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The Redesign of Sustainable Agricultural Crop Ecosystems by Increasing Natural Ecosystem Services Provided by Insects

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Abstract: Agriculture is the cornerstone of the South African economy and farmers must ensure that they produce enough to keep up with the needs of our growing population, within the limits of nature's increasingly constrained and over-used resources. To meet this challenge successfully we need to change our food production systems to more sustainable systems. Natural ecosystems are resilient and able to survive extreme climatic changes because of the diversity in these systems. Conventional agriculture has decreased biodiversity on many different levels including plant genetic resources, insects, and soil organisms. Agrobiodiversity should be considered as the basis for redesigning sustainable agroecosystems by mimicking natural ecosystems, with insects providing ecosystem services. A deeper understanding of the mechanisms driving the relationships between crop diversity, beneficial insects, and pests or diseases will be needed in order to make cropping system diversification an effective and reliable tool. In terrestrial ecosystems, insects play key ecological roles and provide ecosystem services in diverse ecological processes. In order to redesign an ecosystem, we need to determine the different components in the system, their functions in the particular ecosystem, and the interaction between these components that is needed to benefit the ecosystem as a whole. We can then use this knowledge to create models for agricultural crop ecosystems that will be resilient enough to survive the challenges of a constantly changing environment.

Key words: Sustainability, crop ecosystems, resilience, agrobiodiversity, insects, ecosystem services

Introduction

Prince Charles, an enthusiatic supporter of organic and sustainable farming, addressed the issue of sustainable food production, urging government officials and global agriculture industries to re-evaluate the current food structure in favor of more sustainable practices in order to secure the resilience of our planet as well as our global economy [1]. Our current food production systems cannot keep up with feeding a fast

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growing human population. Global food security will not only depend on productivity in agriculture, but also on the efficiency in using scarce resources, stability and sustainability [2]. The steady rise in food prices and social unrest in numerous countries associated with this, reiterates the importance of the agricultural sector for social and economic stability. In the past farmers might not have produced at the high capacity seen today, but their practices were sustainable and efficient for their specific needs [3]. Before the 1940s in the United States and Europe, intercropping was common practice [4]. The demand for greater production capacities by the ever-growing human population, however, led to the increased intensification of agriculture, where crop monocultures and increased dependence on fossil energy enabled specialization in certain commodities [5]. With mechanization and the availability of relatively cheap synthetic fertilizers and pesticides, mono-cropping became the most cost effective way to produce food [6]. Crop yields were dramatically increased during this agricultural intensification, known as the ‘green revolution’, but it is questionable whether these intensive practices are sustainable in the long term [7]. The green revolution was also introduced to the developing world as high-yielding varieties were developed and fertilized to feed rapidly growing populations [8]. This resulted in the agricultural ecosystems that we see today and the true cost of the green revolution is becoming apparent. The green revolution was a major driver in the dramatic losses of global biodiversity during the last decades [9-10]. Complex natural ecosystems have been converted to simplified managed systems. These agroecosystems are relatively open systems where external inputs, such as application of agrochemicals, are high and energy is lost from the system. The high costs of these practices can be seen in the depletion of natural resources. Despite all the modern technology, agriculture still cannot keep up with the growing demand while rapidly depleting scarce non-renewable resources. Environmental problems associated with heavy fertilizer use such as surface-and groundwater pollution, soil acidification and ammonia volatilization are becoming wide spread. Our existing agricultural systems are simply not equipped to deal with the global challenges of population growth, food insecurity, climate change and resource scarcity. To meet these challenges, we will have to redesign our agricultural crop ecosystems to more sustainable systems that will be resilient enough to cope with environmental change and at the same time produce stable yields.

1. Challenges for agriculture in South Africa

Agriculture is the cornerstone of the South African economy. Agriculture in South Africa, however, have two separate ‘economies’, which operate side by side, large commercial farmers who produce most of South Africa’s food, and subsistence farmers who struggle to survive. Farmers must also ensure that they produce enough food to keep up with the needs of the rapidly growing population, within the limits of increasingly constrained and over-used resources. South Africa is a semi-arid, water-scarce country with a high degree of variability in its weather systems and extreme events like droughts and flooding are common. With climate change, these extreme events will only become more apparent. With farmers already having to deal with increasing resource scarcity and limited direct investment in the agricultural sector, they are not able to survive. This is the main reason why the country has recently become a net importer of key food items, including wheat [11], despite the fact that there are local resources and a wealth of indigenous knowledge in South Africa to produce food locally without having to import from other countries.

