BIODIVERSITY AND THE FUNCTIONING OF SELECTED TERRESTRIAL ECOSYSTEMS: AGRICULTURAL SYSTEMS

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Summary

Agricultural ecosystems are a major component of the biosphere, forming an estimated 38% of the land surface of the earth and housing substantial biodiversity. Two components of biodiversity can be identified in agroecosystems, the planned component including those elements actively managed by humans, and the unplanned component including the wild or unmanaged species that inhabit these systems. The diversity of both of these components has an important role in the functioning and sustainability of agricultural ecosystems.

Planned diversity at genetic, species, habitat and landscape levels can have an impact on agroecosystem functioning. Modern agriculture relies on lower diversity of species, fewer varieties within species and fewer genotypes within varieties, compared with traditional agriculture. This reduced diversity leaves agricultural production vulnerable to those pests and diseases that are able to exploit the common varieties. The most common technological solution to this problem is the breeding or engineering of resistance to pest and disease, but evidence suggests that increased diversity of genotypes, crop types and landscapes can help mitigate pest and disease problems while, increasing the persistence of pest and disease resistance.

Increasing planned genetic, species, habitat and landscape diversity in agroecosystems also tends to increase the diversity of unmanaged species inhabiting those ecosystems. This can be beneficial for the sustainability of agricultural production because unplanned diversity delivers production-supporting ecosystem services, such as pollination, natural pest control and the maintenance of soil health. Importantly, these services may also be threatened by other elements of agricultural intensification that impact on unplanned biodiversity, such as pesticide use.

A key challenge of ecological science is to improve our understanding of the link between agricultural management and biodiversity, and the role of biodiversity in the mitigation of production constraints. This will facilitate the development of sustainable management strategies which minimise impact on biodiversity, while maintaining (or increasing) production.

1. Introduction—biodiversity in agricultural ecosystems

Agricultural ecosystems, comprising arable land and permanent pasture, are estimated to cover 38% of the land surface of the earth. They are, therefore, a major component of the biosphere and house a large portion of the earth's biodiversity. However, the study of the functioning of agroecosystems, and managed ecosystems more generally, has conventionally formed a distinct discipline from the study of unmanaged ecosystems. Ecologists have tended towards pristine unmanaged ecosystems and those ecologists working in managed systems have focussed, largely, on the interactions among the elements such as pests and biological control agents, under their direct control. The processes of maintenance of biodiversity and the role of biodiversity in ecosystem functioning are similar in both managed and unmanaged ecosystems; the major distinction being that in agroecosystems and other managed systems, a certain portion of biodiversity, the productive animals and plants and the organisms we introduce to support production, is directly controlled by management intervention.

Management of agricultural ecosystems has increasingly involved the removal of problematic species and the simplification of the intra- and inter-specific diversity of productive species. Consequently, the replacement of unmanaged ecosystems with simplified agro-ecosystems is one of the principal causes of declining biodiversity worldwide. This does not mean that agricultural ecosystems can be written off as biological wastelands and their functioning disregarded. Efforts to ease the integration of agricultural and wild ecosystems to reduce the impact of agricultural and landscape management on biodiversity are a prominent feature in the developed world. Although these systems are managed with a particular ecosystem function in mind, the production of food, fibre, and other materials, these are not the only functions that are derived from agro-ecosystems. Like other ecosystems they play a role in the global dynamics of carbon, nitrogen and water and in that sense these functions are as validly studied in agricultural as any other ecosystem type. It is also becoming clear that intensification of agriculture, which reduces the biodiversity living within agricultural systems, may hinder the sustainability of agriculture, and that efforts to increase the biodiversity in our agricultural systems may have benefits for long-term production, in addition to facilitating agricultural and environmental sustainability. Moreover, in regions such as Europe, agricultural systems are increasingly being seen as providers of biodiversity, recreation, and aesthetic value in addition to material products, and fiscal policy reflects this change.

Vandermeer and Perfecto (1995) defined two basic types of biodiversity linked to agricultural systems and their functioning. The first, planned diversity, describes the biodiversity purposely introduced or managed to have a direct effect on agroecosystem function. Unplanned, or associated biodiversity describes the flora and fauna (soil microorganisms, pollinators, insect herbivores, plant pathogens, natural enemies, etc.) that exist in, or colonise the agroecosystem. An important feature of this framework is the recognition that planned diversity influences and interacts with associated diversity to determine overall functioning of the agroecosystem. These interactions between planned and associated diversity (which in effect represent the direct and indirect effects of planned diversity on agroecosystem functioning) are represented in Figure 1. Below we build on this framework, describing some of the key elements of planned and associated diversity and identifying some of their key roles and interactions.

