concept of integrated control and then of integrated production or integrated crop management.

The UN Conference on the Environment and Development in Rio de Janeiro in 1992 drew attention to the need to preserve the biological diversity of ecosystems in general and agro-ecosystems in particular. The subsequent publication of diverse works aimed at advancing the IPM paradigm, helped in the national adoption of IPM strategies (Benbrook et al., 1996). The simultaneous elaboration of the scientific principles underlying this field of agro-ecology, rendered these calls more credible (Altieri, 1995; Dalgaard et al., 2003). It was then necessary to move to the practical stage of conceiving growing systems which capitalised on the resilience of agro-ecosystems (Clements and Shrestha, 2004). To this end, 'agro-ecosystems management' or 'agro-ecological engineering' is today recognised as one the up and coming concepts in crop protection (Lewis et al., 1997; Gurr et al., 2004; Clements and Shrestha, 2004; Nicholls and Altieri, 2004).

More generally, this development is presented in the form of an 'IPM continuum' (Jacobsen, 1997), where it is clear that much of what is necessary will be a continuous evolution of traditional concepts and understanding in crop protection (Clements and Shrestha, 2004). The principles of a bio-centered agriculture, developed during the last decades, have led to new orientations to crop production which will require a return to utilising knowledge and skills progressive lost of over the last several decades.

Production which is technically 'organic', in the accepted sense of the certifying organic agriculture bodies, has had a certain success in cotton from the mid 1990s, but it does not represent today more than a miniscule part of the market (c.30,000 tonnes or 0.1% of global production in 2005), even if for some it seems a promising route for resource-poor small scale producers (Galanopoulou-Sendouca and Oosterhuis, 2004). Organic cotton is currently produced in 22 countries; largely by Turkey (40%), India (25%), the USA, (8%) and China (7%). The number of small brands and retailers in North America and Europe interested in marketing organic cotton products is growing rapidly (Organic Exchange 2006), but it may be argued that this is a high-price, low-volume, niche market which is unlikely to significantly expand. For growers there can be a price premium but there has almost always been a yield cost to organic production. Currently there appear to be no significantly effective pest management techniques unique to organic cotton production systems, although this position may change with further research. Within this overall movement, the BASIC programme (Biological Agricultural Systems in Cotton) in operation in California for 12 years or so, illustrates a possible method for transition form traditional IPM towards a true 'biological' production system (Swezey and Goldman, 1999).

Area-wide and community-based cotton pest management

As previously described, cotton crop protection was one of the earliest in the agricultural world to experiment with the application of eradication techniques*.* Many other ways of responding to the criteria of area-wide pest management have also been envisaged, including the use of microbial control of heliothine pests in the USA with the aid of entomopathogenic viruses (Street et al., 2000), and capitalising on the long-term effects on pest populations offered by the deployment of Bt-cotton (Carriere et al., 2003).

One of the precursors of area-wide management ran in Arkansas in the mid 1970s (King et al., 1996; Hardee and Henneberry, 2004). The main thrust was to gain the active support of the growers to a regional, co-ordinated, phytosanitary effort and to secure their adhesion to the agreed practices. In southern Queensland (Australia) a similar strategy has been successfully applied since the end of the 1990s in the Darling Downs region (Murray et al., 2005). This system rests on the application of the following tactics: a) reducing the survival of over-wintering, insecticide-resistant *H.armigera* pupae, b) reducing the early season build-up of *Helicoverpa* spp. on a district/regional scale, and c) reducing the mid-season population pressure on *Helicoverpa*-susceptible crops. A key component of this programme was the use of early and late-season trap crops.

These new, area-wide, strategies have generally been welcomed, particularly in industrialised cotton production systems, as they form a rational response to the collective need of growers to reduce production costs. They are more difficult to implement in aridland, small-farmer, systems where their priorities take second place to the immediate need for local food crop production. The relative complexity of these systems and technical practices proposed, and the need for a much larger number of growers to co-operate over a given cropping area, are effective barriers to adoption by small-scale producers in traditional agricultural systems. The difficulties encountered in adopting even simple scouting methods are indicative of these constraints.

Lessons learned in the Farmer Field Schools have resulted in the development of learning systems better adapted to the needs of these growers (Ooi et al., 2005). The importance of genuinely participative processes is underlined by experiences in all type of production systems. There has been relatively little research into implanting these newer concepts into small-farming systems in ways which take into account local constraints (Lancon et al. 2004).