The only way that we will meet all these challenges successfully is to change our food production systems to more sustainable systems. A model of an agricultural system that will be resilient enough to meet future challenges will be one that incorporates high levels of diversity, productivity and efficiency [12]. Natural ecosystems are very resilient and able to survive extreme climatic changes, because of the diversity characteristic of natural ecosystems. This biodiversity found in natural ecosystems is also the key to sustainable agricultural production and food security. Unfortunately, conventional agriculture has decreased biodiversity on many different levels including plant genetic resources, insects and soil organisms. The loss of biodiversity in habitats surrounding agricultural areas also results in the disruption of the ecosystem services provided by that biodiversity such as pollination, water retention, nutrient cycling and decomposition. The conflict between agriculture and biodiversity can be overcome by changing to sustainable farming practices, increasing diversity and reestablishing lost ecosystem services. Practices that conserve, sustainably use and enhance biodiversity at all levels in farming systems will maintain healthy ecosystems and ensure food security, as well as conserve the environment in the long term.

2. What is Agrobiodiversity?

Biodiversity is the abundance of life and refers to plants, animals and microorganisms existing and interacting within a specific ecosystem. Biodiversity enables a variety of ecological services in an agroecosystem, which support one another and work together to form a stable and sustainable ecosystem. When these natural services are lost, there is not only a cost to the environment, but the social and economic costs can also be quite significant [13]. Newbold et al believes that losses of local species richness exceeding

20% are likely to substantially impair the contribution of biodiversity to ecosystem function and services, and thus to human well-being [14]. Biodiversity is therefore a vital resource for humanity [15]. Two important aspects relating to the effects of biodiversity on a system are stability and productivity [16]. We need stable systems to survive drastic changes, but within these systems we need to produce enough food for the growing human population. Unfortunately, most agro-ecosystems are unstable and highly disturbed where production might be sufficient, but constant managing and expensive external inputs is needed to keep the system functional. This makes these systems vulnerable to environmental changes. The homogenization of species and of farming systems increases vulnerability to insect pests and diseases [17]. Natural, biodiverse systems on the other hand are dynamic systems that can adapt and change amid environmental changes. There are notable differences between conventional agricultural systems and agricultural systems which incorporates agrobiodiversity (Table 1).

Table 1 Differences between a conventional agricultural systems and an agro biodiverse systems.

Conventional system	Agro-biodiverse system
1. Crop planted as monoculture	Intercropping, crop rotation [8]
2. Chemical fertilizer to enrich soil	Manure, cover crops and mulches to enrich soil [18]
3. Herbicide applications to manage weeds	Weeds managed by cover crops, mulches and insects
4. Pesticide applications to manage insects and diseases	Insects and diseases managed by natural predators and parasites [13]; [19]
5. Open system where energy is lost	Closed system where energy is recycled in the system
6. System needs continuous external inputs of agrochemicals to maintain	System is self-sustained by a diversity of organisms [20]

A conventional agricultural system is essentially an open system where energy is lost from the system. This system therefore needs continual costly external inputs. A natural ecosystem on the other hand is a closed system where energy is recycled within the system. This system is therefore self-sustained and needs no or very little external inputs. Agrobiodiversity includes a wide variety of species and genetic resources, as well as many ways in which farmers can use biological diversity to produce and manage crops [20]. Agricultural biodiversity supports ecosystem services on farms, such as pollination, fertility and nutrient enhancement, insect and disease management and water retention [17]. The loss of this agricultural biodiversity will have immediate risks, both financial and social, and lasting effects on agricultural productivity, affecting food security in the long term. In unpredictable and changing environments, conservation of maximum biodiversity is necessary for continued sustainable land use [21]. A shift to sustainable agriculture requires changes in production methods that will enhance diversity in farming systems.

3. The Role of Insects in Ecosystems

Insects are extremely successful organisms in terms of both species richness and abundance, making up the most numerous group of organisms on earth, around 75% of all animal species (Fig. 1). Although many insect species are not yet identified, it is estimated that there are around eight million species of insects on earth [22]. Insects are good dispersers and can exploit virtually all types of organic matter and are found almost everywhere. Insects therefore, form an important part of every ecosystem and are also vital within our food supply chains. Insects have the ability as a group to transfer vast amounts of energy [22] and are ecologically important as determinants of community structure and shapers of habitats. It is estimated that if all insects were to die, human beings would run out of food in just four years.

