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# DIVECOSYS: Bringing together researchers to design ecologically-based pest management for small-scale farming systems in West Africa

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ABSTRACT

Crop pests are a major constraint to the intensification of agricultural production in the tropics, with novel issues related to global change (climate, land use, biological invasions, etc.), food security and preservation of natural resources and biodiversity. A research, extension and education network called DIVECOSYS (Diversity of cropping systems and ecologically-based pest management in West Africa) was launched in 2010 to synergize applied research actions in response to growing concerns on the vulnerability of agricultural systems to pest management in West Africa. This scientific network brings together research and academic institutions, with expertise spanning a multidisciplinary perspective from biology and ecology to remote sensing, agronomy and integrated pest management. Its main scientific objective is to explore the potential of biodiversity and ecological processes such as pest regulation, enabling novel ecologically-based models for productive systems, reduction of pesticide use, and adaptation or resilience of farming systems in the face of environmental disruptions. From Northern Senegal to Southern Benin, the research group explores a wide range of ecoregions and socio-ecological contexts, including stakeholders and their objectives, land use and agricultural practices, and management of biodiversity for enhancing biological control. Main challenges to be turned into opportunities include (i) encouraging collaborations amongst researchers from different scientific fields, (ii) fostering interactive research and synergies among research institutions and among countries, and (iii) developing an ecological engineering approach for the design of sustainable agricultural systems for smallholder farmers.



## 1. Introduction

Between 1982 and 2007, the overall production of cereals and grain legumes was multiplied by 3 and 2.4 times respectively in sub-Saharan Africa, where the population more than doubled over

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the same period (Uhder et al., 2011). Such a rise in production was mostly achieved by extending cultivated areas, without any or only limited increases in yields. In order to meet the demand, cultivated areas would need to increase 2–3-fold by 2050. Such an expansion leading to large-scale farming systems is barely feasible in most African countries due to the limited availability of arable land and water resources. In addition, such an extension would have a detrimental impact on natural areas where biodiversity must be preserved. On the contrary, smallholder agriculture must be supported as the backbone of global food security in most African countries (Tscharntke et al., 2012). Hence, there is an impending challenge of achieving efficient and productive agricultural land use, while preserving natural resources.

Crop pests are a major constraint to the intensification of agricultural production, especially in the tropical areas (Oerke, 2006; FAO, 2012; Savary et al., 2012). They include all organisms harmful to crops: arthropods (insects and mites), fungi, bacteria, viruses, along with nematodes, rodents, birds and weeds. Losses caused by crop pests along the value chain of agricultural production remain abnormally high and threats are set to increase with climate change (Maxmen, 2013). The massive use of synthetic pesticides has shown major limitations, including serious hazards for the environment and human health, and sometimes evolution of resistance in target organisms. In addition, detrimental effects on biodiversity can result in pest outbreaks due to the alteration of ecosystem services such as natural pest regulation (Power, 2010; Meehan et al., 2011). In West Africa, where family agriculture dominates, pesticide use remains limited to and reserved for certain high value cash crops (particularly cotton –*Gossypium hirsutum* L., cocoa –*Theobroma cacao* L., fruits and horticultural crops). Rainfed staple crops are mainly grown without pesticides, with the exception of rice and cowpea. However, the overall simplification of landscapes resulting from the reduction of crop diversity and the expansion of monoculture, and in some cases from urban expansion, has contributed to the loss of biodiversity. As a result, cultivated ecosystems could become more susceptible to pest outbreaks and biological invasions (Tscharntke et al., 2012), particularly in a context of global warming and climate change (Pettorelli, 2012).

DIVECOSYS, a French acronym for ‘Diversité des systèmes de production et gestion agro-écologique des bio-agresseurs en Afrique de l'Ouest’ (Diversity of cropping systems and ecologically-based pest management in West Africa), was launched in 2010 as a research, extension and education network, in response to concerns related to the vulnerability of agricultural systems to pest outbreaks in West Africa. This partner network brought together more than fifty researchers, teachers, extensionists and research fellows from eleven research and academic institutions based in Benin, Mali, and Senegal (see list of authors). Its main scientific objective is to explore the potential of biodiversity and ecological processes involved in pest regulation, enabling novel ecologically-based models for productive systems (produce more sustainably), reduction of pesticide use (produce more safely), and adaptation or resilience of farming systems in the face of global change and environmental disruptions (produce more durably). Main challenges to be turned into opportunities include (i) encouraging the exchange of ideas and information amongst researchers from different scientific fields spanning from biology and ecology to remote sensing and modelling, (ii) fostering interactive research and synergies among research institutions and among countries, and (iii) developing ecological engineering for the design of sustainable agricultural systems by combining agronomy, theoretical and applied ecology.

