Review

Functional biodiversity: An agroecosystem approach

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ABSTRACT

Research and policies aimed at biodiversity conservation in agricultural ecosystems are often less successful than expected. One common assumption is that more research is needed to develop improved measures and indicators of biodiversity. The authors' opinion is that this is only partly true and that most of the problems arise from the lack of a well-focussed approach to this subject. Based on the knowledge available in the scientific literature, a methodological framework was developed which can help researchers and policy makers to think in a better, more structured way about issues related to biodiversity conservation in a given agroecosystem. In order to frame the importance of biodiversity in agroecosystems, three main questions were addressed through literature search: (1) What does biodiversity mean in natural and agricultural ecosystems? (2) How is the concept of functionality used in relation to biodiversity? (3) Which biodiversity measures are currently used to express agriculture–biodiversity relationships?

Analysis of the literature resulted in a framework consisting of three steps. At first the objectives of biodiversity research and policies have to be defined. Three options can be foreseen here: (a) species, community, habitat or overall biodiversity conservation regardless of its functions, (b) biodiversity conservation to attain production and environmental protection services, and (c) use of bio-indicators for agroecosystem monitoring. In the second step the appropriate target elements for conservation have to be chosen based on an agroecosystem approach, and in the third step adequate biodiversity measures of composition, structure and function have to be selected for each target element.

Functional biodiversity is important in relation to the provision of specific agroecosystem services. The study of functional biodiversity should start with the definition of agroecosystem functional groups comprising all elements that interact with the desired service, and the consequent determination of the role of diversity within these functional groups for the fulfilment of the agroecosystem service. Therefore a more precise definition of 'functional biodiversity' would 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*".

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1. Introduction

After the signing of the 'Convention on Biological Diversity' in Rio de Janeiro in 1992 the word 'biodiversity' has become a widely used term in science (number of publications with 'biodiversity' in title, abstract or key words in Scopus©: 3 for 1988, 133 for 1992, 1170 for 1998 and 4526 for 2005) and in policy making (Buchs, 2003). The success of 'biodiversity conservation' depends on the successful interactions between science and policy making. If research and policy making do not give the same meaning to the term 'biodiversity' and if they do not define precisely what objectives they pursue, there cannot be a good interaction between them and the results of research will not be used correctly. Ultimately, the policies chosen will not be as successful as they could have been.

The absence of detailed objectives for biodiversity conservation projects and policies does not only result in research projects which are hard to relate to policy making, and policies which are hard to evaluate (Kleijn and Sutherland, 2003), but it also increases the risk of unforeseen and negative side effects on other facets of biodiversity (Marshall and Moonen, 2002; Moonen et al., 2006).

Policy makers have responded to the alarm launched by researchers with regard to the need for 'biodiversity conservation'. A reference to 'the conservation of biodiversity' is present in almost all conservation, land use management and environmental protection policies proposed at local, national and international scale. As can be seen from some reports and projects written at European Community (EC) level, policy makers use biodiversity for various goals and objectives without much specification. To start with, often there is no clear distinction between the use of biotic indicators and biodiversity indicators for the determination of the state of environmental aspects of ecosystems (Duelli and Obrist, 2003). 'Biodiversity conservation' has been defined as one of the aims of agri-environmental policies (AEP) (Parris, 2001; p. 7–8), and measures (AEM) (European Commission, 2005; p. 11–12), including the definition of High Nature Value Farmland (European Environment Agency, 2004), and it is at the same time used to measure impacts of AEP and AEM on 'biodiversity'. Furthermore, it is used to measure impacts of agriculture on the environment and on agricultural sustainability (Parris, 2001; p. 7), and to measure the impacts of agriculture on 'biodiversity' (Parris, 2001; p. 13). All of these reports use 'biodiversity' without specification of the level or type that is desirable, and it is assumed that there is a cause–effect relationship between biodiversity (not specified) and environmental quality, agricultural sustainability, and between certain biodiversity indicators and the overall biodiversity level.

The lack of robust evaluation studies for the determination of the success of European AEM in conserving and promoting biodiversity as pointed out by Kleijn and Sutherland (2003), and for the same reason of other agro-environmental or conservation projects and policies at local, national or international scale, could be related to the absence of a well-defined quantitative measure for 'biodiversity', as proposed by Spangenberg (2007).

Instead, the impression of the authors of this paper is that the main problem is related to the wide variety of interpretations given to the terms 'biodiversity' and 'functional biodiversity', to the inefficient use of existing biodiversity measures, and also to the fact that, so far, mostly ecologists have been involved in the definition of research and policy making regarding biodiversity, which resulted in a biased perspective. This paper will underline the importance of an agroecosystem approach for questions involving agriculture–biodiversity relationships. Based on this approach, the aim is to create a methodological framework which provides guidelines for the determination of more effective biodiversity measures in agroecosystems. This framework differs from previously proposed frameworks for biodiversity or lists of bio-indicators in that it does not provide names of target elements to be studied, but gives guidelines for determination of the typology of biodiversity that should be addressed in relation to the various usages of biodiversity in agroecosystems. The exact names and measurers of target elements have to be defined based on agroecosystem characteristics, which will obviously vary depending on the context.

2. Methodology

In order to frame the importance of biodiversity in agroecosystems and to make it more tangible for research and policy making, three main questions had to be addressed through literature search:

(1) What is biodiversity?
   (a) Disentangling 'biodiversity' in natural and agricultural ecosystems.
   (b) Which objectives for biodiversity are pursued?
(2) What is functionality?
   (a) The 'functionality' concept in relation to biodiversity in agroecosystems.
   (b) Has research demonstrated the presumed mechanistic relations between 'biodiversity' and agroecosystem sustainability, agroecosystem processes and overall biodiversity?
(3) Which biodiversity measures?
   (a) Which biodiversity measures have been proposed so far?
   (b) How to apply existing biodiversity measures efficiently in agroecosystems?

If there are multiple objectives, a more specific terminology should be used for biodiversity issues. Analogously, different interpretations of the functionality concept should be made more explicit. The resulting categories can be the basis for a more appropriate use of existing biodiversity measures and bio-indicators. Bio-indicators used to express agroecosystem characteristics such as agroecosystem processes, overall sustainability and overall biodiversity should be based on proven cause–effect relationships.

The core of this paper is composed of four sections. Each section evolves around one of the three main questions, and the last section consists of the presentation of the resulting methodological framework.

The literature search was performed with Scopus© combining keywords such as 'biodiversity', 'ecosystem functioning', 'functional biodiversity', and 'agroecosystem'. Similar keywords were combined in Google.

2.1. Biodiversity in natural versus agricultural ecosystems

With the ratification of the 'Convention on Biological Diversity' in 1992, biodiversity has officially been defined as diversity at genetic, species and ecosystem level (United Nations, 1992), although the importance of the three levels has been recognised long before (U.S. Congress, 1987). However, in practice the term 'biodiversity' is still mainly associated with the conservation of individual species in natural or semi-natural habitats, i.e. areas not managed with a production goal. Occasionally, it is related to habitat or ecosystem conservation, but mostly when the habitat is specific to certain species that have to be conserved (e.g. little pools for amphibians), when the ecosystem as a whole fulfils a specific function for human well-being (e.g. tropical rain forests, that are considered the 'lungs' of the earth) or when the ecosystem is supposed to host species, the so-called 'wild species', that might be of direct importance to society (e.g. species with medicinal properties). In the latter two cases, the benefits (food, medicine,

goods or environmental protection) that humankind derives from the ecosystem are called the 'ecosystem services' (Costanza et al., 1997). The rationales, mostly unpronounced, behind species or habitat/ecosystem conservation in natural areas are the intrinsic and aesthetic values attributed to them and the risk of destroying species or ecosystems which might provide a service to society.

