Chapter 1

Functional Agrobiodiversity: The Key to Sustainability?

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1. INTRODUCTION

It is a common assumption that biodiversity has an important role to play in efforts to achieve agricultural sustainability (Altieri, 1995). However, the scientific literature is often unclear as to what type of "biodiversity" is necessary for agriculture. The problem results in part from lack of agreement in defining agrobiodiversity and related priorities.

Some scientists tend to identify biodiversity (species and habitats) conservation as the main priority for agriculture (e.g., Jeanneret et al., 2003). This is a dominant view in Europe, where it has resulted in considerable public financial support to farmers engaging in "agri-environmental schemes" (AESs) aimed at biodiversity conservation (European Commission, 2005). However, AESs have often failed, due to unclear definition of goals and management tools expected to meet them (Kleijn and Sutherland, 2003).

Other scientists tend to prioritize (agro)ecological functions aimed to optimize and/or stabilize agricultural production through increased agroecosystem biodiversity, e.g., crop rotation, intercropping, and cultural practices diversification (e.g., Malézieux et al., 2009). Priority is then given to species and habitats linked to production and related functions, e.g., soil fertility, biological pest control, and pollination (Altieri and Nicholls, 2004).

Indeed the concept of "agricultural sustainability" is also fuzzy, because priorities (and indicators) of environmental, economic, and social sustainability are continuously evolving (Pretty, 2008). In order to fully evaluate the potential of biodiversity to meet global agricultural challenges, we first need to define what is agricultural sustainability nowadays and then identify the elements of agricultural biodiversity that are more likely to help humans tackle those challenges. In the context of this chapter, the term "function" is considered to be a synonym of "service" and refers to processes that—either directly or indirectly—contribute to the provision of agricultural goods. It is worthwhile

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noticing that ecologists instead tend to distinguish between "functions" (self-regulating ecosystem processes) and "services" (processes providing material or immaterial outputs that are valued by humans). A thorough discussion on usage of these terms can be found in Jax (2005) and Violle et al. (2007).

2. AGRICULTURAL SUSTAINABILITY AT THE ONSET OF THE THIRD MILLENNIUM

Nowadays we can identify three major challenges to agricultural sustainability: (a) climate change, (b) energy availability, and (c) global economic insecurity.

There seems to be a general consensus on the likelihood of human (co) cause of global climate change (IPCC, 2007). The most common manifestation of climate change is the intensification of extreme climate events such as floods, droughts, and heat/cold waves that are jeopardizing agriculture in many areas around the world. Agricultural science and practice are asked to provide solutions to both mitigate the effects of climate change and increase adaptation of cropping/farming systems (Fleming and Vanclay, 2010).

Fossil fuels are becoming short in supply and increasingly inaccessible (Giampietro et al., 2012), with resulting increased prices. Biofuels have long been suggested as a possible solution to fossil fuel shortage, but their cost/benefit analyses and energy budgets do not seem to play for long-term sustainability, at least for some annual crops, e.g., corn (de Vries et al., 2010). Consequently, it seems wiser to reduce external energy use and increase energy efficiency in agriculture. This can be achieved through substitution of external inputs (seeds, fertilizers, and pesticides) with renewable and local resources (Altieri et al., 1983).

Like extreme climate events, price fluctuation of agricultural food commodities (e.g., wheat, corn, or rice) has been intensifying in the latest decade (Akram, 2009). Coupled with the current long-lasting global economic crisis, this is causing dire problems for many farmers and farmdwellers worldwide. Farmers producing for the global market are particularly vulnerable, because they are facing increasingly unpredictable market trends whilst cost of agricultural inputs is rising following the rise in oil price (Mitchell, 2008). Concurrently, recent phenomena like urban sprawl (Couch et al., 2007) and land grabbing (De Schutter, 2011) are eating up agricultural land. In the light of a continuously increasing world population, approaches and solutions to overcome these crises are urgently needed.

The emerging question is then: is increased biodiversity in agricultural practices and systems a possible solution to global challenges that jeopardize agricultural sustainability?

3. AGROBIODIVERSITY: A CONCEPTUAL FRAMEWORK

The United Nations Convention on Biological Diversity (CBD) and The Organisation for Economic Co-operation and Development (OECD) (Parris, 2001)

TABLE 1.1 Elements of Planned and Associated Agrobiodiversity Included (+) and Missing (–) in the OECD Definition (Parris, 2001), with Relevant Examples

Type of Agrobiodiversity	Level of Agrobiodiversity		
	Genetic	**Species**	**Ecosystem**
Planned	Crop cultivars and livestock breeds (+)	Crops included in the rotation, beneficial arthropods released for biological pest control (–)	Crop management practices, planted hedgerows, ratio of UAA[a] in the territory (+)
Associated	Genetic variation within wild plants and insects (–)	Wild plants and animals, endemic (non-released) beneficial arthropods (+)	Natural (non-planted) hedgerows and other non-cropped areas, e.g., natural woodland (+)

[a] *UAA, utilized agricultural area.*

define three levels of agricultural biodiversity (hereafter "agrobiodiversity"): genetic, species, and ecosystem. The elements of each level that are included in the OECD definition, as well as the missing ones, are summarized in Table 1.1.

3.1 Genetic Agrobiodiversity

Genetic agrobiodiversity refers to any variation in the nucleotides, genes, chromosomes, or whole genomes of organisms, i.e., it deals with within-species diversity. In the OECD definition, genetic agrobiodiversity includes variation within species of crops, livestock, and their wild relatives. Conservation and use of locally adapted cultivars of major crops, of neglected and underutilized crop species, and of livestock breeds has a value in itself because it contributes to save overall biodiversity. However, its main value is that a wider genetic pool in crops and livestock ensures adaptation to a changing environment and provides useful traits to be used in genetic breeding programs (Hajjar et al., 2008).