We present here the paradigm and conceptual framework underlying research issues explored by the research group DIVECOSYS, according to the diversity of socio-ecological contexts and challenges for enhanced pest control. During this process, knowledge gaps are identified and addressed for better targeting ecologically-based pest management for small-scale agricultural systems in West Africa.

## 2. Dealing with emerging concerns for pest management

In West Africa, farmer field schools (Settle and Garba, 2011), threshold-based interventions (Renou et al., 2012; Silvie et al., 2013), insecticidal transgenic crops such as Bt cotton (Héma et al., 2009), or biological methods, e.g. spraying bio-insecticides or releasing beneficial insects (Neuenschwander, 2001), have the potential to help reducing the use of broad spectrum insecticides. However, concurrent emergence of new pest problems has been observed. Evolution of multiple resistance to pesticides (including Bt-formulations) has been demonstrated in some populations of the whitefly, *Bemisia tabaci* (Gennadius) (Gnankiné et al., 2013), and the cabbage diamondback moth, *Plutella xylostella* (L.) (Grzywacz et al., 2010). Emerging pests have been observed as part of the release of ecological niches, e.g. sucking pests replacing bollworms on Bt cotton (Deguine et al., 2008). Expansion of the host range has been reported in the cotton bollworm, *Helicoverpa armigera* (Hübner) (T. Brévault, unpublished data). Increased rate of biological invasions has also been recorded (Youm et al., 2011), with recent cases such as the fruit fly, *Bactrocera invadens* Drew-Tsuruta-White (Vayssières et al., 2009a; Goergen et al., 2011), or the tomato leafminer, *Tuta absoluta* Meyrick (Brévault et al., 2014). Weeds form a particular group of pests, whose control takes up a major share of producers' farming calendars. Herbicide use is increasing in West Africa, notably non-selective herbicides such as glyphosate, whose generalized use could lead to the evolution of weed resistance and could have negative consequences for the environment (Busi et al., 2013). Regarding the dynamics of insect populations, weeds may also serve as a reservoir or a refuge for pest insects (e.g. *Cleome* spp. for *H. armigera* or local Euphorbiaceae for *B. tabaci*), or a source of food for natural enemies (Ratnadass et al., 2012).

The adaptation of crop protection to risks arising from global environmental change is a major challenge for agricultural research. In this perspective, DIVECOSYS has based its approach in the general framework of agro-ecology, defined as the application of ecological concepts and principles to the design of sustainable agricultural systems (Altieri, 1987; Gliessman, 1990). Among the various concepts and approaches underlying agro-ecology (Mendez et al., 2013), our research posture is close to that of Tscharntke et al. (2005), who postulate that agriculture can contribute to conservation of high-diversity systems, which may in return provide ecosystem services such as pollination and biological control. Improving our knowledge on the relative importance of local (field scale) and landscape management of biodiversity is thus critical to better manage or enhance ecosystem services.

DIVECOSYS also considers side-effects of control strategies across agricultural landscapes (Brévault and Bouyer, 2014). Even ecologically sound pest management using biological control agents have the potential to disrupt ecosystem communities. Non-intentional effects of exotic natural enemy releases on native species need to be assessed before implementing biological control programs. Environmental risks include global or local extinction of a native species (target or non-target), large reductions in their distribution or abundance, competition with other natural enemies, and transmission of pathogens to native organisms (Van Lenteren et al., 2006). However, because of our commitment to smallholder farming systems, our ambition is to deliver not only technical recommendations, but also to integrate in a near future local knowledge and social sciences for participatory design of pest management strategies.

## 3. Exploring the diversity of socio-ecological contexts

From Northern Senegal to Southern Benin, the research group DIVECOSYS has been exploring a wide range of ecoregions, mainly determined by rainfall patterns, from 250 mm in the North, up to 1,200–1400 mm in the southern areas (Fig. 1, Table 1). A wide range of socio-ecological contexts is also addressed, including stakeholders and their objectives, land use and agricultural practices (pesticide use), and management of biodiversity (particularly pests and their natural enemies) for enhanced biological control.