The first interest in 'biodiversity' in managed agroecosystems was in the selection of the more productive species, varieties and races, and in the reduction of the unproductive species. It can therefore be characterised by an interest in reduction of diversity, and increase in 'functionality' of some components present in the agroecosystem. It follows that the approach to biodiversity conservation in agroecosystems should be different from the one in natural ecosystems.

In the first place, natural ecosystems are mostly large areas that are perceived as a rather homogeneous matrix, consisting of various micro-habitats with different species associated but still clearly part of the same system. Instead, agroecosystems consist of three intermingled and strongly interacting sub-systems: the managed fields, referred to as the productive sub-system, the semi-natural or natural habitats surrounding them and the human sub-system composed of settlements and infrastructures. Biodiversity conservation is mostly focused on the semi-natural sub-system. Human settlements and infrastructures are rarely considered for their biodiversity, and their impact on biodiversity in the surrounding natural, semi-natural or productive areas is generally ignored. The productive sub-system instead, is often perceived to have a negative impact on biodiversity in the surrounding areas. At the same time, farmers perceive the semi-natural sub-system as a threat to their productive areas (e.g. as a source of pest organisms) and, again, the human sub-system is usually ignored. Disproportionate attention is given to the negative interactions between the semi-natural and productive sub-systems whereas their mutual dependence is often neglected.

Secondly, agroecosystems exist by the grace of humankind and are managed with a clear scope: to produce food, feed, goods such as timber, fibres and other natural products for own use and/or for the market. Analogously to a natural ecosystem, any benefit humankind derives from an agroecosystem is referred to as an 'ecosystem service'. The difference is that ecosystem services provided by an agroecosystem are primarily services that provide benefits to the primary production processes, and through that, to humankind (Tables 1 and 2). The interest of society in agroecosystem services related to environmental protection are in the first place to compensate for the air, water and soil pollution and consumption by modern agricultural practices, and only recently some projects have taken into account the possibility to use agroecosystems to remediate environmental pollution deriving from industrial activities (Gupta et al., 2002). The productive sub-system of the agroecosystem and the biota of which it is composed have an economic function for humankind and, as a consequence, the rationale of biodiversity conservation or management is to increase the ecosystem services [defined by Duelli and Obrist (2003) as ecological resilience and biological control] and to preserve its cultural and/or traditional values. Biodiversity conservation related to the semi-natural sub-system is primarily related to the intrinsic or aesthetic values, whereas the positive impact of the semi-natural biodiversity on the productive sub-system is only clearly recognised in the case of biological control by agents relying on the semi-natural subsystem to spend part of their life cycle. Environmental protection services can be provided by both sub-systems, but they are considered only if the primary services are guaranteed.

At last, from the way agroecosystems are structured it follows that the inhabiting biota or habitat can be divided in five different groups: (1) the cultivated or bred species producing a good [agricultural diversity (Clergue et al., 2005)] or the productive units, (2) the auxiliary species; spontaneous or introduced species which support the production process [para-agricultural diversity (Clergue et al., 2005)] or auxiliary habitat (e.g. windbreaks, drainage channels), (3) pest species; spontaneous species damaging the production process and managed to be controlled (including species supporting pests) or contaminating habitat (e.g. salt water bodies), (4) wild species producing goods, managed or not, which can sporadically be present within a non-productive vegetation or grouped together in stands thus becoming a habitat (e.g. blackberry (*Rubus fruticosus* L.) or trees for fire wood) and (5) spontaneous neutral species [extra-agricultural diversity (Clergue et al., 2005)] or semi-natural habitat such as woodlots and rivers, whose presence does not affect the production services. The principal aim of elements of the first four groups is to provide services related to production of goods, whereas conservation of elements of the last group is mostly related to aesthetic and intrinsic reasons, or to ecosystem services related to environmental protection. It is obvious that the attribution of species to these groups is rather flexible and dependent on the agroecosystem characteristics and managers. A blackberry bush can belong to groups 2, 3 and 4 at the same time: it provides fruits, it may invade cropped field, it hosts pest insects and it attracts beneficial insects such as pollinators and pest antagonists. A durum wheat (*Triticum durum* Desf.) plant can be a crop today, and a weed tomorrow, if it appears as a volunteer in the following crop. Species belonging to groups 1, 2 and 3 are commonly present in the productive sub-system whereas species belonging to groups 3, 4 and 5 characterise the semi-natural sub-system. In natural ecosystems only wild and neutral species can be recognised. In reality they can host also pest species, referred to as invasive or exotic species. There is a growing interest in these species since they can threaten local communities and disrupt ecosystem functioning. However, they are not further taken into consideration given the general assumption that they are not desirable.

Projects aiming at biodiversity conservation in agroecosystems often focus, without clearly stating this, on only one or few of these groups of organisms or habitats. Traditionally, agronomists are interested in the crop diversity aspects for production purposes, agroecologists in crop and auxiliary species (Altieri, 1995; Cardinale et al., 2003) and auxiliary habitat diversity (Baudry et al., 2000) for the increase of agroecosystem sustainability, and ecologists and conservation biologists in the wild species and the spontaneous neutral species diversity and semi-natural habitats for intrinsic and aesthetic reasons. Only recently, both ecologists and weed and pest managers have realised the importance of weed and pest species diversity as support to natural species (e.g. farmland birds) related to the agroecosystem (Albrecht, 2003; Marshall et al., 2003; Storkey, 2006; Makowski et al., 2007) or, in the case of weeds, for the support they give to the auxiliary species (function in the life cycle of pest antagonists) (Lenne and Wood, 1999; Norris and Kogan, 2000; Marshall et al., 2003; Makowski et al., 2007). In a few cases there is an interest in species conservation of weed species to the brink of extinction (Spahillari et al., 1999; Recasens and Conesa, 2004; Sutcliffe, 2004; Makowski et al., 2007).

When studying aspects of diversity at the agroecosystem level, attention should be paid to both habitat diversity within one agroecosystem and agroecosystem diversity at regional, national or trans-national scale. Diversity of agroecosystems in a same territory is like having an 'insurance' for income production on at least part of the territory in case changing environmental or political (socio-economic) conditions are unfavourable for some production systems. This diversity can also serve as a buffer against the presence of intensive and low diverse agroecosystems such as continuous cropping or against large-scale land abandonment, and

Table 1
Processes related to the production service (columns) affected by several important auxiliary and pest biota present in most agroecosystems

Auxiliary and pest biota	Soil related processes					Food web services				Gene flow	Production	
	Nutrient cycling (mineralisation and uptake)	Decomposition	Soil aggregate stability	Soil organic matter formation	Water regulation	Food source for other pest or auxiliary species	Disease control	Weed control	Insect pest control	Pollination	Primary production	Yield reduction
Soil bacteria (Kennedy, 1999)	X	X	X	X		X	X	X	X		X	
Arbuscular mycorrhizal fungi (Douds and Millner, 1999)	X		X		X		X		X		X	
Soil protozoa (Foissner, 1999)	X	X				X						
Nematodes (Yeates and Bongers, 1999)			X				X				X	X
Earthworms (Paoletti, 1999)		X	X			X						
Woodlice (Paoletti and Hassall, 1999)	X	X				X						
Staphylinid beetles (Bohac, 1999)		X					X		X	X		
Soil dwelling diptera (mostly their larvae) (Frouz, 1999)	X	X					X	X	X			X
Predatory mites (Koehler, 1999)		X					X		X			
Oribatid mites (Behan Pelletier, 1999)	X	X	X	X								
Ants (Lobry de Bruyn, 1999)	X				X							
Above ground insects (Duelli et al., 1999)						X			X	X		X
Carabids (Kromp, 1999)								X	X			X
Spiders (Marc et al., 1999)									X			
Syrphidae (Sommaggio, 1999)	X	X							X	X		
Heteroptera (Fauvel, 1999)									X	X		
Neuroptera (Stelzl and Devetak, 1999)									X	X		
Ladybirds (Iperti, 1999)						X			X			
Anthophiles (Kevan, 1999)						X				X	X	
Flowering plants (Kevan, 1999)						X						
Arable weeds (Marshall et al., 2003; Storkey, 2006)						X			X			X

Biota can affect production directly, or indirectly through soil related processes, food web services and gene flow. The collection of all biota contributing to a specific function is called a 'functional group'.