Genetic agrobiodiversity can be conserved *ex situ* or *in situ*. For plants, *ex situ* conservation is commonly done in seed banks under sterile and strictly controlled environmental conditions and protocols (Li and Pritchard, 2009). Considerable financial investments have recently been done in facilities hosting wide germplasm collections, e.g., the Kew Gardens' Millennium Seed Bank Partnership, UK (http://www.kew.org/science-conservation/save-seed-prosper/millennium-seed-bank/index.htm) or the Svalbard Global Seed Vault, Norway (http://www.regjeringen.no/en/dep/lmd/campain/svalbard-global-seed-vault.html?id=462220).

Despite the importance of global seed collections, it is being recognized that *in situ* methods offer a higher potential to ensure conservation and use of genotypes, because of direct involvement of farmers in the selection and maintenance processes (Altieri and Merrick, 1987). Furthermore, *in situ* methods make conservation of genetic agrobiodiversity also accessible to developing countries, due to reduced facilities costs (Jarvis et al., 2000).

3.2 Species Agrobiodiversity

For the OECD, species agrobiodiversity includes the variation between *wild* species that are directly or indirectly relevant to agriculture (Table 2.1). These are grouped in three categories: (a) species supporting agricultural production; (b) wild species depending directly or indirectly on agriculture and its effects, and (c) non-native species threatening agroecosystems.

Category (a) includes species guilds sustaining agricultural production through their effects on agroecosystem functions like soil fertility, pollination, and biological pest control. Examples are soil microorganisms involved in the organic matter cycle, arbuscular-mycorrhyzal fungi, earthworms, natural enemies of crop pests, and pollinators (Parris, 2001). This category only includes species exerting a positive function in the agroecosystem.

Category (b) includes wild species like bats, birds, or rodents that are directly dependent on agroecosystems for their survival and reproduction. Two thirds of European endangered or vulnerable bird species live exclusively in agroecosystems (Tucker and Heath, 1994), therefore adequate farming practices are essential for their conservation (European Environment Agency, 2004). Category (b) also includes marine or fluvial species that indirectly depend on agricultural activities, e.g., because they suffer from agricultural pollution due to fertilizers or pesticides runoff. Regarding their effects on agroecosystem functions, category (b) species can be considered as neutral.

Category (c) includes exotic species that can directly threaten agricultural production, e.g., newly introduced pests, diseases, and weeds. This is a worldwide problem, exacerbated by the development of global trade (Bright, 1999). Recent introductions of highly noxious organisms are, for example: *Tuta absoluta* Meyrick, a Lepidoptera pest of Mediterranean tomato crops native to South America (Desneux et al., 2010); wheat stem rust (*Puccinia graminis* f. sp. *tritici* Eriks. E. Henn.) race Ug99, spreading from Uganda to East Africa, the Middle East, and Asia (Singh et al., 2008); and *Commelina benghalensis* L., a creeping herb native to Africa and Asia that is invading vast pasture and cropland areas in southern USA (Webster et al., 2005). Clearly, all species in category (c) exert a negative function in the agroecosystem.

3.3 Ecosystem Agrobiodiversity

The OECD definition of ecosystem diversity embraces three components: (a) the diversity in farming systems and cultural practices and their change in time and space, (b) the ratio between land utilized for agriculture and for other uses (e.g., natural or urban areas), and (c) the interactions between agroecosystems and nearby ecosystems (Parris, 2001).

It must be noticed that this definition extends well beyond biodiversity *per se*, including elements of agroecosystem structure and management. This is very much in line with a functional approach to agrobiodiversity, as envisaged in agroecology (Altieri and Nicholls, 2004).

3.4 Limitations of the OECD Definition of Agrobiodiversity

Many authors distinguish between *planned* agrobiodiversity (the biodiversity elements—at gene, species, or ecosystem level—deliberately introduced in the agroecosystem) and *associated* agrobiodiversity (the biodiversity elements—at any level—inhabiting the agroecosystem without being introduced) (Jackson et al., 2007). If we examine the OECD agrobiodiversity definition in the light of planned and associated biodiversity at any of the three levels (Table 2.1), we notice that all combinations "planned/associated biodiversity × level" are taken into account except two: associated agrobiodiversity at gene level and planned agrobiodiversity at species level.

Associated agrobiodiversity at gene level includes, e.g., the genetic variation within populations of weeds, crop pests, and diseases and of natural (endemic) enemies of crop pests, which is important to determine the level and extent of their interactions (Crutsinger et al., 2008). Planned agrobiodiversity at the species level includes, e.g., the diversity of crops grown in rotation and cover crops introduced for various purposes (soil fertility building, weed suppression, attraction of beneficial arthropods and/or repulsion of crop pests, etc.). These are very important *functional* tools to increase crop performance in the framework of external input reduction, and hence they are likely to contribute to agroecosystem sustainability (Tilman et al., 2002). The reasons why these two categories have not been included in the OECD definition is unknown; the latter, especially, is an important component of the arsenal of biodiversity tools available to farmers and land managers.

Additionally, there is no reason to focus only on the diversity of non-native (exotic) pests, diseases, and weeds—category (c) of species agrobiodiversity—since native biotic stressors can be more detrimental than newly introduced ones (Gressel, 2006).

Lastly, the OECD definition does not mention elements that can exert multiple functions, positive or negative depending on the context. For example, *Rubus fruticosus* L. (blackberry) can be a crop, an invasive weed, a windbreak, a hedgerow supporting both pests and beneficial arthropods, and a pleasant or unpleasant landscape element depending on varying human perceptions in different environments (Moonen and Bàrberi, 2008). It is then clear that functions associated with agrobiodiversity components are strictly context-dependent, and thus definition of the context (agroecosystem) and its priorities is a fundamental step in agrobiodiversity evaluation.