Farmscaping, landscape farming, habitat management and cotton intercropping

Manipulations of the cotton agro-ecosystem have been recommended since the 1970s. They have concerned both modifications of normal agricultural practices and completely novel measures. Amongst the latter, intercropping with lucerne, or deliberately maintaining residual populations of pests within cotton fields to allow the survival of their parasitoids and predators, are often cited as examples of integrated management (Smith and Reynolds, 1972). Other technical solutions have been proposed: management of the vegetation in field borders, rearrangements of the spatio-temporal structure of cultures in the fields themselves, and appropriate management of weeds (Altieri and Letourneau, 1982; Clements and Shrestha, 2004; Nestel et al., 2004). Table 1 compares Integrated Control and Habitat Management for Pest Management. The expression 'farmscaping' has been proposed to designate 'a whole-farm, ecological, approach to pest management' (Dufour, 2000).

Multiple cropping, where two or more crops may be taken from the field in a single year, is an example of traditional practices which are still common in tropical developing countries. They may take the form of sequential cropping, with crops succeeding each other in the same field, or intercropping – growing more than one crop in a pattern in the same field using the techniques of mixed- or multiple-, row-, strip- or relay-intercropping). For the majority of resource-poor small-scale producers, it is often necessary to meet a significant portion of daily food requirements from the same area of land used for cash cropping and this requires a judicious understanding of the biological risks which this may engender (to soil fertility as well as pest management) (Altieri and Nicholls, 2004). The abundance of the resulting pest populations naturally varies strongly between one particular case and the next. These populations are influenced by a variety of factors, amongst which are those which affect the behaviors of the pests and their natural enemies (Gurr et al., 2004). The idea that crop diversification would, of itself, result in the reduction of pest impacts has now been abandoned, although the positive role of trap crops is acknowledged, and particular cropping geometries and sequences can be strongly beneficial (Vandermeer, 1990; Smith and McSorley, 2000; Altieri and Nicholls, 2004; Shelton and Badenes-Perez, 2006).

These various new practices form part of the recommendations being proposed to producers under the rubric of 'better cotton management practices' or BMPs. Again in Australia, intercrops such as sunflower, safflower, sorghum, tomato and lucerne, are considered to be favourable in their influence on the pest/predator situation, with the lucerne acting as a nursery crop for the beneficials. Having established that the abundance of natural enemies declines rapidly with the distance between the two crops, it is recommended, for example, to grow a band of lucerne 8-12m wide, as a single median strip, between two cotton fields up to 300m wide (Mensah, 1999). Cutting parts of this medium strip and/or the spraying of food additives allows the management of movements of predators (Mensah and Singleton, 2004). These same intercalated rows of lucerne may also play a role as trap crops for the pests themselves, such as the green mirid, *Creontiades dilutus*. One should not, however, underestimate the likelihood that these intercrops may also favour infestations of certain pests. This can be an obstacle to the adoption of these practices, even with the use of selective biopesticides on the intercalated crop (Gurr et al., 2004; Mensah and Singleton, 2004; Duraimurugan and Regupathy, 2005).

It is in China that the practice of intercropping is the most common and the most diversified. Cotton is frequently sown in spring between lines of winter wheat, which helps in the management of early-season aphids. One particular success in this area has been the growing of alfalfa (*Medicago sativa* L.) around cotton field margins as a nursery crop for ladybirds (*Coccinella septempunctata*, *Propylea quatrodecimpunctata* and *Hypodama variagata*), chrysopids and other beneficial arthropods in Xinjiang province of Eastern China. The alfalfa is cut several times in a season and the beneficials move from alfalfa, where they have been feeding on the non-cotton aphid *Therioaphid maculata*, into the cotton, where they significantly reduce the number of cotton aphids (*A. gossypii),* which are by far he most important cotton pests in the region (Lin *et al.* 2003). Agro-forestry, under the name of 'alley cropping' or 'tree-based intercropping' is undertaken in some areas with poplar, *Paulownia* and Elm (Yin and He, 1997). Poplar acts as an oviposition attractant to *H.armigera* whose larvae are then not able to survive on the trees. This utilisation of tree intercrops, characteristic of peasant agriculture in many parts of China since the 1980s, must be seen as primarily an insurance against the risks of aeolian erosion, as wind-breaks and as a local source of wood for cooking, heating and construction. The phytosanitary consequences of these systems are not very well documented (Altieri and Nicholls, 2004; Clements and Shrestha, 2004; Landis et al., 2000; Wu and Guo, 2005), and they may not fit well into the criteria of ecological management, today gathered under the term 'ecological infrastructures', which preserve the biodiversity and so the functioning of agro-ecosystems. These 'infrastructures' attempt on the one hand to provide physical linkages between different parts of the agricultural landscape which are suitable for the survival of indigenous fauna (corridors, hedgerows *etc*.), and on the other hand to organise the cropping land into physical units which favour the free movement of natural enemies, particularly of generalist predators (Altieri and Nicholls, 2004; Boller et al., 2004; Ferron and Deguine, 2005). Figure 1 shows the coherence and the convergence on Habitat Manipulation from differents perspectives including Crop Protection.