Table 2
Services of natural and agricultural ecosystems provided by diversity at the genetic and species level in five categories of species (synthesis of references listed in this paper)

Natural ecosystems		Agricultural ecosystems			
Neutral species	Wild species	Producers of goods	Auxiliary species	Pest species	Wild and neutral species
• Buffering human and natural disturbance and climate change	• Extraction of new medicinal compounds	• Buffering disturbance effect on crop production	• Increased resource acquisition and partitioning also to higher food web levels	• Increased resource use efficiency	• Provision of genes for improving performance or adaptation of cultivated species
• Increased nutrient and carbon cycling	• Sources of new food and raw materials	• Buffering climate fluctuation and climate change effect on production	• Increased stability of agroecosystem processes (e.g. soil formation, nutrient cycling, biological pest control) under changing agroecosystem conditions	• Increased evolutionary capacity and adaptation to changing conditions (e.g. pesticide resistance)	• Buffering disturbance and impact of management on environment
• Provision of genes for improving performance or adaptation of cultivated species		• Increased resource use efficiency and thus increased production		• Decreased risk of dominance of few aggressive species (e.g. weeds)	

it is likely to increase regional species pools and genome diversity. Habitat diversity within agroecosystems brings along diversity at all other levels, it can serve as a buffer against large-scale pest invasion, and it increases multi-functionality in terms of direct economic activities.

This analysis shows that there are five categories of biota in agroecosystems and only two of them apply to natural ecosystems (wild and neutral species or habitat). The rationales for biodiversity conservation are similar in natural and agricultural ecosystems, but they are different for the five categories of biota. The neutral biota can be conserved for their intrinsic and aesthetic values, or for the buffer role they have in ecosystem ecological functioning and environmental protection. The wild biota are conserved for their cultural or traditional values, or for the services to human health and well-being. Biodiversity conservation of productive, auxiliary and pest species, whose presence is restricted to the agroecosystem, is mainly pursued for their ecosystem services related to the production process, increasingly for environmental protection, sometimes for their cultural and traditional values, and rarely for their intrinsic or aesthetic values, or for the support they give to neutral or wild species. In all five categories elements can be found which contribute to the agroecosystem services related to environmental protection, but according to the stakeholders background, different importance is given to this aspect. A division in categories related to different objectives and sub-systems may be useful in the selection of appropriate target elements for each biodiversity objective.

From the analysis of the objectives for biodiversity conservation, it emerges that except in case of conservation for intrinsic, aesthetic, cultural and tradition reasons, these objectives are related to at least one function which is attributed to each element (biota or habitat). In this case, it is important to notice that the term 'function' is used to indicate (agro)ecosystem functioning and not a function in relation to the organism itself.

2.2. Functional biodiversity

Although the intrinsic, aesthetic and cultural values of biodiversity are important (Hector et al., 2001b), it is hard to believe that they are strong enough to justify the amount of money and time, research and politics (Kleijn and Sutherland, 2003; European Commission, 2005) invested in biodiversity studies and biodiversity conservation (Schwartz et al., 2000). This effort can only be justified by assuming that biodiversity must play a key role in the regulation of ecosystem functioning and through that, or directly, affect the quality of human society. In fact, in the previous section it has been shown that part of the 'biodiversity', both in natural and in agricultural ecosystems, provides services. The part of the biosphere providing the desired ecosystem services is related to the 'functional biodiversity'. This term derives from the so-called 'functional groups' and from the diversity at allele, species or habitat level present. The following two sub-sections explore through a literature analysis, how 'diversity' and 'functional groups' are related to ecosystem functioning and to agroecosystem services.

3. Functional groups for agroecosystem services

In the more classical ecology it is thought that functional groups are the principal *determinants* of the species communities composition. Therefore species are clustered into groups with similar ecophysiological and life-history traits such as dispersal strategy or the ruderal-competitor-stress tolerator characterisation (Grime et al., 1990). In this case, the 'functional groups' are not directly related to the services provided by natural ecosystems, but they are used to explain the state of the ecosystem. For example,

plant species are clustered into 'functional groups' according to dispersal mechanism, because this trait is thought to be one of the main determinants of the actual species pool composition. It would therefore be more correct to refer to them as 'driver groups'. In any case, it is strictly an ecological functionality. More recently, this assumption has been questioned as formulated by Hubbell's (2005) 'neutral theory'. This theory is based on the 'functional equivalence' of all species at the same trophic level, meaning that the ecophysiological and life-history traits of the species do not matter for the determination of the species community composition.

In agroecosystems, on the other hand, communities are not mainly formed by processes of natural competition and dispersal because agricultural management heavily interferes with the nature and intensity of these processes and introduces new, exotic species to the community which can out-compete local species. Community composition is then more the effect of elimination of those species that are not tolerating the actual or past management frequency and intensity, and habitat isolation. As a consequence, the groups that can be distinguished within a community based on ecophysiological and life-history traits are the result of management intensity and frequency and habitat quality, instead of the determinants of the composition of natural communities. These traits are interesting in relation to the objectives of agroecosystem managers and for interpretation of the biota as bio-indicators. For example, to determine effective weed control strategies it may be important to know the diversity and frequency of dispersal mechanisms present in a plant community, or to determine soil quality using bio-indicators it may be useful to establish trait groups of soil bacteria. These types of questions result again in the determination of what are generally called plant or animal 'functional groups'. In this case it would be more correct to talk about life-trait groups for management or for bio-indication. Instead, other species traits such as capacity to host beneficial insects, which are the basis for the 'services' provided by these communities, are the important 'functional groups' in an agroecosystem context. Agroecosystem managers can try to affect the agroecosystem services provided through manipulation of the 'agroecosystem functional groups'. It might therefore be necessary to determine 'management functional groups' within an 'agroecosystem functional group'. For example, if the aim is to increase agroecosystem support to aphid predators and parasitoids, the 'agroecosystem functional group' consists of those plant and insect species known to host or attract them. If from this analysis it appears that most of the plant species are found in the grassy field boundary, it might be important to establish the 'management functional groups' of the boundary vegetation. Knowledge of life form and life history can give indications regarding best mowing time and height for protection of the beneficial plants. Compatibility of these techniques with weed control can be verified at the same time.

Studies aimed at the determination of 'functional groups' are commonly applied in agricultural research. In a special issue of this Journal, introduced by Paoletti (1999), contributors were supposed to examine the value of small organisms as bio-indicators for the environmental status of agricultural landscapes. However, the use of these small organisms as bio-indicators is confused with their contribution to the 'functional biodiversity', i.e. the role they have in the determination of agroecosystem processes and through that, in the provision of agroecosystem services. Most of the contributions use the term 'functional group', but with different meanings. The review on oribatid mites (Behan Pelletier, 1999) mentions that 'functional groups' of these organisms can be used as indicator for soil quality in agroecosystems, and therefore they are 'life-trait' functional groups. The reviews on AMF (Douds and Millner, 1999) and soil bacteria (Kennedy, 1999) instead, indicate the importance of these biota for the agroecosystem services they provide, and the

difficulties in measuring their functionality. The review on predatory mites (Koehler, 1999) and spiders (Marc et al., 1999) distinguish between measures for bio-indication and agroecosystem processes affected by these groups of organisms. Importance of ants (Lobry de Bruyn, 1999) is discussed mostly in relation to their impact on agroecosystem processes, whereas the ant functional groups are based on life traits which not necessarily reflect differences in interaction with the agroecosystem processes. Nematode functional groups are intended as feeding groups, and are related to the agroecosystem functions each feeding group expresses (Yeates and Bongers, 1999). Consequently, indicator species for each feeding group are determined. A clear distinction between the use of bio-indicators and 'agroecosystem functional groups' is fundamental because good bio-indicators have to respond to environmental change or to reflect a clear environmental status, whereas not necessarily they interact and regulate the agroecosystem processes. Examples are bio-indicators for environmental pollution (Marc et al., 1999; Paoletti and Hassall, 1999). It would be more correct to consider as 'functional groups' all clusters of biota providing the same agroecosystem service. All biotic groups introduced in the above-mentioned special issue of this Journal were listed, and the various production-related agroecosystem processes and services elements these biotic groups contribute to were summarised (Table 1). Based on the characteristics of the agroecosystem, all biota providing the desired service should be taken into account in the study in order to reflect the potential of the agroecosystem to provide that service. Based on specific knowledge regarding the agroecosystem and the present biota, it can be decided to concentrate the study on a sub-sample of the biota in a functional group. Calling individual biota a 'functional group' is confusing because one biota can deliver several ecosystem functions and a single biota does not reflect the whole agroecosystem potential for that specific service.