4. FROM AGROBIODIVERSITY TO FUNCTIONAL AGROBIODIVERSITY

The OECD definition of agrobiodiversity already refers to biodiversity components (e.g., species supporting agricultural production) that are particularly relevant to the functionality of agroecosystems. However, there is neither a clear definition of functional agrobiodiversity nor an indication of which functions should have priority in agroecosystems. This is an issue to be clarified if agrobiodiversity is to become a key component of sustainable cropping/farming systems.

4.1 Functional Biodiversity: A Plethora of Definitions

From the analysis of the scientific literature it emerges that there is no commonly accepted definition of functional biodiversity. As already said, this is due partly to lack of clear objectives—see Moonen and Bàrberi (2008) for in-depth discussion—and partly to the different views and priorities set forth by ecologists, agroecologists, and agronomists. A sample of the different definitions is reported hereafter.

A classical ecological definition is, e.g., that of Pearce and Moran (1994), who define “functional diversity” simply as the relative abundance of organisms expressing different functions. There is reference neither to the role that these organisms exert in an ecosystem nor to the positive or negative functions they are likely to influence. Although formally correct, this definition is not useful for agroecosystems, whose objectives and priorities (production, to start with) are usually clear.

The term “multi-function agricultural biodiversity” has been used, after Gurr et al. (2003), to indicate the positive “domino effect” observed between plant diversity and biological pest control at multiple spatial scales. Plant diversity has been seen to improve biological pest control at field scale, which in turn improves the pest control function at landscape scale. The magnitude of this effect depended on agroecosystem diversity at either scales. The value of this definition is that it recognizes the importance of biodiversity-driven interactions across different trophic levels and spatial scales, but it only focuses on one function and on positive plant–insect interactions. Indeed, Conservation Biological Control—i.e., the maintenance or (re)introduction of (semi)natural habitats in agroecosystems to support native populations of biological control agents (Barbosa, 1998)—is a synonym of functional biodiversity for many entomologists (see, e.g., the IOBC Working Group “Landscape management for functional biodiversity”: http://www.iobc-wprs.org/expert_groups/19_wg_landscape_management.html).

Peeters et al. (cited in Clergue et al., 2005) distinguished three types of agrobiodiversity: (1) agrobiodiversity *sensu stricto*, i.e., the diversity of organisms *directly* useful for production (crops, varieties, and livestock species and breeds); (2) para-agrobiodiversity (also called “functional biodiversity”), i.e., the diversity of organisms *indirectly* useful for production (e.g., soil microorganisms, beneficial arthropods, unsown grassland plants), corresponding to category (a) of species agrobiodiversity in the OECD definition; (3) extra-agricultural biodiversity, i.e., all biodiversity present in an agroecosystem which is unrelated to production (e.g., wild species of plants and animals that are not providing a function). Peeters et al.’s types are interesting because they clearly relate agrobiodiversity to the main agroecosystem function (production), but they do not clearly address the three OECD/CBD levels and do not incorporate species exerting a negative function.

Instead, a comprehensive and objective evaluation of the effects of biodiversity should include the positive as well as the neutral and negative functions exerted by agroecosystem components at any of the three levels (gene, species, and ecosystem). A fine-tuned definition of functional (agro) biodiversity could then be “that part of the total biodiversity composed of clusters of elements (at the gene, species, or habitat level) providing the same (agro)ecosystem service, that is driven by within-cluster diversity” (Moonen and Bàrberi, 2008). Its aims and consequences for agrobiodiversity evaluation are illustrated below.

4.2 Functional Agrobiodiversity: A Methodological Approach

If the goal of functional biodiversity study is to understand which components can help to improve crop production and thereby agricultural sustainability, the analysis should encompass four subsequent steps, summarized in Table 1.2.

First, the operational context and the related objectives must be clearly defined: this includes the description of the agroecosystem and its goals, which may differ between, e.g., conventional and organic management of the same crop.

Second, one should list the agroecosystem functions that are deemed a priority in a given context. For example, in olive (*Olea europaea* L.) groves, one of the major problems is olive fly (*Bactrocera oleae* Rossi) control. As such, biological pest control should be a priority function for the study and application of functional agrobiodiversity in olive.

Third, the “agroecosystem functional group” (the “cluster” in Moonen and Bàrberi’s definition) comprising all elements (at gene, species, and ecosystem level) that are relevant for the target function in the given context should be defined. This group will be the subject of the functional agrobiodiversity

TABLE 1.2 Steps to be Included in a Functional Agrobiodiversity Analysis, with Relevant Examples

Step No.	Description	Example
1	Definition of the context (target agroecosystem) and related objectives	Olive grove with organic management
2	Definition of priority agroecosystem functions	Control of the olive fly
3	Definition of the agroecosystem functional group	Species of parasitoids and hyper-parasitoids of the olive fly, wild plant species and structures (e.g., hedgerows, woodland) attracting natural enemies of the olive fly, olive cultural practices known to affect olive fly (e.g., cultivar type, pruning, types and amount of natural pesticides sprayed)
4	Definition of space and time boundaries for the study of the agroecosystem functional group and of pertinent indicators	Field and landscape scale, whole year, number of fruits with fly punctures (sample), number of parasitized fruits and natural enemies species (sample), presence and abundance (e.g., percent area cover) of wild plants and structures supporting natural enemies of the olive fly, details (e.g., type and rates of active ingredients used) of cultural practices known to affect the olive fly (see step 3)

Modified from Moonen and Bàrberi (2008).

analysis. In the olive fly case, the agroecosystem functional group would, e.g., include the guilds of parasitoids and hyper-parasitoids potentially able to keep the pest under control, plant species (other than olive) supporting the complex of beneficial arthropods, and (semi)natural areas (e.g., woodland and hedgerows) ecologically important for them. It must be stressed that, in agreement with the OECD definition of ecosystem agrobiodiversity, agricultural management is very much part of an agroecosystem functional group. If one is able to identify the management elements (e.g., mowing, pruning, fertilizer and pesticides application, as well as their details—timing, rates, etc.) that are likely to enhance the function by favoring the components of the agroecosystem functional group, these would form a "management functional group" (Moonen and Bàrberi, 2008).