Aridity is the main abiotic constraint in the Northern areas, with a short rainy season from June–July to October (4–5 months). Intensification of agriculture and farming systems (cereals, grain legumes, or cotton) has contributed to the simplification of landscapes, both in terms of land use and biodiversity, in the groundnut basin in Senegal, on the Mandingue plateau in Mali, and to a lesser extent in the cotton-producing area in Northern Benin. In some areas where access to water is possible during the dry season, e.g. in the Niayes or the Senegal River valley in Senegal or in the Niger Valley (North of Benin), patches of irrigated crops (vegetables, cereals, legumes, etc.), orchards (mango –*Mangifera indica* L., citrus) and perennial ecosystems (forests, galleries) in lowlands and along irrigation channels, form potential habitats where some biodiversity can persist in space and time. Benin is dominated by shrub cover (closed open, deciduous) followed by broad leaves tree cover and mosaics of crops and savannahs. Cotton is the major cash crop grown in the country followed by cashew nuts (*Anacardium occidentale* L.). In central-Northern Benin, orchards (mainly mango) are integrated in different types of tree savannahs alongside cashew orchards most of the time. In the south, most of the original vegetation has been replaced by secondary grasslands and thickets. Maize (*Zea mays* L.) and cassava (*Manihot esculenta* Crantz) are the main staple food crops in the south with scattered orchards (mango and mainly citrus) and horticultural crops.

Variability in rural population density (from 10 up to 300 inhab. $km^{-2}$) needs to be seen in line with local natural resources. With low population densities, arid territories face constraints linked to the availability of water resources for irrigation, to low soil fertility and to land availability, sometimes associated with salinization of cultivated soils. With a population density equal to 80–250 inhab. $km^{-2}$, the Senegalese groundnut basin is more at risk from a food security viewpoint than in the more populated zones in Benin.

DIVECOSYS is also interested in the cultivated diversity implied in food security for populations in rural areas and urban centres with which they interfere (peri-urban agriculture). Current research focus on cereal food crops including millet -*Pennisetum glaucum* (L.), sorghum –*Sorghum vulgare* (L.), maize and rice -*Oryza sativa* (L.), grain legumes such as groundnut –*Arachis hypogaea* (L.), or cowpea –*Vigna unguiculata* (L.), fruit trees (mango, citrus, pineapple -*Ananas comosus* (L.) Merr., and cashew orchards), and market gardening (tomato –*Solanum lycopersicum* L., cabbage -*Brassica oleracea* L., onion -*Allium cepa* L., okra -*Abelmoschus esculentus* (L.), traditional vegetables, etc.). Cash crops (cotton, cashew, mango, citrus, horticulture, etc.) are also investigated, as a major contribution to the income of rural populations, but also as parts of landscape mosaics and ecological processes. Insects are the most studied pests in DIVECOSYS, probably due to their economic importance among crop pests, but also partly due the predominance of entomologists within the research group. Life history traits of the wide range of pests encountered in these tropical areas, offer a complexity gradient in terms of management, depending on their mobility (local movement versus migration or diapause), their trophic specialization (monophagy versus polyphagy), the extent of their spatio-temporal distribution according to crop season. Farming systems in these ecoregions generally consist of a mosaic of cultivated and semi-natural habitats that vary over time. Remnant forests, hedges, field margins, dry residue from previous annual crops, grazing land, trees, shrubs and fallow are potential habitats from which insect pests (or natural enemies of pests) can colonize crops.

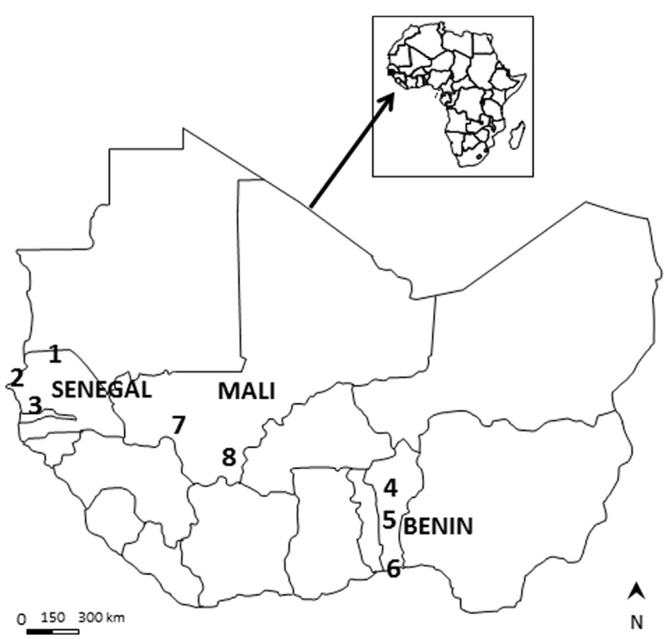


**Fig. 1.** Main ecoregions explored by the research group DIVECOSYS. An ecoregion is defined here as a “recurring pattern of ecosystems associated with characteristic combinations of soil and landform that characterise that region” (Omernik, 2004). (1) Niayes, (2) Senegal river delta, (3) groundnut basin in Senegal, (4) North, (5) Centre, (6) South and coast of Benin, (7) Mandingue plateau, and (8) Koutiala plateau in Mali.