The agroecosystem services for production provided by the functional groups can be divided into soil-related processes (e.g. increased nutrient cycling, decomposition rate, aggregate stability, organic matter formation and water regulation), food web services, gene flow and the direct crop production service. The crop production service is strictly speaking the result of increased soil-related processes, food web services and gene flow. Yield reduction can be considered a negative primary production service caused by crop antagonists. Food web services consist of those organisms that are a food source for auxiliary biota in the productive or semi-natural sub-systems (positive service), for biota that feed on the crop antagonists (positive service), and for biota that feed on the crop (pests delivering a negative service). The gene flow service for crop production is carried out by pollinators.

Studies concentrating on functional groups may also need to take into account the importance of diversity. For example, a study establishing the importance of soil micro-organisms in agroecosystems by determining their impact on soil respiration and soil organic matter cycling (Brussaard et al., 2007) starts with the definition of the functional groups. If the (groups of) micro-organisms are complementary and contribute to different phases of a process (e.g. decomposition of different components of soil organic matter), or they perform under diverse environmental conditions, the importance of diversity becomes evident. It has to be decided if diversity is needed at genetic, species or habitat level. In an agroecosystem context both approaches can be complementary but, based on the objectives of the study, they can also be used separately.

4. Diversity for ecosystem functioning

The question if 'biodiversity' (diversity in composition of alleles, species and habitat) really interferes with ecosystem functioning

has been asked ever since Darwin, and ecologists have for long tried to gather scientific proof for it (Tilman and Lehman, 2002). However, the major reviews regarding this subject (Schwartz et al., 2000; Ekschmitt et al., 2001; Hector et al., 2001a; Schmid et al., 2002; Naeem and Wright, 2003; Hooper et al., 2005; Jackson et al., 2007) have shown that the mechanistic relationships between biodiversity and ecosystem functioning that have been proven by field observations or experiments were mainly limited to the effects of plant or micro-organism species richness on primary production (van der Heijden et al., 1998; Hector et al., 1999; Tilman, 1999; Loreau et al., 2001), nitrogen retention (Tilman et al., 1996; Tilman, 1999; Kahmen et al., 2006) and susceptibility to invasions (Tilman, 1999; Hector et al., 2001a) at small spatial and temporal scales (Srivastava and Vellend, 2005), and the increased stability of some ecosystem processes (McGrady-Steed et al., 1997; Tilman et al., 2006) on a relatively small time scale. The established correlations can be directly or indirectly explained by a combined 'niche differentiation effect' (Tilman, 1999) or 'complementarity effect' (Loreau, 2000) and a 'sampling effect' (Tilman, 1999) or 'selection effect' (Loreau, 2000) and seem to be more pronounced in species poor communities than in species rich communities (Ekschmitt et al., 2001). This basically means that the way in which increased biodiversity affects ecosystem functioning depends on whether the newly added species uses different resources than the already present ones (niche differentiation and therefore the species are functionally complementary) and, in case they use the same resource, whether they have a higher or a lower resource use intensity than the already present species. Since species diversity increase happens through random sampling from the surrounding species pool and since it is often assumed that the dominant species are the most productive ones, the species with a higher probability of being selected in the random sampling process are the more productive (sampling or selection effect). As a result, an initial increase in ecosystem productivity can be expected following an increase in diversity. The impact of increased biodiversity through these two mechanisms on ecosystem functioning is modified by species redundancy and species specific resource-use intensity (Loreau, 2000), often resulting in idiosyncratic relationships between diversity and ecosystem functioning as has been shown for biological control of aphid pests (Tscharntke et al., 2005) and litter decomposition in relation to plant diversity (Ekschmitt et al., 2001). In the few cases where consistent relationships were found, this could sometimes be attributed to hidden treatment effects and not to causal relationships between biodiversity and ecosystem functioning. Huston (1997) and Wardle (1999) put into doubt the legitimacy of calling the sampling effect a biological mechanism and consider this as a hidden treatment effect. Tilman (1999) showed how species richness effects on ecosystem functioning change according to the level of interest; community stability increased with species richness whereas population stability decreased.

Besides these criticisms regarding the universal validity of these experimental studies and the responsible mechanisms (Bengtsson, 1998; Xu et al., 2004), most studies were carried out in artificially created, perennial grassland communities (Schmid et al., 2002) with only one or few trophic levels (Thebault and Loreau, 2006), ignoring the fact that herbivores and predators alter the structure of and the processes taking place at lower food web levels through consumption of organisms (plants, insects, soil fauna) at those levels (Cardinale et al., 2003; Duffy, 2003). For the above-mentioned reasons, these experiments cannot be considered representative for natural ecosystems and even though grassland systems are managed ecosystems for production purposes, they are far from being representative for the major part of agroecosystems either.

Others argued that it is not species richness per se but the higher phenotypic trait variation brought along by increased richness which is responsible for the relationships found between biodiversity and ecosystem functioning (Wardle et al., 1997; Hector et al., 1999; Tilman, 1999; Loreau, 2000; Kahmen et al., 2006). This would explain why there seems to be a greater impact of increased richness on ecosystem functioning in species poor systems with respect to species rich systems. In species poor systems, each newly added species has a high probability of being complementary, whereas in species rich systems newly added species are more likely to bring in redundant characteristics because the function is already fulfilled by other species. The importance of functionally redundant species at short time scales is often denied (Wohl et al., 2004), whereas great importance has been given to this phenomenon at greater time scales, where it is responsible for the so-called 'insurance effect' (inversion of functional redundancy in time following environmental changes or disturbances). At small time scales on the other hand, species complementarity is considered the most important aspect of biodiversity (Walker et al., 1999; Loreau et al., 2001).

The conservation of genetic diversity is hardly ever an issue in natural ecosystems and it seems that in wild populations demography is more important in determining population viability than population genetics (Lande, 1988). The only examples showing the importance of genetic variability for ecosystem resilience are from species-poor ecosystems. Genetic diversity in seagrass (Zostera marina L.) communities was found to support the ecosystems' resistance to disturbance and climate change (Hughes and Stachowicz, 2004; Duffy, 2006; Reusch and Hughes, 2006).