Fourth, the agroecosystem functional group should be studied by selecting the most pertinent indicators, level(s) (*sensu* CBD/OECD) and spatio-temporal scale(s). The methodological details are determined by the type and extent of the ecological interactions occurring among the agroecosystem functional groups components (Bàrberi et al., 2010). Here, it must be pointed out that the ultimate goal of this study is to determine whether or not *diversity* within the functional group is important for the fulfillment of the function. For example, would the presence of three species of aphid predators instead of just one increase the biological pest control function (i.e., aphid predation)? If the answer is yes, the conclusion is that diversity in the agroecosystem functional group matters, thus functional biodiversity helps. If the answer is no, the conclusion is that the *identity* ("biofunctionality") of the functional group components (in this case the only predator species present) is more important than the diversity within the functional group, thus functional biodiversity does not help. However, it should not be neglected that, according to the "insurance hypothesis" (Yachi and Loreau, 1999), a higher level of biodiversity insures (agro)ecosystems against declines in their functioning because the presence of many species guarantee that some will maintain the function if others disappear. This is particularly relevant in the presence of the major challenges to agricultural sustainability outlined in this chapter.

5. FUNCTIONAL AGROBIODIVERSITY IN PRACTICE

In a cropping system, once the priority functions have been selected, one important question to be answered is: what are the traits that crops should possess to express these functions at best? Similarly to the use of the term "function", use of the term "functional trait" is somewhat different between ecologists (see, e.g., Garnier and Navas, 2012) and agroecologists. For consistency, the term "functional trait" is used here to indicate any characteristics of a crop that might favor the expression of an agronomically important function: e.g., crop production, crop nutrition, or weed suppression. Similar to what was said before, these functions can be accomplished either by a single, very effective functional trait or by a suite of functional traits, thus highlighting the importance of functional trait diversity. The second option is more promising because it is in accordance with the aforementioned insurance hypothesis.

Some case studies illustrating how the concept of functional agrobiodiversity can be turned into practice through selection of suitable functional traits are reported hereafter.

5.1 Genetic Agrobiodiversity

Modern cultivars and hybrids are characterized by a narrow genetic base, carrying a combination of traits which are primarily aimed at increasing yield. However, their yield potential can only be expressed in an optimized environment created by continuous assistance from the farmer, with large supply of external inputs (water, fertilizers, and pesticides). As such, these cultivars do not seem well equipped to withstand the challenge implied by the necessity to reduce energy (input) consumption and to adapt to harsher environments consequent to global climate change (Mendelsohn and Dinar, 1999).

Crop genetic diversity can be increased by sowing cultivar mixtures instead of a single, high-yielding cultivar. The cultivars in the mixture should differ in their functional traits: e.g., resistance or tolerance to diseases or the ability to exploit unlimited (light) and limited (soil nutrients and water) resources. The assumption is that a more diverse crop stand should better cope with environmental variation consequent to climate and/or management conditions. Cultivar mixtures have been shown, e.g., to reduce incidence of rusts and powdery mildews in small grain crops (Mundt, 2002) and of late blight in potato (Garrett et al., 2001).

One step beyond cultivar mixtures is the use of Composite Cross Populations (CCPs) in small grain cereals like wheat (*Triticum* spp.) or barley (*Hordeum vulgare* L.). CCPs originate from a high number of initial crosses between several cultivars, grown in the target environment. Every year part of the grain is saved and sown in the next season, giving rise to a composite population whose traits co-evolve with local climate and management conditions, upon the concept of "evolutionary breeding" (Wolfe et al., 2008). Seven or eight years are usually enough to segregate the functional traits that are best "collectively" adapted to the target environment. Due to their very high genetic diversity, composite populations will be able to withstand high fluctuations in climate or suboptimal management conditions, which make them a well suited genotype for adaptation to climate change or to low input and organic systems. CCPs are often the outcome of participatory plant breeding schemes, an example of *in situ* conservation of genetic diversity seeking the highest involvement of local farmers and other stakeholders (Pimbert, 2011).

5.2 Species Agrobiodiversity

Optimum design of crop rotation is the most common way to exploit species agrobiodiversity to increase agroecosystem sustainability. The benefits of crop rotation are manifold and well known (Karlen et al., 1994). In the context of low-input and organic agriculture, functional traits of component crops in the rotation as well as their functional interactions are particularly important because they are expected to surrogate (part of) external inputs while maintaining adequate levels of crop production and related agroecosystem functions. In temperate organic arable cropping systems, increasing species agrobiodiversity through the introduction of winter cover crops (green manures) is an important tool to increase agroecosystem functioning and hence sustainability. In a long-term experiment, Mazzoncini et al. (2010) compared organic and conventional management of a five-year arable crop rotation where the organic cropping system included a red clover (*Trifolium pratense* L.) green manure crop not included in the conventional system. Five years after the onset of the experiment the organic system already showed higher soil carbon sequestration

(+22%) and potentially mineralizable C (+9%) than the conventional system. In contrast, mites/collembolans ratio was nearly double in the conventional system, likely a consequence of more frequent soil tillage disturbance (mechanical weed control) in the organic system. These findings suggest that although higher species agrobiodiversity in crop rotations has the potential to improve the soil fertility function in a relatively short period of time, some of the accompanying management practices can partially overcome the gained benefits. A current major challenge in organic farming research is to try to optimize cropping systems functionality and sustainability by combining cover crops with conservation tillage techniques (including no-till) without jeopardizing crop yield (Peigné et al., 2007).