## 4. Designing pest management strategies from a three-pillar approach

### 4.1. From the integration of conventional and alternative tactics

The DIVECOSYS approach considers farming and ecological dimensions for development of pest control strategies (Table 1). This includes chemical control (calendar or threshold-based spraying of conventional pesticides), host resistance (genotype), cultural control (crop management such as sowing date, crop rotation, intercropping, sanitation, trap crops, etc.), biological control (antagonists, parasitoids, predators, pathogens, etc.), physical and mechanical control (screens, nets, traps, temperature, tillage, etc.) and behavioural control (sexual disruption, pheromone trapping, etc.). These tactics alone are no longer relevant for an effective and sustainable control system. The challenge of DIVECOSYS is to consider alternatives to chemical control as potentially efficient by themselves or complementary, and to combine them appropriately (synergies) to significantly reduce the use of pesticides. The approach we propose here rely on the action (i) at different stages of the pest life cycle or at different stages of targeted crops (from initial inoculum to population outbreaks), and (ii) at different organizational levels of the landscape (field, mosaic composition, spatial configuration of mosaic units). This landscape approach offers new opportunities to activating ecological processes for the

**Table 1**
Farming systems and ecological contexts explored.

| Country | Ecoregion | Biome (residual cover %) | Landscape | Farming system | Biological model | Life traits |
|---|---|---|---|---|---|---|
| Senegal | 1-Niayes | Bush savannah (20–90) | June–Nov.: mosaic of crops<br>Dec.–June: patches of irrigated crops | Agropastoralism, market gardening orchards | Cabbage moth<br>Fruit flies<br>Tomato leafminer | Polyphagy<br>Oligophagy<br>Resistance<br>Invasion<br>Migration |
| | 2-Senegal river delta | Herbaceous savannah (20–80) | Patches of irrigated areas | Agropastoralism, rice, flood-recession sorghum, market gardening | Stem borers,<br>Sorghum bugs<br>Tomato leafminer | Diapause<br>Diversity<br>Invasion |
| | 3-Groundnut basin | Tree savannah (0–20) | Mosaic of crops under tree park cover | Agropastoralism, dry cereals, legumes | Groundnut weevil<br>Millet head miner | Host races<br>Egg-laying<br>Monophagy<br>Diapause<br>Behaviour |
| Benin | 4-North | Tree savannah (30–40) | Mosaic of crops under tree park, orchards. Savannahs and dry forests | Cotton, cereals and legumes<br>Mangoes and cashew nuts | Bollworms<br>Fruit flies<br>Scale insects<br>Bugs, ants<br>Fruit borers | Polyphagy<br>Mobility<br>Competition<br>Transmission of plant pathogens<br>Diversity |
| | 5-Centre | Tree savannah (20–40) | Patches of humid zones, orchards. Savannah and forests | Tubers, cereals, legumes, lowland rice and market gardening<br>Mangoes, pineapple and cashew nuts | Aphids, thrips<br>Cowpea bugs<br>Stem borers<br>Weeds<br>Fruit flies | Oligophagy<br>Polyphagy<br>Mobility<br>Competition<br>Transmission of plant pathogens<br>Diversity |
| | 6-South and coast | Tree savannah (10) and coastal forest (50) | Savannah and gallery forest. Patches of irrigated areas, orchards | Citrus and mangoes<br>Market gardening,<br>Maize, cassava | Fruit flies<br>Leaf rollers, ants<br>Seed weevil<br>Whiteflies<br>Nematodes | Polyphagy<br>Mobility<br>Diversity<br>Fecundity<br>Transmission of plant pathogens |
| Mali | 7-Mandingue plateau | Herbaceous savannah (0–20) | Mosaic of crops | Cereals, legumes Orchards<br>Market gardening | Stem borers<br>Fruit flies<br>Okra virus disease | Oligophagy Monophagy<br>Polyphagy |
| | 8-Koutiala plateau | Tree savannah (0–20) | Mosaic of crops under tree park | Cotton, cereals, legumes<br>Rice, market gardening<br>Orchards | Bollworms<br>Stem borers<br>Fruit flies<br>Weeds | Polyphagy<br>Diversity |

This table summarizes the contributions of twenty researchers.

control of mobile pests in space and time. In addition, landscape ecology provides a hierarchical and integrative ecological basis for dealing with issues of biodiversity and ecosystem functioning at multiple scales (Wu, 2006; Birch et al., 2011).