Biodiversity, biocomplexity and the future of cotton pest management

The emphasis placed on respect for the sustainable development of the planet obliges the researcher to find a balance between the immediate needs of humanity and the preservation of the diversity of the living world. To this end, we have no doubt accorded too great an importance to biodiversity for its own sake, at the expense of a functional biodiversity which helps to provide a sustainable integration of human activity with the functioning of ecosystems (Letourneau, 1998; Altieri and Nicholls, 2004).

The term biocomplexity, is to be understood as 'properties emerging from the interplay of behavioural, biological, chemical, physical and social interactions that affect, sustain, or are modified by, living organisms, including humans' (Michener et al., 2001). Applied to crop protection, this implies finding the delicate balance between curative treatments applied at the level of the individual field and the management of pest systems at the level of the overall agro-ecosystem.

These agro-ecosystems are characterised by an, often considerable, reduction in their diversity at the species level because of current methods of land utilisation; monoculture in a 'naked field', cleared of all weeds (Andow, 1983). Under these very constrained conditions, infestations of herbivores are favoured. The limited effects of their accompanying beneficial complexes on the dynamics of their populations comes too late, even when they are not blocked altogether by non-selective phytosanitary interventions. The generalist predatory fauna is most often neither diverse nor abundant in these systems, which lack enough alternative prey (Altieri and Letourneau, 1982). It is for this reason that crop diversification is the cultural technique generally promoted, in order to favour populations of beneficials and so to reduce the need for insecticidal treatments (Gurr et al., 2004; Prasifka et al, 2004; Clements and Shrestha, 2004).

The popularisation of genetically modified plants as a response to phytosanitary problems, as with cotton, has recently added supplementary questions as to their likely role and impact in agro-ecosystems as a whole (Altieri, 2000). At this stage we have only preliminary results in this area (Andow and Zwalhen, 2006). Modifications of the relative importance of the different pest species within the agro-ecosystem as a whole, in relation to their specific susceptibility to the Bt toxins, are already emerging. For example, circumstantial evidence is accruing of the reduction in importance of *H.armigera* as a pest of many crops since the introduction of Bt cotton in both China (1996-7) and India (2002). Questions on the importance of these entomotoxins in the biology of soils have been asked recently (Altieri and Nicholls, 2004). Positive impacts on diversity within Bt cotton field are generally reported, but measured impacts on the diversity of arthropod populations around cotton fields, which are weak but significant in certain cases, has encouraged the pursuit of investigations in this area of whole system impacts (Head et al., 2005; Torres et al., 2005; Whitehouse et al., 2005; Naranjo, 2005).

These are the contexts within which the design of a new concept of sustainable crop protection in general, and sustainable cotton crop protection in particular, is emerging (Tilman, 1999). This new concept implies a change of strategy, to one composed, under the structure of a total-system approach, of three major components: a) management practices established at the level of agro-ecosystems, b) the systematic exploitation of multi-trophic interactions among plants, herbivores and parasitoids/predators, c) recourse to pesticide applications only as a last resort (Lewis et al., 1997; Walter, 2003).