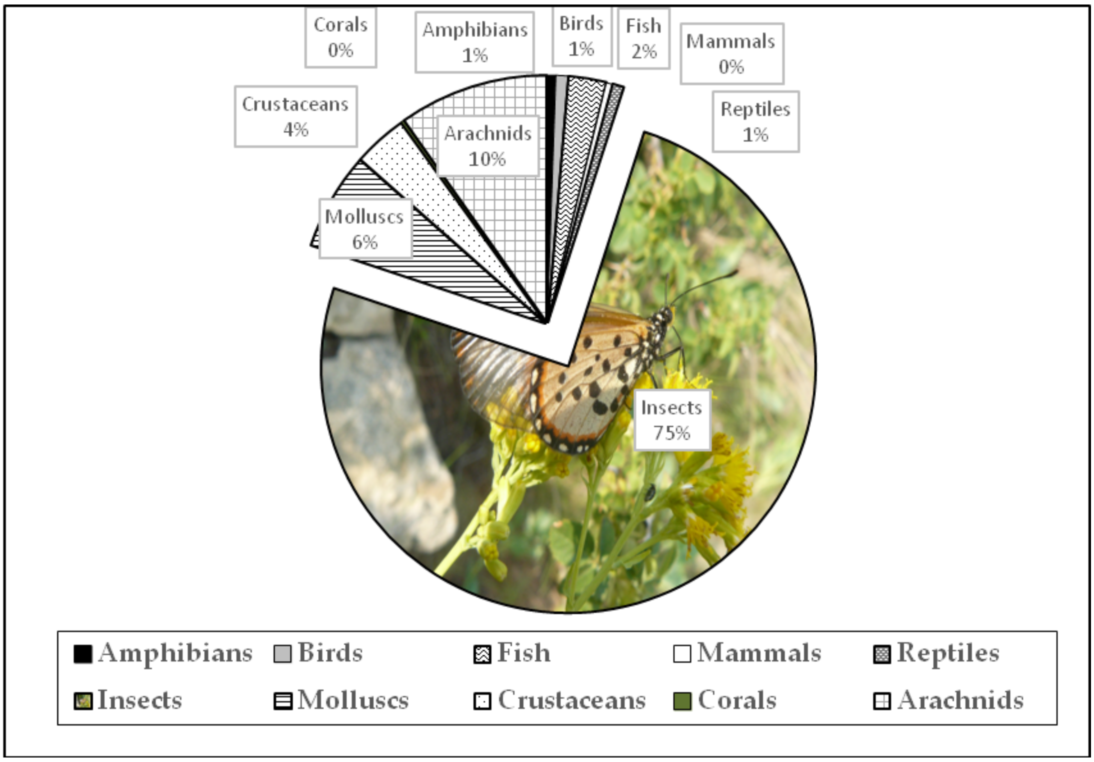

Fig. 1: Estimated number of animal species on earth (The World Conservation Union. 2014.)

Insects form an integral part of the life of a farmer. Only a small fraction of insects are damaging agricultural pests, while the majority of insects are valuable, not only as natural enemies to insect pests and crop diseases, but also as contributions to biomass and by providing important ecosystem services such as nutrient productions and cycling, pollination, and decomposition. Ecosystem services (ES) can be defined as the benefits that humans derive from ecosystems [23-24]. In terrestrial ecosystems insects perform key ecological functions in diverse ecological processes such as nutrient cycling, seed dispersal, bioturbation