### 4.2. To the activation of ecological processes

Activating the ecological processes involved in pest regulation is a major challenge for designing agro-ecological pest management for farming systems. Ecological regulation of insect pest populations may be achieved i) at the lower trophic level (bottom-up) by host plants through their genotype (tolerance) and distribution in the agricultural landscape or ii) at the higher trophic level (top-down) by predators and parasitoids (Gurr et al., 2003). Agricultural practices can affect the abundance of a pest population by acting on the environment (Fig. 2), with a potential of suppression within the targeted area (e.g. field, orchard). Agricultural practices can also affect the abundance of a pest population at the landscape scale considered as a mosaic of habitats, by modifying the quantity and quality of resources for pests or by offering suitable habitats for different species of natural enemies for biological control (Carrière et al., 2012; Woltz et al., 2012; Monteiro et al., 2013). Composition and configuration of landscapes determine the potential of resources, but also their accessibility, acting either as a biological corridor or, on the contrary, acting as physical and chemical barriers. These landscape properties determine the spatio-temporal variability of pest populations and may limit or delay crop colonization (Mazzi and Dorn, 2012). They also determine abundance, diversity and effectiveness of natural enemy communities through the nature of resources (refuges, food source, alternative hosts, etc.)

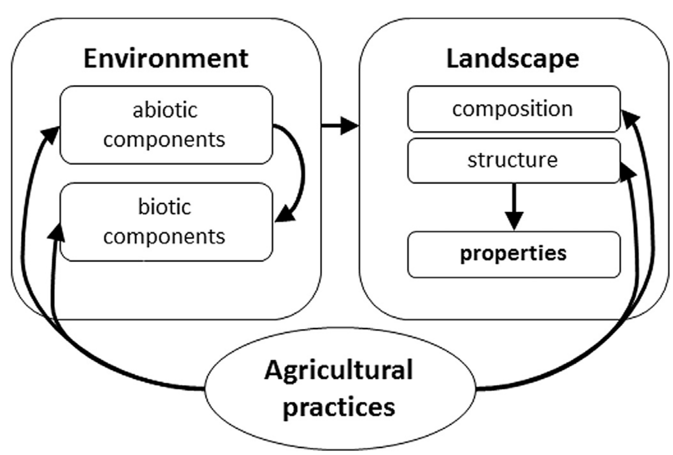


**Fig. 2.** Interactions between agricultural practices, landscape context and environment. To contribute to ecological intensification of agricultural systems in the explored systems, we propose to act (i) upon environment to reduce negative externalities associated to crop management, such as pesticide applications, and (ii) upon landscape to activate ecological processes that underlie pest regulation. The biotic compartment includes crop pests.

that cultivated habitats, natural and semi-natural areas can provide (Tscharntke et al., 2005; Rusch et al., 2013; Veres et al., 2013). Generally, ecological pest regulation increases with landscape complexity (Bianchi et al., 2006; Chaplin-Kramer et al., 2011).

The abundance of a pest population results from dynamic interactions with the biotic and abiotic environment, which occur over time and space steps that usually exceed the crop growth cycle (multiannual variability) or the cultivated plot alone (landscape). According to Burel (1996) and Burel and Baudry (1999), the landscape, in constant interaction with the ecological processes that arise from it, is the result of the environmental and social dynamics that have developed there (Fig. 3). Given that, we postulate that the landscape is the appropriate level of analysis for a holistic approach to action, i.e. individual and collective pest control programs, their efficiency in relation to the target biological system and their externalities, with a particular view to sustainable production management.

### 4.3. Taking into account local socio-ecological systems

Our ambition to contribute to the implementation of innovative strategies for sustainable pest management needs increased interactions with farmers to collectively identify technical action-levers. Recent experiences highlight the complexity to adoption of agro-ecological methods by smallholders in developing countries (Parsa et al., 2014). As reported by Giller et al. (2009), farmers in Sub-Saharan Africa often attribute a substantially higher value to immediate costs and benefits than those incurred or realized in the future due to the constraints of production and food security that they face. Yet, while farmers seek substantial, visible and immediate benefits when considering adoption of conservation agriculture (CA), many of the benefits of employing CA are only realized in the longer term (FAO, 2008). Institutional elements required for all successful strategies for agricultural intensification include a stable macroeconomic environment, provision of incentives through markets in areas where markets do function, development of market institutions where they do not, and public and private investment in an appropriate mix of physical, human, natural, and social capital (Ehui and Pender, 2005). An integrated approach to pest control is more knowledge intensive, requiring monitoring and decision systems, and currently incurs higher operational costs than does the sole use of insecticides (Cook et al., 2007). A similar diagnostic could be made regarding implementation of innovative strategies for integrated pest management (IPM): namely the market as a major driver. In East Africa, some smallholder farmers use push–pull strategies to protect their maize and sorghum crops (Khan and Pickett, 2004). Their success relies on ecological but also specific social conditions, including reduced access to costly pesticides, increased benefits with the introduction of multifunctional plants (grain legumes, livestock feed, etc.) in cropping systems, significant increase of crop yield, and well-thought information campaigns.