In agroecosystems, the few attempts that have been made so far to define the mechanisms responsible for positive effects of 'diversity' on agroecosystem functioning looked at increased crop production following intercropping, which can be seen as increased species richness at crop level (Connolly et al., 2001). Mechanisms which are possibly responsible for this interaction are related to the lower pest and pathogen incidence found in intercrops and to the higher resource use efficiency of crops with different root systems and leaf morphology (Altieri, 1995). Recently, some studies have shown the importance of genetic diversity among the auxiliary and pest species. Genetically, diverse patches of Oenothera biennis L. attracted more omnivorous and predaceous arthropods (Johnson et al., 2006) and Hawes et al. (2005) demonstrated the importance of genetic diversity of Capsella bursa-pastoris (L.) Medic. for ecosystem functioning (resource acquisition, partitioning and energy distribution in the food web). Analogous to the risks derived from the introduction of new species in natural ecosystems or agroecosystems, for example Lolium spp. that was imported in Australia, care has to be taken with genetic diversification with non-local genes (Gustafson et al., 2004). This indicates that also at gene level, specific genotype characteristics (and phenotypic traits) might be more important than genetic diversity per se. On the other hand, the fact that many weed populations develop herbicide resistance (Powles and Preston, 2006) is a clear proof of the evolutionary capacity of species through genetic diversity and this possibly implies that agroecosystem resilience relies strongly on the genetic variability and adaptability of (some of) its individuals.

To summarise, it can be said that (agro)ecosystem management aimed at increased diversity might be successful in the following situations (examples in Table 2):

(a) Prevention of invasive species, in natural or semi-natural habitat or the control of dominant weed species in agroecosystems.

(b) Increase of (agro)ecosystem resilience and stability by the presence of redundant species which gain importance following agroecosystem changes or disturbance.

(c) Increased (agro)ecosystem functioning (in terms of processes or magnitude of processes) in species-poor (agro)ecosystems at a short time scale.

Therefore, unless the objectives of biodiversity conservation in agroecosystems are related to the above-mentioned situations, it seems unwise to focus on the general increase of biodiversity and assume that this will have a positive impact on the specific agroecosystem processes, their environmental impact or their sustainability. It is likely more successful to concentrate on conservation and management of the biota or habitat whose functional traits influence the agroecosystem processes of interest (Douds and Millner, 1999; Foissner, 1999; Kennedy, 1999). As mentioned before, increased diversity within functional groups might increase the magnitude of the agroecosystem processes. Since agroecosystems are frequently poor in terms of genetic, species and habitat composition, the chances to increase functioning through increasing diversity of the functional groups can be considered high.

5. Fine-tuned definitions of functional biodiversity

From the above it becomes evident that the classical approach towards 'functional biodiversity' should be split up in a two-step approach to determine the functionality of biodiversity in agroecosystems. The first step consists of the definition of the 'agroecosystem functional groups', i.e. clusters of genes, species or ecosystems which contribute to the performance of determinate agroecosystem processes (services). This can be expressed as the determination of the '*bio-functionality*'. Strictly speaking, this approach has nothing to do with diversity. The definition of 'functional groups' can be the endpoint of the study. The second step integrates the importance of having diversity of a certain trait of the elements composing the 'functional group' to fulfil the desired agroecosystem service(s). This can be called the '*functionality of biodiversity*'.

Altieri (1993) defined functional biodiversity as the biotic components that stimulate the ecological processes driving the agroecosystem and that provide the ecosystem services. Strictly speaking, this is the definition of the 'bio-functionality' because it does not take into account the importance of having diversity. A more precise definition would be that functional biodiversity is "*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*".

Agroecosystem services (production and environmental protection) are based on processes carried out by the various functional groups (examples in Table 1). The level of detail at which a process is defined determines if the functional group consists of very different elements (plant and animal species might both be present) or in only one species or even in one specific genetic expression form of a species. This implies that in relation to the desired process, diversity is not always an issue, because the definition of a functional group is based on homogeneity with respect to that process at that level. However, a high genetic, species or habitat diversity within a functional group is likely to have an insurance (on the long term) or buffer (on short time scales) effect. At the same time, a high diversity of elements in the functional group likely affects the magnitude of the agroecosystem process. In the case of species, community or habitat conservation for their intrinsic, aesthetic, cultural or traditional value, measures of diversity can equally be important (e.g. genetic diversity for species adaptation to climate change), but the exact expression forms of the genes are not of interest. These are

forms of ecological functionality for species survival or management functionality for species protection and conservation, which do not interfere with the services the agroecosystem has to provide.

From a review based on older literature (Statzner and Moss, 2004) and a survey of the modern literature regarding relationships between 'biodiversity' and 'ecosystem functioning' (Scopus©, 455 publications in the period 1999–2006, of which 43 papers with also 'agriculture' in title, abstract or key words), it emerges that studies trying to understand the 'functionality of biodiversity' (as defined in this paper) are older [started with Darwin (Tilman and Lehman, 2002)] and are mostly carried out by ecologists, whereas the bio-functionality approach is dominant in agricultural sciences and started with agricultural entomologists (Southwood and Way, 1970; van Emden and Williams, 1974) and soil scientists (Moore and Hunt, 1988) investigating the beneficial effects that specific organisms can have on the self-regulatory capacity of the agroecosystem. More recently, bio-functionality studies have gained importance for the development of bio-indicators for environmental and agroecosystem monitoring (Foissner, 1999; Paoletti, 1999).

In the scientific literature, there seems to be a lack of distinction between the choice of target elements for the management of biodiversity aimed at increased agroecosystem functioning (functional biodiversity) and the use of bio-indicators for monitoring the state and resilience of agroecosystem processes, agroecosystem sustainability and overall biodiversity. In general, bio-indicators are a selection of that part of the total biodiversity which have the best cause–effect relationship with the monitoring objective. The target elements for functional biodiversity conservation in agroecosystems are different from bio-indicators because for the definition of the functional groups all elements related to a determinate agroecosystem process should be taken into consideration, instead of a selection of them. However, functional groups can provide the bio-indicators for monitoring agroecosystem processes.

6. Selection of bio-indicators

Biota or groups of biota (from genetic to community level) can be clustered based on their ecological and life-history traits, and therefore on their interaction with the agroecosystem. This results in two groups of bio-indicators: process-related bio-indicators and health-related bio-indicators, where 'process' and 'health' refer to the agroecosystem (Table 3). Not included in this classification are bio-indicators at landscape level, such as habitat or ecosystem measures. However, in general these are good bio-indicators for the overall biodiversity. The higher the habitat diversity, the more niche possibilities, hence more species can be expected in the agroecosystem.

Process-related bio-indicators are most likely organisms at the base of the food web which interact with the main agroecosystem processes (examples in Table 1). The impact of one individual organism on the processes is determined on a rather small scale, but in compensation there are many individuals present in a rather homogeneous way on the territory. In case the organisms are not mobile, landscape structure and configuration do not play an important role in the life cycle of the individuals but they can affect their population dynamics through gene flow. These organisms are very vulnerable to management and disturbances since they cannot 'escape' from the impact. Their only defence is by recovery from propagules or surviving individuals and therefore disturbance intensity and frequency in relation to recovery velocity determine their chances of survival. Optimisation and diversification of the main processes taking place at a landscape scale increase niche possibilities for organisms higher in the food web and therefore it is expected that high diversity at the lower food web levels results in high overall biodiversity. However, unless this

Table 3
Characteristics, ecological sensitivities, indicator power and examples of 'process-related' and 'health-related' bio-indicators (see text for detailed definition) commonly used for the evaluation of the state and resilience of agroecosystem processes, agroecosystem sustainability and overall biodiversity

	Process-related bio-indicators	Health-related bio-indicators
Characteristics		
Organisms size	Small	Large or medium size
Number of individuals	High to very high	Low
Food web level	Low: producers or consumers	High: consumers
Mobility	Immobile/low/small scale	High/large scale
Niche diversification	Rely on one main habitat	Rely on several different habitats
Impact on agroecosystem processes	Direct determinant	Not or indirect through effect on lower food web level organisms
Ecological sensitivities		
Importance of landscape configuration and diversity	Low	High
Effect of disturbance and management		
Risk of being eliminated	High because of no escape possibility	Low because of escape possibilities
	Low because in great numbers and everywhere	High because few and more vulnerable
Indicator power		
For overall biodiversity at species level	Low, because diversity at higher level co-depends on other factors	High, if their diversity is high because they rely on many other species and habitats
		Low, if their diversity is low because this might be due to direct elimination of the biota and not necessarily to problems at the lower food web level
For state of agroecosystem processes	High	Low
For resilience of agroecosystem processes		
For agroecosystem sustainability	High	Low
	High, as long as stability of individual agroecosystem processes is concerned. It does not indicate anything about food web complexity	High, if stability and health of indicator population is measured
Examples	Soil bacteria	Ground-dwelling carabids
	Arbuscular mycorrhyzal fungi	Birds
	Earthworms	Mice
	Vascular plants	Spiders

approach takes into account the effects of disturbances, management practices and landscape configuration directly affecting the diversity at higher food web levels, such as hunting, pesticide use or habitat destruction, it is unlikely that process-related bio-indicators can be good indicators for the assessment of biodiversity at higher food web levels and their use can better be restricted to the assessment of the specific agroecosystem processes they are related to. Diversity measures of process-related indicators are likely good predictors of how well agroecosystem functioning is insured against environmental change and disturbance, and thus of the resilience of agroecosystem processes.