[25-27], pollination [28-29] and pest control [30-33]. Diverse insect communities provide ecosystem functions in the soil. Dung beetles instigate a series of ecosystem functions ranging from secondary seed dispersal to nutrient cycling and parasite suppression [26]. The activity of dung beetles in the soil increase nitrogen, phosphorous, potassium, calcium and magnesium or total proteins content [34] and can significantly elevate the yield of wheat plants relative to chemical fertilizers [25]. In addition to nutrient cycling dung beetles can also reduce GHG emissions by between 7 and 12% [27] and contribute significantly to the carbon cycle. Evans et al. found that ants and termites, the soil macrofauna in dry and hot regions, increased wheat crop yield as well as increasing the mineral nitrogen in the soil. [35]. This might be attributed to the digging of tunnels that allow more rainwater to infiltrate into the soil where greater infiltration leads to lower water run-off and erosion. Maintaining these macrofuana may therefore help to lower fertilizer costs [35]. Another essential ecosystem function provided by insects is the pollination of flowering crops. The yield, quality and stability of 75% of globally important crops are increased by the ecosystem service provided by bees [36]. Managed honeybees are however not the only insects providing this function. Ecosystem services provided by diverse wild-bee communities are potentially more valuable and provide greater stability over space and time than single, managed species [37-38]. Occupying the higher trophic levels as secondary or tertiary consumers, predators help control the populations of primary consumers or phytophagous organisms. Ecosystem services are therefore provided by many different insect species belonging to a range of different insect orders and families.

4. Influence of Conventional Agriculture on Biodiversity of Insects and Related Ecosystem Services

Because of a larger global human population, rapid global agricultural expansion combined with effects of pollution, pesticides, fragmentation, global warming, and loss of habitat and habitat fragmentation, may have devastating consequences for many insect species [22]. In conventional agriculture, production practices focuses on few preferred species and their specific requirements, yet the potential services of many other species are ignored [39]. Agricultural production systems are intensified by increased use of external inputs to increase yield, but at the cost of decreased biodiversity, causing ecosystems to become destabilized [40- 41]. One way to maximize production is to plant crops in a monoculture. Ecosystems are, however, more complicated and dependent on more than one species or interaction to provide ecosystem services. Even simplified agroecosystems such as annually ploughed, arable fields exhibit a huge complexity of food web interactions [42]. There are, therefore, many problems associated with monocultures ranging from simplification within crop habitat by single-variety cropping to simplification of the landscape by the destruction of non-crop habitats [43]. The lack of diversity in monocultures causes weed problems and increased disease and insect pressure and this leads to the continuous need to use pesticides. Despite the substantial pesticide use, crop yields continue to be threatened by weeds, insects, and disease due to built-up of pesticide resistance, outbreaks of secondary pests, and susceptibility in the plants [44]. Agrochemicals kill the insects providing valuable ecosystem services in addition to the ‘target’ pest. Pesticides destroy a wide array of susceptible species in the ecosystem while also changing the normal structure and function of the ecosystem and the decline of natural habitat around farms reduces or eliminates beneficial insects in agricultural systems. Conventional agricultural practices, not only results in a decrease in biodiversity, but also the loss of valuable and complex ecosystem services associated with this biodiversity. This leads to unstable systems that needs to be managed with expensive, resource dependent, external inputs.