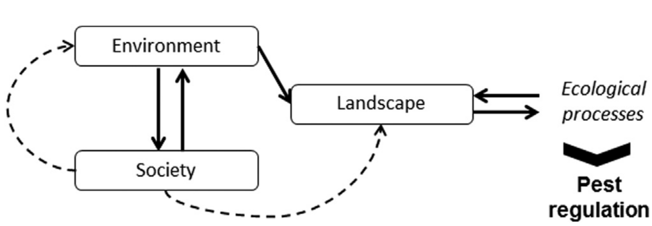


**Fig. 3.** Action and assessment framework based on concepts derived from landscape ecology (Burel and Baudry, 1999). Landscape configuration results from the dynamics of environment and society which has developed there (black arrows).

Considering the diversity of socio-ecological systems explored by our research network, we propose to distinguish three major territory scales depending upon provision of incentives through markets where markets function, and development of market institutions where they do not exist: (i) worldwide market opportunities (fruit production, cotton), (ii) local market opportunities, especially for urban areas (vegetable and fruit production), and (iii) regional market opportunities and on-farm consumption (cereals, grain legumes). For stakeholders involved in (i), the emergence of considerations relating to the environment, food safety (e.g. contamination by pesticides), and risks of crop losses due to diseases and insect pests, are incentives by the market or by the payment of environmental services associated with the reduction of pesticide use (Power, 2010). For (ii), the emergence of commercial niches and general requirements for product safety is one way to encourage the market to evolve towards food systems. For (iii), in the absence of incitation by the market, strategies should provide visible and immediate benefits to be adopted.

## 5. Basic research issues

We distinguish here between applied research specific to the particular socio-ecological contexts explored by the research group DIVECOSYS in West Africa, and more theoretical or basic research needs which are knowledge gaps. The activation of ecological processes involved in pest regulation requires a thorough knowledge of the life system of targeted pests (reproduction rate, local movements and migration, competition, gene flow and metapopulation structure, etc.), of food webs including plants (primary producers), pests (primary consumers) and communities of predators, parasitoids (secondary and tertiary consumers), and hyperparasitoids. It also assumes an understanding of the effect of agricultural practices on environment and on landscape multifunctional properties (connectivity, permeability, etc.) that govern short distance movements of targeted pests and access to resources, together with interacting communities of the considered ecosystem (Box 1).

Crossing representations of biological systems linked to agronomy and ecology gives rise to more theoretical and basic research issues, in order to produce knowledge, methods and tools (especially models) for individual and collective action. A few key research issues are listed below:

- What is the spatial structure and area of the targeted pest populations? On what scale do sub-populations interact genetically and demographically?
- What are the effects of crop management and landscape context on the spatio-temporal abundance of targeted pests and the effectiveness of biological control?
- What experimental designs are to be implemented to study and model ecological processes, in relation to landscape attributes and life system of targeted pests?
- What are the relevant spatial organizations for individual and collective action, with a view to sustainable production management in a given area?
- In the context of global change, what are the scenarios of landscape evolution for the socio-ecological systems considered? What are their foreseeable impacts on ecological processes, and how can habitats (cultivated or non-cultivated) be managed to preserve functional biodiversity and pest regulation services? As a result, what models might be developed to explore the abovementioned scenarios, notably with a view to an *ex ante* assessment of emerging production systems as innovations?

**Box 1**
Landscape and habitat connectivity.

Connectivity is not a general property of a landscape; it has to be defined in reference to the movements of the species to be managed (Burel and Baudry, 2005). It is therefore necessary to take into account the movement methods and ecological requirements of the species in question. A connected landscape for one species may have numerous barriers for another species. The landscape is dynamic, varies from season to season; the time dimension has to be taken into account. For example, fallow and rangelands offer resources and movement possibilities for anthophilous species; their mowing or grazing date affect their use, hence their role in connectivity.