Intercropping and living mulches (i.e., systems where a non-cash crop is grown alongside a cash crop) are alternative management tools to improve agroecosystem sustainability through increased species agrobiodiversity. An analysis of the various positive effects ascribed to intercropping can be found, e.g., in Coolman and Hoyt (1993). In both intercropping and living mulch systems the key point is to combine crops that are complementary in the use of environmental resources (light, soil nutrients, and water), to optimize it and to minimize competitive effects between companion crops. As such, they should clearly differ in, e.g., height, growth habit, and root architecture, i.e., in those functional traits ultimately resulting in, e.g., increased (overall) yield, soil fertility, crop nutrition, and weed suppression (Vandermeer, 1989). Intercropping and living mulches are clear examples of cultural practices that should be based on the concept of functional agrobiodiversity to be successful.

One example of intercropping which is common in part of the Horn of Africa is 'hanfets', i.e., a mixture of wheat and barley. Woldeamlak et al. (2008) tested 16 hanfets constituted by all combinations of four barley landraces and four wheat (two landraces and two varieties) at three locations in Eritrea, where farmers (both men and women) were involved in plant selection. Hanfets grain yield was on average similar to that of pure barley but significantly higher than that of wheat. The Land Equivalent Ratio (LER) did not differ between hanfets types but was on average over 50% greater than in the pure crops, showing a clear advantage of the diversified system. Stability analysis showed that the most stable entries always included some hanfets, although not all of them were more stable than pure crops. Both men and women selected for traits like high grain yield, earliness, short heads, low kernel weight, and short-statured plants, and seemed to prefer hanfets in which both components were early heading and maturing. It has been hypothesized that differences in root architecture among component genotypes might make hanfets more efficient in exploiting soil water resources than pure crops, a functional trait which is of utmost importance in a geographical area with chronic water shortage and famine. It is worthwhile noticing that hanfets is a cropping system which is based on the concurrent application of genetic and species agrobiodiversity.

5.3 Ecosystem Agrobiodiversity

By their own nature, the management tools ascribable to ecosystem agrobiodiversity often have an effect which goes beyond the farm gate (Bàrberi et al., 2010; Gabriel et al., 2010), and therefore should be tackled by consortia of neighboring farmers rather than by individual farmers, except where the farm size is wide enough to encircle any possible ecological interactions occurring among the elements in the agroecosystem functional group.

Besides Conservation Biological Control, another way to exploit ecosystem agrobiodiversity to improve the pest control function is via the use of "push-pull" strategies. These involve the behavioral manipulation of insect pests and their natural enemies via the integration of stimuli that make crops unattractive or unsuitable to the pests ("push") while luring them toward an attractive source ("pull") from where they are subsequently removed (Cook et al., 2007). Naturally generated plant stimuli can be exploited using vegetation diversification. This includes tools pertaining to both species agrobiodiversity (e.g., intercropping and trap cropping; see, e.g., Finch and Collier, 2000) and ecosystem agrobiodiversity (e.g., flower strips, grass strips, or other measures targeting the field margin rather than the field itself; see, e.g., Olson and Wäckers, 2007). The "push" tools act through visual distraction and production of semiochemicals like non-host volatiles, anti-aggregation or alarm pheromones, oviposition deterrents, and antifeedants. Instead, the "pull" tools provide visual stimulants, host volatiles, aggregation or sex pheromones, and oviposition or gustatory stimulants (Cook et al., 2007).

Field Margin Complexes (FMCs) comprise all structural elements in the space between crop outer rows and the adjacent field (Moonen et al., 2006). FMCs can be simple (e.g., a barbed wire fence or a ditch) or complex, including different layers/types of structure (e.g., ditches, grass or flower strips, headlands, hedgerows, different width/height), vegetation (e.g., grasses, forbs, shrubs, trees), and management (e.g., pruning, mowing, spraying) (Greaves and Marshall, 1987). Moonen et al. (2006) tested the hypothesis that more structurally complex FMCs (i.e., higher ecosystem agrobiodiversity) would improve the weed and pest control functions, by reducing the number of weed propagules invading the field from the margin and creating habitats more suitable for natural enemies of insect pests, respectively. Structure, vegetation, and management diversity was analyzed in 62 FMCs in an organic arable farm and related to the presence of beneficial arthropods (Coccinellidae, Syrphidae, and Chrysopidae, representing the agroecosystem functional group) known to potentially control aphids in the study area. FMC diversity was positively correlated with plant species richness in the margins ($r = 0.35$, $P = 0.005^{**}$), which in turn was negatively correlated with the percentage of weeds ("weediness") present in the margins ($r = -0.47$, $P = 0.0001^{***}$). However, FMC weediness was strongly positively correlated with the presence of aphid natural enemies ($r = 0.93$, $P = 0.002^{**}$), likely because they need weeds for part of their life cycle, e.g., as overwintering or oviposition habitat. These findings show that the same element of ecosystem agrobiodiversity may cause conflicts between two functions. In this situation, one must define which of the two functions is more important. In the previous case study, if biological pest control is considered high priority, for example, it is advisable to reduce FMC structural complexity, since this would promote higher field margin weediness which would favor natural enemies' populations. In that case, however, farmers should accept a higher risk of weed invasion from the margin to the field.

6. FUNCTIONAL AGROBIODIVERSITY: OPPORTUNITIES AND BOTTLENECKS

The previous case studies show that functional agrobiodiversity has potential to improve agroecosystem sustainability and that this potential is higher when genetic, species, and ecosystem agrobiodiversity are combined in novel cropping systems. However, despite scientific evidence, actual large-scale adoption of functional agrobiodiversity will only be possible if global policy, science, and public opinion objectives converge. Opportunities and threats for functional agrobiodiversity in the foreseeable future are discussed below.