5. Re-establishing Ecosystem Functions Provided by Insects

In agriculture the maximization of productivity as the target are being replaced by concerns for sustainability [45]. Simplification of agroecosystems resulting from intensification of agricultural practices may affect important ecosystem services through the loss of biodiversity. The maintenance of insect diversity is central in the maintenance of ecosystem form and function, with diverse ecosystems having diverse insect communities [22]. Knowledge of natural ecosystems and associated patterns of succession, community organization, energy budgets, and nutrient cycles could provide valuable models on how agroecosystems should be structured for energy-efficient crop production [5]. Biodiversity may enhance functioning of an ecosystem where individual species add to the function by occupation of the total niche [46]. There exists resource partitioning within a group of species in an ecosystem and this promotes positive intraguild interactions, improving the ecological functioning of the system. In monocultures, there is a higher density of specialist insect herbivores, but a lower general insect diversity than in more diverse systems. The composition of insect assemblages changes with a change from monocultures to more diverse systems. One characteristic of polycultures are higher ratios of natural enemies to herbivores [47]. Strategies to enhance the ecosystem service of pest control in agricultural landscapes often rely on manipulating the structure of the landscape to reduce pest population build-up [33] or facilitate natural enemy activity [32]. Siddiqui et al believes that through suitable scientific manipulations of polyculture, agricultural sustainability can be achieved [48]. Species or structural diversity can be achieved by adding different plant species to monocultures, by intercropping or by allowing weed growth within the crop [49]. Intercropping is one way of introducing more biodiversity into agroecosystems and results from intercropping studies indicate that increased crop diversity may increase the number of ecosystem services provided [50]. It is however, important to consider the choice of crops for inclusion into an intercropping system aimed at reducing herbivore densities through the impact of enhanced populations of natural enemies [51]. It is important that such crops should have a shown capacity to attract and act as sources of natural enemies for the main crop. Not only diversity in the crop habitat but also the diversity in the surrounding landscape and connection to this landscape is important. Habitat manipulation within and bordering cereal fields and within the broader landscape in which crop production resides can improve the effectiveness of biological control [30]. Aphid predators are differently affected by the type of agro-ecosystem management as well as by ecological infrastructures adjacent to fields [19]. The goal of habitat management therefore is to create a suitable ecological infrastructure within the agricultural landscape to provide resources such as food for adult natural enemies, alternative prey or hosts and shelter from adverse conditions. The 'enemies' hypothesis states that diverse cropping systems provide a greater diversity of habitat for arthropods, and offer a greater abundance and variety of prey and hosts for predators and parasitoids [52]. Habitat management may occur at the within-crop, within-farm, or landscape levels. The type and abundance of biodiversity in agriculture change across agroecosystems, which differ in age, diversity, structure and management [19]. The degree of biodiversity in a specific ecosystem will depend on four characteristics [53]: i) diversity of vegetation; ii) permanence of crops; iii) management; iv) connection with natural vegetation. A diversified farming system includes i) genetic diversity within the crop varieties; ii) varietal diversity within a single crop; iii) multiple intercropped species; iv) noncrop plantings [54]. Habitat management at the within-crop level includes increasing genetic diversity through either different cultivars (genetic divergence between cultivars), diverse cultivars (genetic heterogeneity within a cultivar) [55] or increasing heterogeneity in plant nutrients [56]. Breeding of ad hoc cultivars, integrating legumes in the crop stand, using cultivar mixtures and implementing new approaches like evolutionary breeding are all pathways to enhance the provision of key agroecosystem services [57]. Weed presence may also reduce pest pressure, similarly to what can be obtained by intercropping wheat and legumes [58]. In an annual crop during seedling growth stages and prior to cultivation, weeds may contribute most of the resources and habitat modification for all other organisms in the ecosystem [59].

In addition to diversifying the plants in a crop ecosystem, it will also be beneficial to increase the soil fauna by using natural compost. In natural ecosystems soil nutrient cycling, soil structure, and other properties are regulated by the activity of a diverse soil community of insects. Cultivation leads to major changes in this community. Compost introduces a detrital food chain into the crop, which is important in supporting generalist predators higher up the food chain. Various types of organic matter have been shown to have a positive impact on numbers of polyphagous predators, including carabid beetles [60]. Bell et al found both direct and indirect links between compost, aphids and predators where compost-treated plots had significantly higher numbers of predators and aphids were in significantly lower numbers than in plots without compost [31]. Increased macrofauna diversity in the soil will also enhance the nutrient cycle efficiency and as a result the yield of the crop. Decomposition and nutrient mineralization are mediated interactions within a diverse community. From studies of keystone organisms such as termites, earthworms, N-fixing bacteria, mycorrhizal fungi, and nematodes, it is evident that reduction in diversity of soil biota under agricultural practice may profoundly alter the biological regulation of decomposition and nutrient availability [9]. Imitating natural systems can help to produce maximum, sustainable yield, while simultaneously reducing the need for chemical fertilizer inputs.

While agrobiodiversity can be used as the basis to redesign sustainable agroecosystems by mimicking natural ecosystems [61], a deeper understanding of the mechanisms driving the relationships between crop diversity, beneficial insects and pests or diseases is needed for cropping system diversification to be an effective and reliable solution [57]. Well-characterized relationships between biodiversity and ecosystem function are essential to predicting the ecological and economic impacts of human activities [62]. The challenge is to achieve increased production without compromising scarce resources and ecosystem functions and the enhancement of more ecologically designed agricultural systems that reintegrate lost ecosystem services into the intensification process can contribute to meeting this challenge. Before ecosystem services can be properly integrated with conservation planning, additional research on biodiversity ecosystem function (BEF) relationships and links between ecosystem functions and services will be required. Kremen suggests future work necessary to identify ecosystem services [63]:

i) The key species or traits providing ecosystem functions
ii) The relationships between ecosystem function and community assembly and disassembly processes
iii) The environmental factors influencing the production of ecosystem functions
iv) The spatio-temporal scales relevant to both providers and their functions