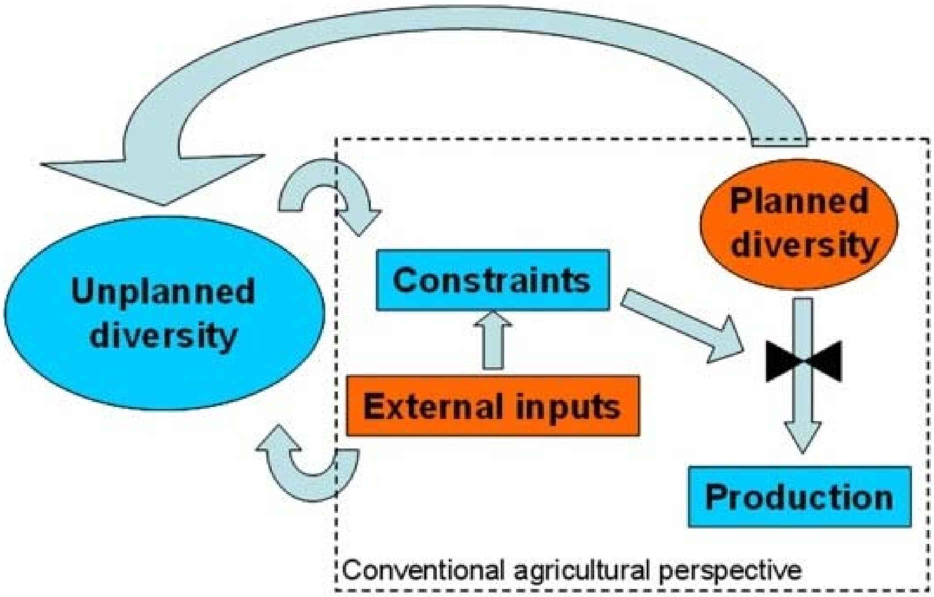

Figure 1. A framework of agroecosystem interactions. The central function of agroecosystem from an anthropocentric perspective is the derivation of agricultural products from a planned set of species in the ecosystem. It is long recognised that numerous constraints determine the efficiency of production, including pests, pathogens, nutrient availability and water availability. Amelioration of constraints has traditionally involved input of externally derived or produced materials and by breeding or manipulating the characteristics of planned diversity (denoted by the dashed box). A broader ecological perspective identifies that planned agroecosystem diversity and the use of external inputs also impacts unplanned diversity in the agroecosystem, which itself may modify the expression of production constraints. In pest resurgence, for example, the use of insecticides to directly manage specific pest constraints fails as unintended impact on unplanned diversity (the natural enemies of the pest) also has a positive feedback effect on the population of the pest, negating the initial negative direct impact of the insecticide.

2. Planned diversity and the functioning of agricultural systems

As with most classifications of biodiversity, we can define planned agrobiodiversity across a continuum from genetic/intraspecific diversity (i.e. within-crop plant), through species diversity (both within field and between fields) to habitat or landscape diversity. Diversity can be actively manipulated (i.e. planned) at any one of these levels through farm management practices. Here we examine diversity at these different levels in more detail, with particular emphasis on how changes in planned diversity can effect functioning of agroecosystems, frequently via effects on associated biodiversity. For this we draw heavily on examples relating to pest and disease control functioning as these provide some of the clearest illustrations of the consequences of biodiversity change. However, the principles and mechanisms we touch on apply more generally to other aspects of ecosystem function (see section on ‘unplanned diversity’).

2.1. Intraspecific diversity

The most obvious and direct element of planned agrobiodiversity is the crop plant. Breeding and selection for desirable agronomic traits has been at the centre of improving crop varieties since farming began. However, it is over the last 20 to 30 years that plant breeders have made greatest progress in producing higher yielding varieties of crops. As a result, for many crops we now rely heavily on a few ‘modern’ varieties that tend to be very uniform, containing less genetic diversity than traditional farmers’ varieties. Moreover, the way the varieties are deployed/adopted means that traditional varieties tend to be replaced in the main production areas. For example, 75% of an area that once accommodated up to 30 000 rice varieties in India is now taken up by only 10 varieties. However, more than 16 000 varieties are still cultivated in the more marginalised areas of India; traditional cultivars adapted to particular microniches are often one of the few resources available to resource-poor farmers to maintain or increase production.