An illustration is provided by the orientation given to research under the expression 'New Cotton Cultivation (NCC)', seen as identifying the best interactions between the plant, the technical context and the natural and sociological environment pertaining in a given localised situation (Deguine et al., 2000). Control of populations of piercing-sucking insects which have risen to be of major importance in the last two decades, may be taken as an example. The recommended strategy gives priority to preventative measures through a process which is at the same time multidisciplinary, adapted and participative (Deguine et al., 2004, table 2, figures 2and 3). Several other integrated management initiatives for sucking-piercing pest control in cotton have been undertaken on similar principles in recent years (Hardee et al., 1994; Ellsworth and Martinez-Carillo, 2001).

Conclusion

More generally, the future of cotton crop protection rests in a fruitful multi-disciplinarity, particularly in the improvement, or genetic transformation of varieties, such as to allow the full expression of their agronomic potential under the new requirement of respecting the principles of sustainable agricultural development. This constraint, as much technical as social, imposes a break with traditional operations in making agricultural activities a part of the functioning of ecosystems, and no longer an artificial exploitation of natural resources requiring high input levels (Fitt et al., 2004; Russell, 2001).

For most authors, the movement from a 'field-by field' to a 'farm by farm' and 'agro-ecosystem by agro-ecosystem' to a 'landscape by landscape' approach is a gradual and evolutionary tendency inherent in the long-term goals of a true IPM perspective. The developments to date seem, *a posteriori*, to be steps in that direction. Others, by contrast, ask themselves whether the reality of moving to a phytosanitary system founded on these new principles, will not involve an obligatory and marked rupture with traditional practices (Irwin *et al*., 2000; Deguine *et al.,* 2000). This question revisits the epistemological arguments of Kuhn (1996): when the inadequacy of a paradigm, such as chemical pest control, becomes more and more obvious, and a replacement paradigm is developed, such as agro-ecological management or 'a total systems approach to sustainable pest management' (Lewis et al., 1997), results in a brutal scientific revolution. Some authors talk today of a 'new' green revolution or 'evergreen revolution' (Borlaugh and Dowdswell, 2004 ; Griffon, 2006) to draw attention to the progress made since the 1960s, a time at which the strategy to respond to the food production needs of humanity rested essentially on the promise of varietal selection and recourse to synthetic inputs.

For agronomists, sociologists, plant protection specialists and growers, cotton production offers a rich field of experiences and large-scale experimental results. The spatio-temporal challenges provided by cotton's phytosanitary problems require a shift in thinking towards seeing agricultural production as one part of the functioning of larger agro-ecosystems. The potential ecological consequences of the actions of the industry require a re-orientation of the players towards management practices which respect the principles of agro-ecology. These will require a change in the mentality of cotton production stakeholders which may, in the end, be driven as much by consumer attitudes as by economics. In plant protection it will be necessary to move from an individual to a collective vision, giving due weight to the foreseeing of risks in the medium and long term, within an essentially preventative approach.

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Table 1. Comparison between Integrated Control and Habitat Manipulation for Pest Management

	Integrated control	Habitat Manipulation
Protection modalities	Control	Management
	Agrochemical basis	Agroecological basis
	Other methods (than chemical) ineffective	Other methods possible and effective
Ecological functioning of agroecosystem	Not taken into account	Taken into account
Study objects	Population of one pest species	Community of arthropods (pests, beneficials, pollinators)
	One cultivated species	Community of cultivated and non cultivated plants
Reasoning scales	The field	The agroecosystem (from plant to landscape)
	Growing cycle	Several years
	The farmer	The stakeholders (farmers, landscape managers, hunters, …)

Table 2. Agroecological approach and ecologically-based management of populations of piercing-sucking insects (aphids and whitefly) in cotton growing (*in* Deguine *et al*., 2004)

1Regulations	
Scales: international, national, regional	
2 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, landscape
Rapid crop installation - early sowing - systems reducing installation time (direct sowing, minimum tillage) Shortening of sowing to fruiting time - choice of variety (short cycle, limited vegetative development, synchronous, short fruiting) - sowing density - growth regulators - seed coating - optimisation of interactions 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: colour, texture, shape, size, leaf area index, sugar and amino acid contents) - fertilisation management (organic and inorganic) - water supply management - crop residue management Other crop management features - genetically modified cotton plants	- cropping systems that can be favourable (minimum tillage, Ultra Narrow Row Cotton, etc.) - the case of genetically modified crops - rotations - cropping patterns - field shape and size - prophylaxis - supervised (rational) fertilisation - crop residues - inter-season reservoir plants - rational associations - trap crops - refuge plants - juxtaposition of crops