The health-related bio-indicator group consists of biota higher up in the food web. These organisms are often bigger in size and are mobile and therefore landscape structure and configuration start to play an important role in the determination of their presence, because it is through these elements that they perceive the position of the main food sources, overwintering sites and other resources that they need to conclude their life-cycle successfully (Farina and Belgrano, 2004). The organisms at higher levels of the food web do not directly affect main agroecosystem processes but depend on them and/or on the organisms determining them, thus they can indirectly affect them through regulation of the organisms at the lower food web level (herbivory, predation). Mostly, higher food web level organisms are not strictly related to the productive sub-system but they use it for part of their life cycle or to satisfy some of their basic needs and migrate between the cultivated and semi-natural elements. Examples from literature are farmland birds depending on overwintering sites with a specific vegetation structure (Marshall, 2002) or on seeds produced by arable weeds such as chickweed (*Stellaria media* L.) (Storkey, 2006), or wood mice migrating from the cropped area to the margins and hedges after harvest (Tattersall et al., 2001). Since organisms at higher

food web levels have more possibilities to escape unfavourable conditions (e.g. mice hiding in the field margin during harvest or tillage operations) and are often more flexible in adapting and resisting to them (pesticides do not usually kill them but rather accumulate in their body mass, affecting, e.g. their reproduction rate), their simple presence cannot directly be related to agroecosystem health and sustainability.

These mobile organisms evaluate their surroundings based on the spatial configurations in relation to the specific resource they need at a certain moment (eco-fields) in order to determine whether to stay or not (Farina and Belgrano, 2006). However, their presence does not automatically mean that local conditions are suitable and that the population is stable and healthy. It is possible that there are configurations which transmit false signs to an organism and therefore they will be present but they may not be able to satisfy their needs for that function. In that case, a local population can be sustained in an unsuitable habitat (sink population) by immigration from surrounding areas (source population) and not by a positive birth:mortality rate. It is estimated that this happens more often than so far has been thought (Pulliam, 2000). This means that mobile organisms from the higher food web levels can be used as indicators for certain landscape configurations and presence of certain habitats but care should be taken to interpretations linked to agroecosystem sustainability without verifying measures related to the stability and health of the population of the indicator organism. The capacity of these bio-indicators to express the overall biodiversity level is not unequivocal: if there is a high diversity of health-related bio-indicators, it means that all food sources and environmental conditions, including disturbance, are favourable and therefore it likely indicates a high diversity at the lower food web levels. If, on the other hand, their diversity is low, this might be due to the absence of the necessary lower food web support, but also to direct elimination

(e.g. hunting) or an unfavourable landscape configuration. In that case, direct study of the lower food web levels would be recommendable. Species diversity of health-related bio-indicators is likely not related to a high insurance of agroecosystem functioning against change and disturbance, for two reasons. Firstly, agroecosystem functioning is affected by process-related bio-indicators and secondly, at high food web levels species numbers are naturally low and are strongly dependent on the carrying capacity and size of the (agro)ecosystem.

The above-mentioned considerations constitute a guideline for the choice of the best type of bio-indicator for the various monitoring objectives. This has been summarised in Table 3. It is important to realise that process-related indicators for the monitoring of agroecosystem functioning can be managed in order to influence the processes according to managers' objectives. Hence they are at the same time bio-indicators and functional biota. This is not so for health-related bio-indicators for overall agroecosystem sustainability or overall biodiversity. The latter do not affect agroecosystem processes directly, but they can regulate them indirectly through their impact on process-related bio-indicators. As such, they reflect if the processes are sufficiently performed to support higher food web levels, if disturbances by management allow for recovery, or if landscape structure and complexity are sufficiently adapted to their ecophysiological needs to sustain a healthy population or community. By simple management of these organisms, agroecosystem sustainability and biodiversity will not automatically increase. To reach this goal, biodiversity management should be directed at increased diversity within or between the functional groups which regulate the main agroecosystem processes, and thus of species belonging to process-related bio-indicators or health-related indicators affecting the previous group through herbivory or predation.

Based on this overview of 'biodiversity' and 'functionality', various usages of biodiversity in agroecosystems can be identified: (a) conservation of species, community, habitat or overall biodiversity for intrinsic, aesthetic, traditional and cultural values; (b) biodiversity for improved agroecosystem functioning, based on definition of agroecosystem functional groups, and (c) bio-indicators for environmental monitoring of the state and resilience of agroecosystem processes, agroecosystem sustainability or overall biodiversity.

6.1. Measuring biodiversity

Most studies aiming at biodiversity conservation or monitoring describe biodiversity in terms of simple compositional parameters such as numbers of species, groups of species or habitats, and less frequently more complex compositional measures (Magurran, 2004) of species equitability, such as evenness, are taken into account (Buchs, 2003). Indicators of structure and function (Noss, 1990) are even more rarely associated to measurement of biodiversity, although they can give important information about the state of biodiversity present, and are more closely related to (agro)ecosystem functioning.

The meaning attributed to richness measures is 'the more, the better' for semi-natural ecosystems and 'the more, the more sustainable' for agroecosystems. However, if there are no mechanistic relationships established between the 'numbers' and the 'objective', or if diversity is not an issue for the fulfilment of the function (case of bio-functionality), expression of biodiversity in numbers has no sense. Therefore numbers should not be confounded with the study of biodiversity (Schwartz et al., 2000).

It was already stated by Noss (1990) that there will never be a clear and simple definition of biodiversity. Instead, he developed a conceptual framework within which the major components of biodiversity are characterised at various levels of organisation. The three aspects of biodiversity are composition (identity and variety of the elements), structure (physical organisation or patterns) and function (ecological and evolutionary processes), defined earlier by Franklin et al. [1981; (Noss, 1990)] and they are nested into a hierarchical framework from genetic to landscape level. To our knowledge this is the only framework which provides guidelines for the selection of measures of biodiversity [Table 1, (Noss, 1990)]. However, it was mainly created to measure biodiversity in itself, and it is not linked to the various ways in which research and policy-making use biodiversity in agroecosystems. This means there are no guidelines for the selection of effective target elements for functional biodiversity in agroecosystems. Noss' framework is as such directly applicable to species, habitat and overall biodiversity conservation for their intrinsic, aesthetic, cultural and traditional values. In order to select adequate target elements of biodiversity for the other uses of biodiversity, the resulting conclusions regarding biodiversity and functionality (based on presented literature and an analysis of this literature following an agroecosystem approach) were summarised in a methodological framework (Tables 4a–c). Specific and adequate biodiversity measures for each target element can be selected from Noss' framework for biodiversity measures [Table 1, (Noss, 1990)].

6.2. The methodological framework

The methodological framework tries to integrate all major considerations that have resulted from the literature review and that were used to answer the three questions posed in the introduction, in order to help policy makers and scientists in defining objectives, target elements (functional groups and bio-indicators), and measures for biodiversity when involving agricultural biodiversity in their projects or policies.