The adoption of monocultures in mainstream agriculture has reduced the numbers of crop species, varieties within species, and genetic differences within varieties. The risk this creates is that if a pest or disease is able to exploit the one dominant variety, then it has almost unlimited potential to spread throughout the field and landscape. The conventional approach to deal with this loss of diversity is to breed resistance traits back into the crop and to compensate for loss of resistance with applications of pesticides (i.e. substitute ecosystem services with external inputs).

However, in a recent study by Zhu et al. (2000) in Yunnan Province in China, rice farmers were able to control a key fungal disease (rice blast) through the use of variety mixtures, interplanting one row of a susceptible glutinous rice variety to every four or six rows of a more resistant commercial variety. This simple increase in diversity led to a substantial reduction in prevalence of rice blast and an increase in yield of the susceptible variety. The varietal mixture also produced more tonnes of rice/ha than the respective monocultures. The mechanism appears to be a combination of the disease resistant variety acting as a physical barrier preventing spread of fungal spores between the resistant variety, coupled with a complex interaction involving induced resistance and multiple pathogen genotypes that prevents the dominance of a single virulent strain of the pathogen. In other systems, there is evidence that mixtures can also buffer against unpredictable abiotic variables, leading to increased stability of yield over different environments relative to monocultures (see Table 1).

Cropping system	**Monoculture (mean of single crops)**	**Polyculture**
Cassava/bean	33.04	27.54
Cassava/maize	28.76	18.09
Cassava/sweet potato	23.87	13.42
Cassava/maize/sweet potato	31.05	21.44
Cassava/maize/bean	25.04	14.95

Table 1. Coefficient of variability of yields registered in different cropping systems during three years in Costa Rica (modified from Francis 1986).

For insects there is less research on effects of varietal mixtures but there are clear examples showing that plant resistance traits and plant architecture can influence density and dispersion of herbivores and searching by enemies. Hairy leaves for example, may increase the fall-off rate of a pest species thus increasing encounters with ground-zone predators. At the between plant level, spatial dimensions are critical in understanding many aspects of plant-pest-enemy interactions. Polycultures (i.e. mixed plant species systems with increased plant diversity) can reduce pest populations by increasing emigration losses and by increasing searching time before location of a suitable host, thus increasing the pest's vulnerability to predation. Thus, habitat modifications, through alterations in pest dispersion, can influence the foraging movement of predators.

This, depending on the circumstances, can interfere with or enhance the control of pest populations. It is possible, therefore, that similar phenomena could apply for alterations in crop diversity through the use of variety mixtures, with implications for pest evolution as well as pest dynamics. This evolutionary dimension has been considered by Wilhoit (1992) using a stochastic, spatially structured model of two aphid genotypes and a predator to investigate the effects of a variety mixture on durability of host plant resistance. The model predicted the rate at which a virulent aphid genotype (one which could overcome the plant resistance) replaced an avirulent genotype (one affected by plant resistance) in a variety mixture with different proportions of resistant and susceptible plants, under various assumptions of aphid and predator movement, and with different population growth rates, predator efficiencies, initial proportion of the virulent genotype, and genetic transmission of virulence.

The results showed that depending on the initial conditions, effective plant resistance could break down in less than five years, or last for several tens of years. The challenge, in practical terms, is to determine which particular conditions apply where and when; unfortunately we have very little understanding of key processes, such as spatial dynamics of herbivores and natural enemies, in most cropping systems.

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Bibliography

Altieri M.A. (1994). *Biodiversity and pest management in agroecosystems*. Haworth Press, New York, 185pp. [Considers the biological control of insect pests, focussing on the interactions among system components and why these are critical to understanding management options]

Andow D.A. (1991). Vegetational diversity and arthropod population response. *Annual Review of Entomology* 36:561-586. [A review of evidence linking plant diversity to arthropod populations in agroecosystems]

Bardgett R.D. (2002). Causes and consequences of biological diversity in soil. *Zoology* 105:367-374. [Discussion of the factors controlling biodiversity soils and its functional significance]

FAOSTAT (2004). landuse database last updated 2004, http://apps.fao.org/faostat/. [a database of global agricultural statistics]

Finnamore B., Neary M. (1978). Blueberry pollinators of Nova Scotia with a check list of the blueberry pollinators of eastern Canada and northeastern United States. *Annals of the Society for Entomology Quebec* 23:161-181. [This study shows how diverse wild pollinator guilds can be]

Francis C.A. (ed.) (1986). *Multiple cropping systems*. MacMillan, New York, 383pp. [Provides a review of multipcropping from various production systems]

Kareiva P.M. (1987). The spatial dimensions of pest-enemy interactions. In: Mackauer M, Ehler LE, Roland J (eds). *Critical Issues in Biological Control*. Intercept, Andover, Hants. [This chapter reviews some empirical and theoretical studies to highlight the importance of including a spatial dimension in the analysis of pest-enemy interactions].