Connectivity does not have an absolute ecological quality value; it may be conducive to the movement of undesirable, parasitic, invasive or predatory species. To assess or restore connectivity, it is therefore necessary to understand: (i) how a species moves within a landscape, (ii) how the manager can facilitate or limit those movements. Of course, it is not a matter of reproducing this process for all species, firstly because species can be grouped by type of behaviour in landscapes, secondly because management is often geared towards a few target species (and the species on which they depend).

- How can landscapes be managed collectively? What governance is required to act upon complex socio-technical systems (e.g. horticultural production based on a plurality of stakeholders and markets, local versus export)?

## 6. Applied research issues

Research activities are undertaken with local stakeholders (farmer groups in Senegal and Benin, regional or local centres for agricultural development in Benin, cotton companies in Mali, etc.) who are actively involved in formulating research issues and bringing out innovations. In the following, some examples of research and extension projects currently developed in West Africa are discussed in the light of ecological engineering for pest management.

### 6.1. Millet head miner

In Senegal, the head miner, *Heliocheilus albipunctella* De Joannis (Lepidoptera, Noctuidae), is the major insect pest of millet. Strengthening ecological regulation of this pest opens an avenue to explore to improve yield and quality of grain cereals, in collaboration with small-scale farmers. At the level of the agricultural landscape, agro-forestry systems offer greater arthropod diversity and more ecological niches in time and space than a mosaic of annual crops. They can act as a source or relay for insect pest populations. They can also increase the effectiveness of biological control by providing populations of natural enemies with additional resources, especially during the dry season. A research project (WAAPP, West Africa Agricultural Productivity Program, waapp.coraf.org/) assesses the importance of biodiversity as a factor in ecological control of insect pests and as a factor of ecosystem resilience in the face of environmental disturbances. Remote sensing, satellite image processing, and geographic information system (GIS) are used as modern tools for understanding the spatial distribution of insects and unravelling ecological processes involved in pest regulation.

### 6.2. Cotton bollworms

In Mali, seed cotton yield can be reduced by 30–40% due to insect pests, especially bollworms (Lepidoptera, Noctuidae) such as *H. armigera*, *Diparopsis watersi* Rothschild and *Earias* spp. Area-wide implementation of threshold-based spraying programs (as opposed to conventional calendar-based spraying) resulted to the reduction of insecticide use by 27% from 1997 to 2008 in Mali (Renou et al., 2012; Silvie et al., 2013). To go further, research is needed to define more simple and efficient rules for decision, from local to regional scales. Among alternatives to chemical sprays, topping cotton plants after the onset of flowering could be a way to reduce bollworm infestations (Renou et al., 2011). Field and laboratory studies (plant volatile compounds) are currently underway to better understand mechanisms involved in the reduction of bollworm infestations (PAFICOT, “Projet d'appui à la filière Coton-Textile”).

In Benin, a two-year study highlights the importance of considering both agricultural practices and landscape context to identify ways to improve the management of bollworm populations (FSP 2006–43). Delayed sowing and frequent weeding reduced the abundance of *H. armigera* in cotton fields. Avoiding high concentration of cotton crops in the surrounding landscape (500 m) or tomato crops, as previous landcover, would also reduce *H. armigera* abundance (Tsafack et al., 2013). Modifying cultural practices or managing landscape at a collective scale to reduce bollworm infestation is a real challenge.

### 6.3. Cabbage diamondback moth

Strengthening ecosystem services such as regulation of insect pests by natural enemies is a potential way to reduce the dependence of small farmers on pesticides, to limit field-evolved resistance to insecticides, and to design new models of ecologically-intensive agriculture. The BIOBIO research project (Biodiversity and pest management in agricultural landscapes, AIRD) aims at evaluating the effect of crop management and landscape composition and configuration on the abundance of the diamond back moth, *P. xylostella*, and the efficiency of natural regulation of its populations by predators and parasitoids (Sow et al., 2013a, 2013b). Sampling is carried out in a network of farmers' cabbage fields in the Niayes, the main vegetable-producing area in Senegal, across two years. Results should clarify the role of insecticide use and landscape context on the abundance of larval populations on cabbage and on the impact of biological control. From an applied perspective, results could lead to the implementation of novel recommendations to stakeholders for integrated management of the cabbage diamondback moth both at the field and landscape scales. Research activities are implemented with local partners (farmer' association in Senegal) to facilitate exchange of ideas with producers and dissemination of information.