Table 4a
Selection of target elements and diversity measures for species, habitat and overall biodiversity conservation for intrinsic, aesthetic, cultural and traditional values

Usages of biodiversity in agroecosystems	Target element selection	Biodiversity measures [see Noss (1990, Table 1) for detailed examples]
1. I am interested in studying or promoting the overall biodiversity at species and habitat level, regardless of its functions 2. I am interested in studying or promoting endangered species or habitats (e.g. IUCN red list species)	• Habitat and landscape diversification in relation to cultivated, auxiliary, pest, wild and neutral species • Varieties or species in risk of extinction or strongly decreasing • Habitat in degradation. • Likely health-related elements • Process-related elements in case of cultivated species	• Compositional, structural and functional measures of landscape configuration and habitat diversity in relation to each of the five categories of species • Measures of composition, structure and function at population and habitat/ecosystem level to indicate population or habitat health and stability

These are guidelines, examples are not exhaustive and exceptions cannot be excluded.

Table 4b
Selection of target elements and diversity measures for provision of agroecosystem services for production and environmental protection

Usages of biodiversity in agroecosystems	Target element selection	Biodiversity measures [see Noss (1990, Table 1) for detailed examples]

1. I am interested in the determination and description of agroecosystem functional groups (following the bio-functionality approach)	• Process-related elements
	  • For productive services, elements from the productive sub-system, hence cultivated, auxiliary or pest elements
	  • For environmental protection services elements from both sub-systems and mostly auxiliary and neutral species
	• Health-related elements
	  • For indirect control of service through effect on process-related indicators
	• Mostly mobile organisms, relying on both sub-systems and they can be bred, auxiliary, pest or neutral species
		• Measures of community or ecosystem structure and function to determine how well various agroecosystem processes are functioning? and thus which processes can be improved by biodiversity management, or else which functional groups are effective and should be protected to guarantee the processes they provide
		• Measures of structure and function at community or ecosystem level, such as herbivory and predation, to determine if these elements are important in a given agroecosystem
		• Measures of composition at genetic, species or community level to determine if increased diversity at any of these levels can increase magnitude of the process

2. I am interested in determining the functionality of biodiversity within functional groups in relation to • Magnitude of processes • Resilience of processes • Buffer capacity of processes	• All elements composing the functional group (see above). This can only be determined if the functional groups have been defined	• Measures of composition at genetic, species or community level to determine if increased diversity at any of these levels can increase process resilience and provide insurance against change or disturbance

These are guidelines, examples are not exhaustive and exceptions cannot be excluded.

In any given case the relevant and specific agroecosystem objectives have to be defined following a characterisation of the specific agroecosystem in terms of habitat complexity, disturbance intensity and frequency, and food web complexity (step 1). Based on this information, specific organisms, groups of organisms or habitats (target elements) can be selected for detailed measuring or monitoring (step 2) and at last the appropriate biodiversity measures can be chosen at multiple scales (step 3). The temporal and spatial scales of the measures should be carefully chosen based on knowledge from (landscape) ecological theories related to the specific entities. This is important since biodiversity at a certain level or scale is expected to be interwoven with biodiversity at higher scales as was shown by Gurr et al. (2003), who called this effect 'multi-function agricultural biodiversity'. In that case, the enhancement of vegetation diversity increased natural pest control at crop level and was hypothesised to create a beneficial 'domino-effect' that could potentially reach the landscape scale.

The framework consists of three tables corresponding to the three main objectives for biodiversity in agroecosystems (Table 4a conservation; Table 4b functional biodiversity; Table 4c bio-indicators), and can be synthesized as following:

- Step 1 (Tables 4a–c, column 1): definition of more detailed usage of or objectives for agro-biodiversity in research or policy making.
- Step 2 (Tables 4a–c, column 2): definition of the target elements (typology of the functional groups or bio-indicators): sub-systems they rely on (productive or semi-natural), the type of bio-indicator (process-related or health-related) most adapted to the monitoring objective, and the categories of biota/habitat (cultivated, auxiliary, pest, wild, or neutral) they represent.
- Step 3 (Tables 4a–c, column 3): determination of the best biodiversity measures derived from the hierarchical framework of Noss (1990; Table 1).

Except in the case of species, community or habitat conservation for intrinsic, aesthetic, cultural or traditional values, the question should not be 'which are the organisms to be protected' but rather 'which are the main services that the agroecosystem should provide'. One should remember that the conservation of any form of 'biodiversity' has little or no sense if it is not preceded or accompanied by the safeguarding of the functional integrity of the ecosystem it is part of (Woodwell, 2002). Facets of functional integrity are well defined within the concept of sustainable agriculture and aspects of this concept can be applied to any type of agroecosystem. Sustainable agroecosystems are both productive, natural resource conserving, economically viable, culturally sensitive and socially just (Altieri, 1995) and can be developed and managed applying agroecological concepts. Agroecology, instead of defining alternative agricultural practices, offers a methodology for the development of agroecosystems managed in an ecosystem context, analysing nutrient, energy and matter flows, and considering the biotic components as the initiators of the system's soil fertility, productivity and crop protection. Self-regulating agroecosystems rely on a high level of interactions between biotic and abiotic components (Altieri and Nicholls, 1999). Agroecology can therefore be considered as a methodology that returns to the biota and habitat the functional values they have often lost in the domestication and industrialisation processes. During these processes, domesticated species have lost the ability to survive in the wild in competition with many other species, because protection by human intervention has made competition less important. With this increasing loss of functionality of plant and animal species in agroecosystems, systems were not managed any longer with the aim to conserve these organisms, and therefore they disappeared and

Table 4c
Selection of target elements and diversity measures for bio-indicators aimed at environmental monitoring

Usages of biodiversity in agroecosystems	Target element selection	Biodiversity measures [see Noss (1990, Table 1) for detailed examples]
1. I am interested in assessment of the state of specific agroecosystem processes (e.g. nutrient or water cycling) or services (e.g. pest control)	• Process-related indicators for production • Elements from the productive sub-system, hence the cultivated, auxiliary or pest elements • Process-related indicators for environmental protection • Elements from the semi-natural and productive sub-systems, mostly auxiliary and neutral species	• Measures of community or ecosystem composition, structure and function. Determination of life-trait functional groups are important since they indicate the effect of management on the agroecosystem
2. I am interested in assessment of the resilience of specific agroecosystem processes (e.g. nutrient or water cycling) or services (e.g. pest control)	• Same as above	• Measures of composition at genetic, population and community level, especially measures able to indicate redundancy level of species and communities, e.g. richness and evenness of elements in the life-trait functional groups
3. I am interested in assessment of the overall agroecosystem sustainability (agroecosystem health)	• Process-related indicators • Elements from the productive sub-system, hence cultivated, pest or auxiliary elements affected by main agroecosystem processes • Health-related indicators for environmental protection • Elements from the semi-natural sub-system relying for part of their life-cycle on the productive sub-system, hence neutral or auxiliary elements	• Measures of function at species and community level, especially if related to indicator health and stability • Measures of function at species, community and landscape level, especially measures indicating health and stability of the indicator population
4. I am interested in assessing the state of the overall agroecosystem biodiversity	• Health-related indicators, most likely dependent on but not limited to the productive sub-system and therefore auxiliary or neutral elements • Habitat and landscape characteristics in agroecosystems with low disturbance frequencies and intensities	• Measures of composition and structure at population and/or community level of the highest level predators in the system • Measures of composition and structure at landscape level related to habitat configuration and diversity

These are guidelines, examples are not exhaustive and exceptions cannot be excluded.