Klein A.M., Steffan-Dewenter I., Buchori D., Tscharntke T. (2003). Pollination of *Coffea canephora* in relation to local and regional agroforestry management. *Journal of Applied Ecology* 40: 837-845. [This study shows how a species rich set of pollinators is required for good pollination efficiency and high yield in coffee]

Kremen C., Williams N.M., Thorp R.W. (2002). Crop pollination from native bees at risk from agricultural intensification. Proceedings of the National Academy of Sciences of The United States of America 99:16812-16816. [This study shows that loss of natural pollinators due to intensification of agriculture can result in insufficient pollination]

Matson P.A., Parton W.J., Power A.G., Swift M.J. (1997). Agricultural intensification and ecosystem properties. Science 277:504-509. [while recognising the benefits of agricultural intensification, this review highlights the potential damaging environmental consequences of some practices]

Menalled F.D., Marino P.C., Gage SH, Landis D.A. (1999). Does agricultural landscape structure affect parasitism and parasitoid diversity? Ecological Applications 9:634-641. [A study showing how variable influences of landscape structure on natural pest control can be]

Riechert S.E., Lawrence K. (1997). Test for predation effects of single versus multiple species of generalist predators: spiders and their insect prey. *Entomologia Experimentalis Et Applicata* 84:147-155. [An experimental report which highlights the benefits of spider species richness for control of herbivorous species]

Root R.B. (1973). Organisation of a plant-arthropod association in simple and diverse habitats: The fauna of collards (*Brassica oleracea*). *Ecological Monographs* 43: 95-124. [The introduction of key hypotheses linking plant diversity to hervivore population size]

Settle W.H., Ariawan H., Astruti E.T., Cahyana W., Hakim A.L., Hindayana D., Lestari A.S. and Sartanto P. (1996). Managing tropical pests through conservation of generalist natural enemies and alternative prey. *Ecology* 77:1975-1988. [a seminal paper highlighting the role of natural enemies in controlling rice pests]

Vandermeer J., Perfecto I (1995). *Breakfast of biodiversity: the truth about rainforest destruction.* Food First Books, Oakland. [This book explores a range of biodiversity issues as they relate to food production and highlights that malnutrition, food production and food security are not specifically scientific or technical problems and challenges, but also political and social ones]

Wilby A., Thomas M.B. (2002). Natural enemy diversity and natural pest control: patterns of pest emergence with agricultural intensification. *Ecology Letters* 5:353-360. [This paper shows that the significance of intensification-induced decline in natural enemy diversity may vary among pest types]

Wilhoit L.R. (1992). Evolution of herbivore virulence to plant resistance: Influence of variety mixtures. In: Fritz RS, Simms EL (eds). Plant Resistance to Herbivores and Pathogens - Ecology, Evolution and Genetics. The University of Chicago Press, Chicago and London. [A theoretical study highlighting the influence of spatial heterogeneity on the potential for insect herbivores to overcome host plant resistance]

Winterer J., Klepetka B., Banks J., Kareiva P. (1994). Strategies for minimizing the vulnerability of rice to pest epidemics. In Teng PS, Heong KL, Moody K (eds). *Rice Pest Science and Management.* Selected papers from the International Rice Research Conference. International Rice Research Institute, Manila, Philippines, pp 53-69. [This study explored the effects of landscape diversity, in particular the relative amounts of rice and non-rice habitat within a landscape, using a simulation model in which dispersal and mortality due to natural enemies varied as a function of local conditions, and whether or not neighbouring land was devoted to rice]

Zhu Y, Chen H, Fan J, Wang Y, Li Y, Chen J, Fan J, Yang S, Hu L, Leung H, Mew TW, Teng PS, Wang Z and Mundt CC. (2000). Genetic diversity and disease control in rice. *Nature* 406:718–722. [A high profile study demonstrating that intraspecific crop diversification can provide an ecological approach to disease control that can be highly effective over a large area and contribute to the sustainability of crop production]

Biographical Sketches

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