6.1 What Could Favor Functional Agrobiodiversity?

In the past 20 years, several international treaties and policies developed at continental or regional scales have set the ground for the conservation and valorization of (agro)biodiversity, a cause and consequence of increased public opinion awareness. The starting point has been the 1992 Convention on Biological Diversity, which includes a Thematic Programme on Agricultural Biodiversity (www.cbd.int/agro). Regarding genetic agrobiodiversity, one important milestone has been the promulgation (2004) of the FAO-supported International Treaty on Plant Genetic Resources for Food and Agriculture (www.planttreaty.org), which aims to favor plant germplasm exchange and equitable sharing of benefits deriving from its use among signatory states, to reach worldwide food security. A synopsis of policy developments to support genetic agrobiodiversity can be found in Bragdon et al. (2009). Regarding common agricultural policies, in October 2009 the European Union released a Framework Directive on the Sustainable Use of Pesticides (EU, 2009), binding all Member States to use Integrated Pest Management (IPM) as the reference agricultural management approach for all farmers. In Annex III, the Directive indicates eight IPM principles which must be taken up in EU agriculture from January 1, 2014; these principles clearly state that diversity in crop rotations and associated cultural practices should be a common goal. This calls upon the importance of (functional) agrobiodiversity for the design of future EU cropping systems, even though the Directive does not mention it explicitly.

In the scientific arena there is increasing awareness of the importance of agrobiodiversity for sustainable agriculture. International networks bringing together scientists from various parts of the world are expanding—see, e.g., the Agrobiodiversity cross-cutting network of the Diversitas platform (www.agrobiodiversity-diversitas.org), and the Platform for Agrobiodiversity Research (PAR, http://agrobiodiversityplatform.org). It is worth noticing that the concept of functional agrobiodiversity (as illustrated in this chapter) is gaining ground—see, e.g., the recent establishment of the European Learning Network on Functional Agro Biodiversity (ELN-FAB, www.eln-fab.eu). Basic and applied research on the functional value of genetic, species, and habitat agrobiodiversity is in progress, often supported by substantial public funding (see, e.g., http://cordis.europa.eu).

6.2 What Could Hinder Functional Agrobiodiversity?

Despite support from policy and public opinion, current global agreements on international trade and intellectual property rights (Correa, 2007) play against widespread adoption of functional agrobiodiversity because they are tailored to the needs of standardized agricultural and food systems (Gonzalez, 2002). In particular, there are strong arguments against farmers' reuse of seeds saved from the previous harvest because this would violate international regulations on seed royalties (Howard, 2009). As such, adoption of innovative solutions based on increased genetic agrobiodiversity (e.g. CCPs) might be hindered by lack of regulatory support. Another issue possibly limiting adoption of cultivar mixtures and CCPs is that they provide produce that is different every year. Does this comply with the requirements and expectations of the food processing industry and of consumers? To date, due to the structure of agricultural trade systems, diversified solutions seem better suited to small-scale farming and local markets attended by consumers well aware of what they buy and why they buy it (Wolfe et al., 2008). From the viewpoint of agricultural management, a major question is whether or not large-scale farms can afford the higher degree of attention, time, and consequent labor costs implied by agroecological solutions. In fact, larger-scale organic farms tend to be based on a substitution approach (use of non-synthetic inputs instead of synthetic ones) without really implementing agroecological solutions, likely because they seek scale economies and standardization of produce and consequently of cultural practices (Best, 2008). The same reasons hinder large-scale introduction of ecosystem agrobiodiversity such as hedgerows or other non-cropped areas, unless they are supported by public funding, or research outcome can clearly be translated into operational guidelines (Kleijn and Sutherland, 2003).

Although research on the relationships between agriculture and biodiversity is progressing, lack of a commonly accepted definition of agrobiodiversity and, to some extent, of agroecology (Wezel et al., 2009) slows down the pace of research findings and their implementation in actual cropping/farming/agricultural systems. The very nature of agroecology requires long-term experiments, multidisciplinary collaboration (hence open-minded scientists), and studies across multiple time and spatial scales (Francis et al., 2008). This extends time to publication of results, which is against present expectations from scientists. In perspective, this might jeopardize public funding to agroecological research (Vanloqueren and Baret, 2009).

7. CONCLUSIONS

Functional agrobiodiversity can provide practical solutions to help shape agroecosystems of the future, but needs time to provide evidence through complex studies carried out beyond the disciplinary boundaries that still characterize science. As well as agroecology, functional agrobiodiversity does not provide standardized solutions but rather an approach to the development of these solutions locally. Society needs to understand that the pace of economic systems would need to be reconciled with that of biological systems, otherwise biodiversity-driven solutions, although they might work at a local scale, would never be instrumental in solving global (agri)environmental problems.

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REFERENCES

Akram, Q.F., 2009. Commodity prices, interest rates and the dollar. Energy Econ. 31, 838–851.

Altieri, M.A. (Ed.), 1995. Agroecology: The Science of Sustainable Agriculture. Springer, Netherlands, Dordrecht.

Altieri, M.A., Letourneau, D.K., Davis, J.R., 1983. Developing sustainable agroecosystems. Biosci. 33, 45–49.

Altieri, M.A., Merrick, L.C., 1987. *In situ* conservation of crop genetic resources through maintenance of traditional farming systems. Econ. Bot. 41, 86–96.

Altieri, M.A., Nicholls, C.I., 2004. Biodiversity and Pest Management in Agroecosystems, Second ed. The Haworth Press, New York.

Bàrberi, P., Burgio, G., Dinelli, G., Moonen, A.C., Otto, S., Vazzana, C., et al., 2010. Functional biodiversity in the agricultural landscape: relationships between weeds and arthropod fauna. Weed Res. 50, 388–401.

Barbosa, P. (Ed.), 1998. Conservation Biological Control Academic Press, San Diego.

Best, H., 2008. Organic agriculture and the conventionalization hypothesis: a case study from West Germany. Agric. Human Values. 25, 95–106.