- weed growth management	
1Risk evaluation	
- Crop surveillance (field or groups of fields) - Forecasting and decision aid tools - Economic, social and environmental threshold	
4 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. Coherence and Convergence of Habitat Manipulation from different concepts including Crop Protection

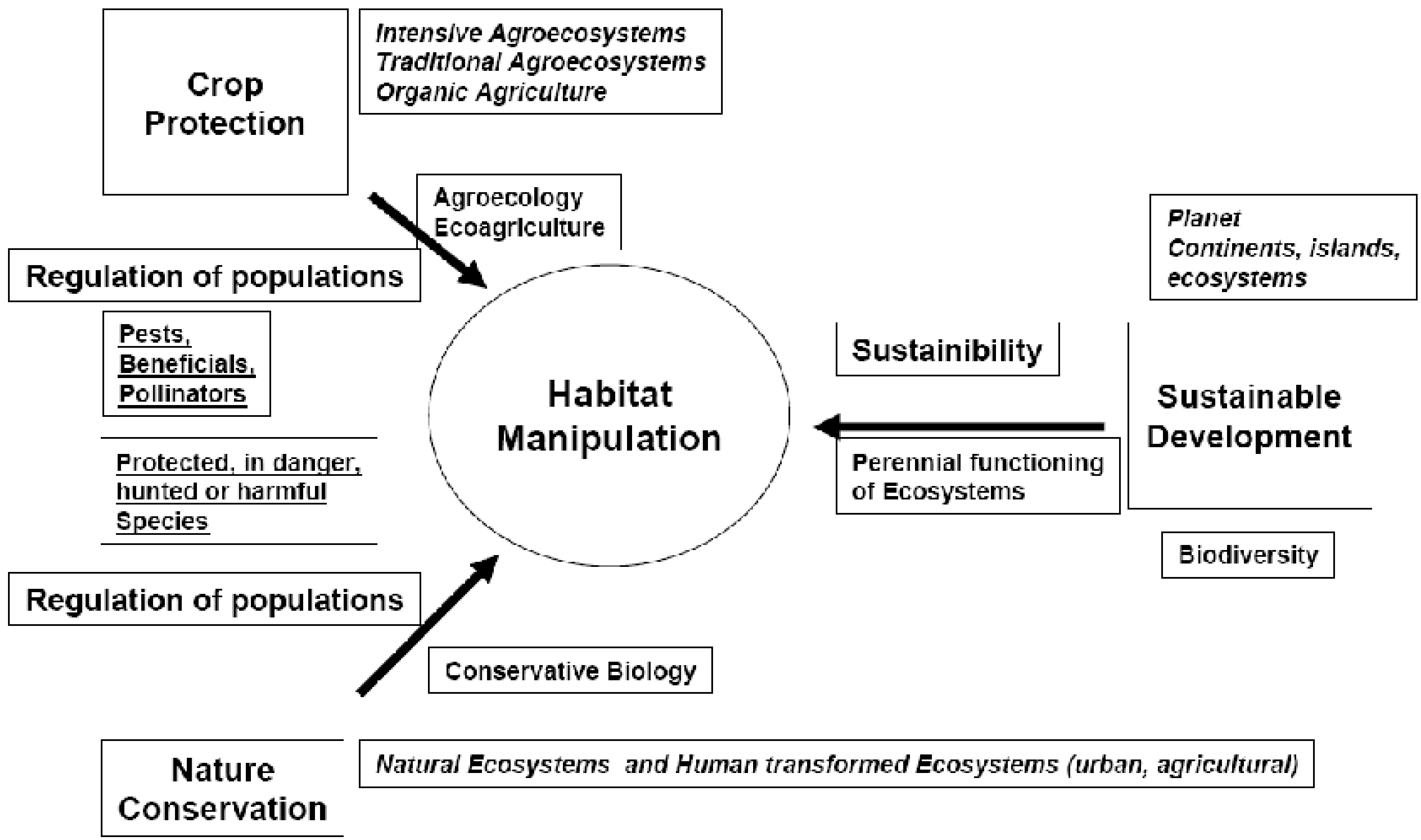

Figure 2. Spatio-temporal relations between piercing-sucking insects (aphids and whiteflies) and their environment in cotton agroecosystems (*in* Deguine *et al.*, 2004)