### 6.4. Mango fruit flies

Fruit flies (Diptera, Tephritidae) have become an increasingly prevalent pest of fruit productions in Benin, but also in sub-Saharan countries, affecting not only mango production but also other important fruit value chains like citrus (Vayssières et al., 2010). A new invasive species, *Bactrocera invadens*, which probably originated from Sri Lanka, has colonized East, Central and West Africa. This polyphagous species can infest more than 40 fruit species in Benin–Cameroon (Goergen et al., 2011) and more than 30 fruit species in Senegal (Ndiaye et al., 2012). An IPM-package has been proposed to growers in the framework of the West African Fruit Fly Initiative (WAFFI). Biological control with weaver ants, *Oecophylla longinoda* (Latreille), and parasitoids (Hymenoptera, Braconidae) is a way to control fruit flies on mango orchards (Van Mele et al., 2007) and also citrus (J.-F. Vayssières, personal communication). Research efforts were conducted towards a better knowledge of weaver ants, especially their predatory behaviour but also their repulsive effect on pests (Adandonon et al., 2009; Van Mele et al., 2009). Other IPM tools for monitoring of mango fruit flies and citrus fruit flies in pilot-orchards, sanitation activities in mango-citrus orchards, threshold-based bio-insecticide bait sprays and conservation of parasitoids (Vayssières et al., 2009b, 2011, 2012; Diatta et al., 2013), are required (Fig. 4). For IPM to be more effective, an area-wide strategy should be deployed. DIVECOSYS should bring knowledge, know-how and tools (GIS) to help researchers implementing a spatial perspective to their research.

### 6.5. Stored product pests

With the global increase in cereal, grain legume and tuber production expected to cover the food requirements of an ever growing population, post-harvest losses are an important field of study. Pests in stored foodstuffs, such as the beetles *Prostephanus truncates* (Horn), *Sitophilus zeamais* Motschulsky and *S. oryzae* (L.), weevils, and the moth *Sitotroga cereallela* (Olivier), cause certain quantitative losses. In addition, they can be a source of fungal contamination in grain stocks, right from the field, involving fungi such as *Aspergillus flavus* or *Fusarium verticillioides*, responsible for the production of mycotoxins of the aflatoxin and fumosinin groups respectively, which are dangerous for human health. In addition to direct infestations of insects in the field, there are tuber exchanges between producers, which may contaminate storage barns. No research has been yet conducted on this issue within the DIVECOSYS group, but the importance of post-harvest losses underlines the need to integrate this topic in the scientific priorities.

## 7. Conclusions

The main objective of the research group DIVECOSYS is the assessment and the understanding of processes that shape

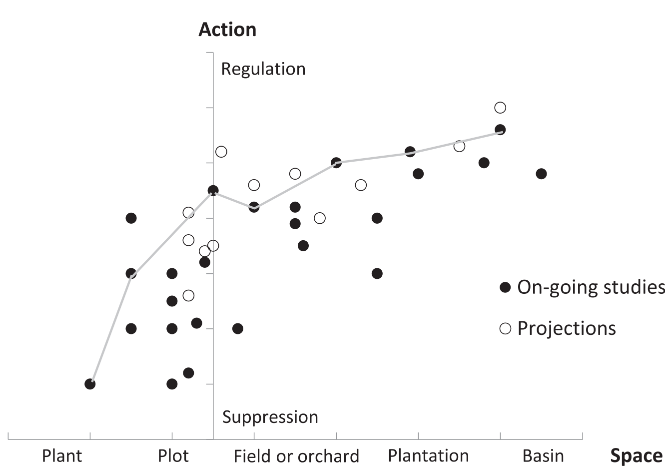


**Fig. 4.** From local suppression to activation of regulation processes for ecological pest management. Diversity of approaches and scales of action within DIVECOSYS. Along the *Y*-axis, action is positioned according to a qualitative gradient of ecosystem service use. To illustrate this, the grey line connects different studies carried out on mango fruit flies in Senegal and Benin.

ecological regulation of crop pests in different socio-agro-ecosystems. One particular challenge is to measure the importance of biodiversity as a provider of ecosystem services such as pest control, and as a factor of ecosystem resilience in the face of environmental change. The research group also contributes to the dissemination of advanced techniques and methods that enable research capacity building among research teams, including geographic information systems, spatial analysis, landscape ecology, population genetics, ecological modelling, and scientific writing skills. By aggregating a high diversity of researchers, disciplines, and contexts, DIVECOSYS is a suitable platform to synergizing proof of concept ideas into advances for agricultural research in Africa.

From an applied perspective, research conducted within DIVECOSYS aims to develop ecologically-based pest management strategies for small-scale farming systems in West Africa. Future research projects will include insect–plant interactions, insect and weed community ecology and biological control, pesticide impacts on biodiversity, landscape ecology and area-wide integrated pest management. As managers of their territories, stakeholders with their own knowledge and innovation capacity are more and more strongly involved for designing and assessing novel and sustainable agricultural systems.

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