Bragdon, S., Jarvis, D.I., Gauchan, D., Mar, I., Hue, N.N., Balma, D., et al., 2009. The agricultural biodiversity policy development process: exploring means of policy development to support the on-farm management of crop genetic diversity. Int. J. Biodivers. Sci & Manage. 5, 10–20.

Bright, C., 1999. Invasive species: pathogens of globalization. Foreign Policy. 116 (50–60 + 62–64).

Clergue, B., Amiaud, B., Pervanchon, F., Lasserre-Joulin, F., Plantureux, S., 2005. Biodiversity: function and assessment in agricultural areas – a review. Agron. Sustainable Dev. 25, 1–15.

Cook, S.M., Khan, Z.R., Pickett, J.A., 2007. The use of push-pull strategies in integrated pest management. Annu. Rev. Entomol. 52, 375–400.

Coolman, R.M., Hoyt, G.D., 1993. Increasing sustainability by intercropping. HortTechnology. 3, 309–312.

Correa, C., 2007. Trade Related Aspects of Intellectual Property Rights. A Commentary on the TRIPS Agreement. Oxford University Press, Oxford.

Couch, C., Petschel-Held, G., Leontidou, L. (Eds.), 2007. Urban Sprawl in Europe: Landscape, Land-Use Change and Policy. Wiley-Blackwell, Oxford.

Crutsinger, G.M., Collins, M.D., Fordyce, J.A., Sanders, N.J., 2008. Temporal dynamics in non-additive responses of arthropods to host-plant genotypic diversity. Oikos. 117, 255–264.

De Schutter, O., 2011. How not to think of land-grabbing: three critiques of large-scale investments in farmland. J. Peasant Stud. 38, 249–279.

Desneux, N., Wajnberg, E., Wyckhuys, K.A.G., Burgio, G., Arpaia, S., Narváez-Vasquez, C.A., et al., 2010. Biological invasion of European tomato crops by *Tuta absoluta*: ecology, geographic expansion and prospects for biological control. J. Pest. Sci. 83, 197–215.

de Vries, S.C., van de Ven, G.W.J., van Ittersum, M.K., Giller, K.E., 2010. Resource use efficiency and environmental performance of nine major biofuel crops, processed by first-generation conversion techniques. Biomass Bioenergy. 34, 588–601.

EU, 2009. Directive 2009/128/Ec of the European Parliament and of the Council of 21 October 2009 establishing a framework for community action to achieve the sustainable use of pesticides. Official Journal of the European Union, 16. (24.11.2009).

European Commission (2005). Agri-Environment Measures – Overview on General Principles, Types of Measures, and Application. European Commission, DG for Agriculture and Rural Development, p. 24.

European Environment Agency, 2004. High Nature Value Farmland – Characteristics, Trends, and Policy Challenges. European Environment Agency, Copenhagen.

Finch, S., Collier, R.H., 2000. Host-plant selection by insects – a theory based on 'appropriate/inappropriate landings' by pest insects of cruciferous plants. Entomol. Exp. Appl. 96, 91–102.

Fleming, A., Vanclay, F., 2010. Farmer responses to climate change and sustainable agriculture. A review. Agron. Sustainable Dev. 30, 11–20.

Francis, C.A., Lieblein, G., Breland, T.A., Salomonsson, L., Geber, U., Sriskandarajah, N., et al., 2008. Transdisciplinary research for a sustainable agriculture and food sector. Agron. J. 100, 771–776.

Gabriel, D., Sait, S.M., Hodgson, J.A., Schmutz, U., Kunin, W.E., Benton, T.G., 2010. Scale matters: the impact of organic farming on biodiversity at different spatial scales. Ecol. Lett. 13, 858–869.

Garnier, E., Navas, M.L., 2012. A trait-based approach to comparative functional plant ecology: concepts, methods and applications for agroecology. A review. Agron. Sustainable Dev. 32, 365–399.

Garrett, K.A., Nelson, R.J., Mundt, C.C., Chacón, G., Jaramillo, R.E., Forbes, G.A., 2001. The effects of host diversity and other management components on epidemics of potato late blight in the humid highland Tropics. Phytopathology 91, 993–1000.

Giampietro, M., Ramos-Martin, J., Ulgiati, S., 2012. Can we break the addiction to fossil energy? Energy 37, 2–4.

Gonzalez, C.G., 2002. Institutionalizing inequality: the WTO Agreement on Agriculture, food security, and developing countries. Columbia. J. Environ. Law. 27, 433–489.

Greaves, M.P., Marshall, E.J.P., 1987. Field margins: definitions and statistics. In: Way, J.M., Greig-Smith, P.J. (Eds.), Field Margins British Crop Protection Council, Thornton Heath, pp. 3–10. (Monograph No. 35).

Gressel, J. (2006). Native species are the most intractable evolving agricultural weeds. In "Proceedings International Symposium on Intractable Weeds and Plant Invaders", Ponta Delgada, Azores, Portugal, 17–21 July, 10–11.

Gurr, G.M., Wratten, S.D., Luna, J.M., 2003. Multi-function agricultural biodiversity: pest management and other benefits. Basic. Appl. Ecol. 4, 107–116.

Hajjar, R., Jarvis, D.I., Gemmill-Herren, B., 2008. The utility of crop genetic diversity in maintaining ecosystem services. Agric., Ecosyst. Environ. 123, 261–270.

Howard, P.H., 2009. Visualizing consolidation in the global seed industry: 1996–2008. Sustainability 1, 1266–1287.

IPCC, 2007. In: Allali, A., Bojariu, R., Diaz, S., Elgizouli, I., Griggs, D., Hawkins, D. (Eds.), Climate Change 2007: Synthesis Report Intergovernmental Panel on Climate Change, Geneva.