agro-biodiversity started to decrease. Analogous processes of loss of functionality and consequent degradation have taken place regarding landscape elements and habitats, e.g. hedgerows degradation following the decreased need for timber production (C. Thenail, personal communication) or terrace degradation following the decreased need for optimisation of the hydraulic system in marginal areas taken out of production (Rizzo et al., 2007). For this precise reason, the agroecosystem approach is fundamental for successful definition of functional biodiversity in agroecosystems and the definition of the type of bio-indicator (process-related or health-related) most adapted to the specific monitoring objectives. Elements of the functional groups and bio-indicators should be sought in each of the five categories of elements composing the agroecosystem (cultivated, auxiliary, pest, wild or neutral) because this allows to describe the structure of the agroecosystem and link the bio-indicators and functional groups to management and disturbance. For example, if the objective of biodiversity conservation is the amelioration of nitrogen cycling in a crop rotation, one should look for process-related organisms. From the cultivated species the leguminous species are important, from the auxiliary species the soil microfauna responsible for decomposition is important, but from the pest, wild and neutral species no important contribution can be expected. This indicates that management of functional biodiversity should be directed at both groups of species, and not only at increasing the diversity of the soil microfauna to increase the magnitude of the nitrogen cycling process. Since both groups are present in the productive sub-system, it also points out that one should improve management practices related to crop rotation and soil cultivation. Another example is species or habitat conservation. This can be applied to all five groups according to the stakeholders interests: an agronomist may want to conserve a local rice variety, whereas a conservation biologist/ecologist may want to conserve a wild bird. Column 2 in Tables 4a–c summarises some of the considerations that can be taken into account for the definition of bio-indicators and functional groups for each of the objectives (usages) defined in the first column.

If objectives of policy making or research are related to objective b, agroecosystem functional groups for specific production or environmental protection services have to be determined. The organisms of which the functional group is composed are the bio-indicators for that specific process, and they are mainly present in the group of process-related bio-indicators. If the process affects the production service, the bio-indicators in the productive sub-system are most significant (auxiliary, pest and cultivated species). If on the other hand the bio-indicator determines a process for the environmental protection services, both organisms from the productive and semi-natural sub-system (mostly auxiliary and neutral species) can be present. Health-related indicators can be important through regulation of process-related organisms (herbivory, predation, etc.).

To increase overall biodiversity (objective a), habitat diversification and connection of similar habitat patches should be pursued. Increased niche possibilities increase species richness and connectivity increases genetic variability of populations. If bio-indicators for overall biodiversity have to be chosen (objective c), measures at species or community level from all five categories (cultivated, auxiliary, pest, wild and neutral) should be selected. Also habitat diversity and connectivity for auxiliary, pest, wild and neutral organisms are important.

Once the functional groups or bio-indicators have been defined, the right measures of biodiversity can ultimately be derived from Tables 4a–c (column 3) [Table 1, (Noss, 1990)]. In general, it can be said that questions related to the functionality of diversity necessitate measures of composition (density, abundance, biomass) in relation to the main function, whereas questions related to bio-functionality are more easily answered by measures of structure and function. If maximisation of the semi-natural biodiversity or species or habitat conservation is the main aim, all three types of measures should be combined in order to evaluate the stability of these organisms, populations, communities or habitat at larger temporal and spatial scales.

7. Discussion

In our opinion, one of the most important aspects emerging from the reflections made in this paper is the importance of an interdisciplinary, agroecosystem approach involving ecological theories about population and community dynamics and structure, food web dynamics, biogeography, and landscape ecological principles related to spatial and temporal heterogeneity of patterns and processes. The integration of this knowledge helped to develop and distinguish valid approaches for biodiversity studies based on the objectives for biodiversity conservation.

Unlike any other study in which the aim directly indicates the study object, when talking about biodiversity the aim is only a starting point in the definition of the entity that can best be measured, and of the spatial and temporal scales at which the study should be applied. The presumed need to maximise biodiversity to increase ecosystem functioning is contradicted by the fact that often few dominant species already guarantee ecosystem functioning. Other species seem redundant and gain importance only in the long-term as an insurance for ecosystem functioning in a changing environment, or after a change in management. On the other hand, agroecosystems are often characterised by a low diversity at all levels, hence increased diversity is likely to add complementary elements and increase agroecosystem functioning or sustainability.

The study of biodiversity in relation to agroecosystem functioning is only useful when it is linked to the role that clusters of functionally similar elements and/or their state of diversity play in ecosystem functioning (Loreau, 2000; Bengtsson, 1998), when the spatial (Gurr et al., 2003; Yamamura, 2006) and temporal (Davidson and Grieve, 2006) scales of the interactions are clearly defined and taken into account (Symstad et al., 2003) and when aspects of ecosystem resilience and stability and/or of the processes (fluxes of material, energy and nutrients) are taken into account (Srivastava and Vellend, 2005). Whether 'biodiversity' should be studied at genetic, species or ecosystem level depends mainly on the principal objectives of the agroecosystem, on its characteristics (disturbance level, food web complexity and habitat configuration) and on the general richness of the elements. Hence, the attention to biodiversity should be shifted from 'biodiversity' in general to the main objectives or functions attributed to or expected from the 'biodiversity' in the agroecosystem in question, as defined in Tables 4a–c. When the aim is species conservation for their intrinsic, aesthetic, cultural or traditional values, it can be called practicing 'Agriculture for Biodiversity' (A for B) [from Duelli (2006), p. 13]. When on the other hand, the policy or research aims are related to the improvement of the agroecosystem functioning, or in other words to increase the agroecosystem services provided by 'biodiversity', it can be called improving 'Biodiversity for Agriculture' (B for A) [from Duelli (2006), p. 13].

The authors do not agree with the call put forward by others (Jackson et al., 2007) that there is a need for more research on 'agrobiodiversity and its ecosystem services' in general. The determination of clear objectives for 'biodiversity' conservation and management, as proposed by the methodological framework and the concurrent definition of the most adapted biodiversity measures, would resolve great part of the unsuccessful attempts to preserve 'biodiversity' and exploit 'agrobiodiversity' in a functional way. However, this paper highlights the need to complement the mechanistic studies performed in grassland, forest and marine

ecosystems with studies performed in arable agroecosystems, and to integrate studies on other agroecosystem processes than primary production only. Since diversity at all levels is generally low in arable systems, it can be hypothesised that increase in species and genetic diversity of the cultivated, auxiliary or pest species will interact substantially to increase the magnitude of agroecosystem processes linked to production and environmental protection.

Some studies have shown how different types of agroecosystem management can actually influence the functional biodiversity and through that, reduce agrochemical inputs. A study in a low-input (LIS) and a conventional (CS) sugarbeet crop rotation system in Pisa, Italy, showed a more severe aphid infestation in CS than in LIS due to the fact that the weed species composition in the CS was dominated by wild beet (*Beta vulgaris* L.), so that aphids colonised sugarbeet from wild beet (Ragaglini et al., 2005). Within the CS there was a less severe aphid infestation on sugarbeet in areas with a higher weed density. This was likely due to the lower sugarbeet sap quality following the higher competition with the weeds. A study carried out in the UK exemplified that field margins managed with the aim to 'keep them clean from weeds' by regular herbicide applications resulted in exactly the opposite effect: they had a lower species richness and were dominated by weeds (Moonen and Marshall, 2001).

In agroecosystems, the recurring disturbance is of human nature and is called management. Therefore, the disturbance inflicted intentionally on the system, in other words the agroecosystem management, should be designed in such a way that the system can develop a mechanism that allows it to recover from the disturbances and perform the main agroecosystem processes autonomously. If management is aimed at supporting biodiversity for the fulfilment of the desired agroecosystem functions, both bio-functionality and functionality of biodiversity can contribute; bio-functionality because it results in species adapted to the chosen objectives, and diversity because it can increase the magnitude of desired agroecosystem processes, it provides an insurance to change and disturbance, and prevents the system from being dominated by negative forms of bio-functionality such as weeds and pests.

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