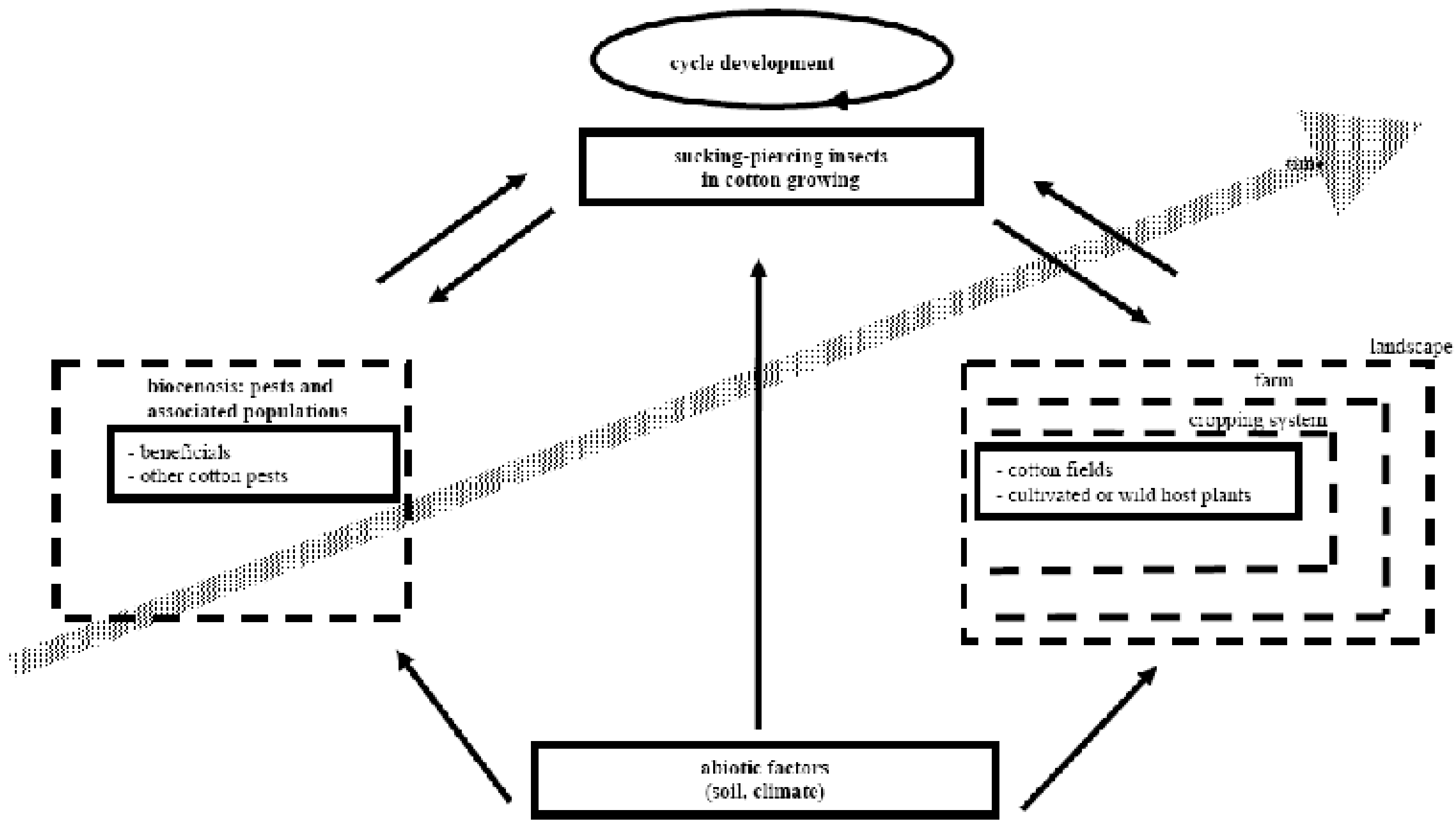

Figure 3. Schematic representation of the evolution of situations of balance or imbalance between populations of piercing-sucking pests in cotton growing and their environment and the evolution of tolerance thresholds for the farmer (*in* Deguine *et al.*, 2004)