Jackson, L.E., Pascual, U., Hodgkin, T., 2007. Utilizing and conserving agrobiodiversity in agricultural landscapes. Agric., Ecosyst. Environ. 121, 196–210.

Jarvis, D.I., Myer, L., Klemick, H., Guarino, L., Smale, M., Brown, A.H.D., et al., 2000. A Training Guide for In Situ Conservation On-farm, Version I. International Plant Genetic Resources Institute, Rome.

Jax, K., 2005. Function and ''functioning'' in ecology: what does it mean? Oikos 111, 641–648.

Jeanneret Ph., Schüpbach, B., Luka, H, 2003. Quantifying the impact of landscape and habitat features on biodiversity in cultivated landscapes. Agric., Ecosyst. Environ. 98, 311–320.

Karlen, D.L., Varvel, G.E., Bullock, D.G., Cruse, R.M., 1994. Crop rotations for the 21st century. Adv. Agron. 53, 1–45.

Kleijn, D., Sutherland, W.J., 2003. How effective are European agri-environment schemes in conserving and promoting biodiversity? J. Appl. Ecol. 40, 947–969.

Li, D.Z., Pritchard, H.W., 2009. The science and economics of *ex situ* plant conservation. Trends. Plant. Sci. 14, 614–621.

Malézieux, E., Crozat, Y., Dupraz, C., Laurans, M., Makowski, D., Ozier-Lafontaine, H., et al., 2009. Mixing plant species in cropping systems: concepts, tools and models. A review. Agron. Sustainable Dev. 29, 43–62.

Mazzoncini, M., Canali, S., Giovannetti, M., Castagnoli, M., Tittarelli, F., Antichi, D., et al., 2010. Organic *vs* conventional stockless arable systems: a multidisciplinary approach to soil quality evaluation. Applied Soil Ecology. 44, 124–132.

Mendelsohn, R., Dinar, A., 1999. Climate change, agriculture, and developing countries: does adaptation matter? World Bank Res. Obs. 14, 277–293.

Mitchell, D. (2008). A note on rising food prices. World Bank Policy Research Working Paper Series, Available at SSRN: <http://ssrn.com/abstract=1233058>.

Moonen, A.C., Bàrberi, P., 2008. Functional biodiversity: an agroecosystem approach. Agric., Ecosyst. Environ. 127, 7–21.

Moonen, A.C., Castro Rodas, N., Bàrberi, P., Petacchi, R., 2006. Field margin structure and vegetation composition effects on beneficial insect diversity at farm scale: a case study on an organic farm near Pisa in: Rossing, W.A.H. Eggenschwiler, L. Poehling, H.M. (Eds.), Landscape Management for Functional Biodiversity, 29 *IOBC wprs Bulletin*, pp. 77–80.

Mundt, C.C., 2002. Use of multiline cultivars and cultivar mixtures for disease management. Annu. Rev. Phytopathol. 40, 381–410.

Olson, D.M., Wäckers, F.L., 2007. Management of field margins to maximize multiple ecological services. J. Appl. Ecol. 44, 13–21.

Parris, K, 2001. OECD Agri-biodiversity indicators: background paper. Proceedings OECD expert meeting on agri-biodiversity indicators. Zurich, Switzerland, p. 42.

Pearce, D., Moran, D., 1994. The Economic Value of Biodiversity. Earthscan, London.

Peigné, J., Ball, B.C., Roger-Estrade, J., David, C., 2007. Is conservation tillage suitable for organic farming? A review. Soil Use Manage. 23, 129–144.

Pimbert, M., 2011. Participatory research and on-farm management of agricultural biodiversity in Europe. IIED, London.

Pretty, J., 2008. Agricultural sustainability: concepts, principles and evidence. Phil. Trans. R. Soc. B. 363, 447–465.

Singh, R.P., Hodson, D.P., Huerta-Espino, J., Jin, Y., Njau, P., Wanyera, R., et al., 2008. Will stem rust destroy the world's wheat crop? Adv. Agron. 98, 271–309.

Tilman, D., Cassman, K.G., Matson, P.A., Naylor, R., Polasky, S., 2002. Agricultural sustainability and intensive production practices. Nature 418, 671–677.

Tucker, G.M., Heath, M.F., 1994. Birds in Europe. Their Conservation Status. Birdlife Conservation Series No 3. Birdlife International, Cambridge.

Vandermeer, J., 1989. The Ecology of Intercropping. Cambridge University Press, Cambridge.

Vanloqueren, G., Baret, P.V., 2009. How agricultural research systems shape a technological regime that develops genetic engineering but locks out agroecological innovations. Res. Policy 38, 971–983.

Violle, C., Navas, M.L., Vile, D., Kazakou, E., Fortunel, C., Hummel, I., et al., 2007. Let the concept of trait be functional! Oikos 116, 882–892.

Webster, T.M., Burton, M.G., Culpepper, A.S., York, A.C., Prostko, E.P., 2005. Tropical spiderwort (*Commelina benghalensis*): a tropical invader threatens agroecosystems of the southern United States. Weed Technol. 19, 501–508.

Wezel, A., Bellon, S., Doré, T., Francis, C., Vallod, D., David, C., 2009. Agroecology as a science, a movement and a practice. A review. Agron. Sustainable Dev. 29, 503–515.

Woldeamlak, A., Grando, S., Maatougui, M., Ceccarelli, S., 2008. Hanfets, a barley and wheat mixture in Eritrea: yield, stability and farmer preferences. Field Crops Res. 109, 50–56.

Wolfe, M.S., Baresel, J.P., Desclaux, D., Goldringer, I., Hoad, S., Kovacs, G., et al., 2008. Euphytica 163, 323–346.

Yachi, S., Loreau, M., 1999. Biodiversity and ecosystem productivity in a fluctuating environment: The insurance hypothesis. Proc. Natl. Acad. Sci. USA. 96, 1463–1468.