In order to redesign an ecosystem, we therefore first need to understand the different components, their functions in the particular ecosystem, and the interaction between these components to benefit the ecosystem as a whole. It is important to design a system that respects the limits of the regional natural resources, including the capacity to provide ecological services [64]. The composition of the plant community, as determined by the farmer, may be described as the ‘planned diversity’ of crop systems; ultimately, this crop diversity is critical not only in terms of production but because it is an important determinant of the total biodiversity [9]. This will influence the composition of the associated biota like the pest insect complex, predatory and parasitic insects and soil invertebrates. The performance and population dynamics of insect herbivores also depend on the nutritive and defensive traits of their host plants [65]. Plant variance could influence herbivores in several ways, including reducing the opportunity for herbivore populations to adapt evolutionarily to plant defenses [66].

To redesign agricultural systems it will be necessary to monitor the insect assemblage as a whole, the ecosystem function of each insect group, and the interaction between the different insect groups, as well as the interaction between the insect groups and the other components in the ecosystem. We can then use this knowledge to create a model for agricultural crop ecosystems that will be resilient enough to survive the challenges of a constantly changing environment. Stability in ecosystems is a measure of resilience, or ability of the system to recover from a disturbance, and the resistance of the system to change [16]. The diversity –stability hypothesis states that increasing species diversity in an ecosystem results in increased stability [47]. Observations of agricultural performance after extreme climatic events in the last two decades have revealed that resilience to climate disasters is closely linked to the level of on-farm biodiversity [67]. When ecosystems are diverse, there is a range of different pathways for primary production and ecological processes, so that if one is damaged or destroyed, an alternative pathway may be used and the ecosystem can continue functioning at its normal level [68]. The ultimate goal therefore is to create an agricultural system with a range of different pathways for ecological functions in order to be resilient enough to survive future challenges.

6. The Role of Non-Native Species

The role of non-native species is important to consider in the redesign of agricultural ecosystems. Non-native or exotic species are often seen as a threat to local ecosystems because they have the potential to become invasive. Mascaro, however, argues that most alien species provide valuable ecosystem services [69]. Our environment is changing all the time and ecosystems need to change and adapt to survive these changes. Nature never goes back, it always moves on and alien species are the pioneers and colonists in this constant renewal [70]. Non-native species could come to fill important ecosystem functions, particularly in places where native species cannot survive as a result of environmental changes. Non-native species may contribute to ecosystem resilience by providing habitat, food, or trophic subsidies for native species, serving as catalysts for the restoration of native species, serving as substitutes for extinct ecosystem engineers, and providing important ecosystem services [71].

An example of the introduction of a number of non-native species to perform a specific ecosystem function is the introduction of several dung beetle species to Australia to remove cattle dung, which fouled pastures and acted as breeding sites for fly pests. There were no suitable local dung beetles in these ecosystems to perform the specific ecosystem function. The dung beetles selected had to show peaks in abundance, which coincided, with the increase in numbers of bush fly during spring in southwestern Australia [72]. Dung beetles species had to be chosen for the specific way in which they performed an ecosystem function. These introductions proved very successful, by 1975 23 dung beetle species were introduced [73], and by 1984, there were 43 dung beetle species adapted to the local ecosystems to perform valuable ecosystem functions [74].

In agricultural systems, the diversity of insects that perform valuable ecosystem functions has been depleted. In redesigning these systems to more diverse and sustainable systems it is a viable option to introduce non-native species when local insects to perform valuable ecosystem functions are absent.

Conclusion

The loss of agrobiodiversity has immediate risks and costs, financial and social, for producers and communities and long-term effects on agricultural productivity, as well as jeopardizing food security. A shift to sustainable agriculture requires changes in production methods to enhance biodiversity in farming systems. In redesigning agricultural systems knowledge of specific ecosystem functions of insects and interaction between different insect species, functional groups and the environment is essential. With increased investment in research and development, the scientific and agricultural communities would realize both greater ecological performance and food production from diversified farming systems, as opposed to continued investment in biotechnology and other reductionist strategies. This will result in a sustainable, resilient system with a lower dependence on external inputs and increased water use efficiency, biodiversity and soil fertility. Lower productivity will be balanced by enhanced environmental benefits and reduced externalities of diversified farming systems. These systems will be better able to survive under conditions of economic and environmental uncertainty (Fig. 2).

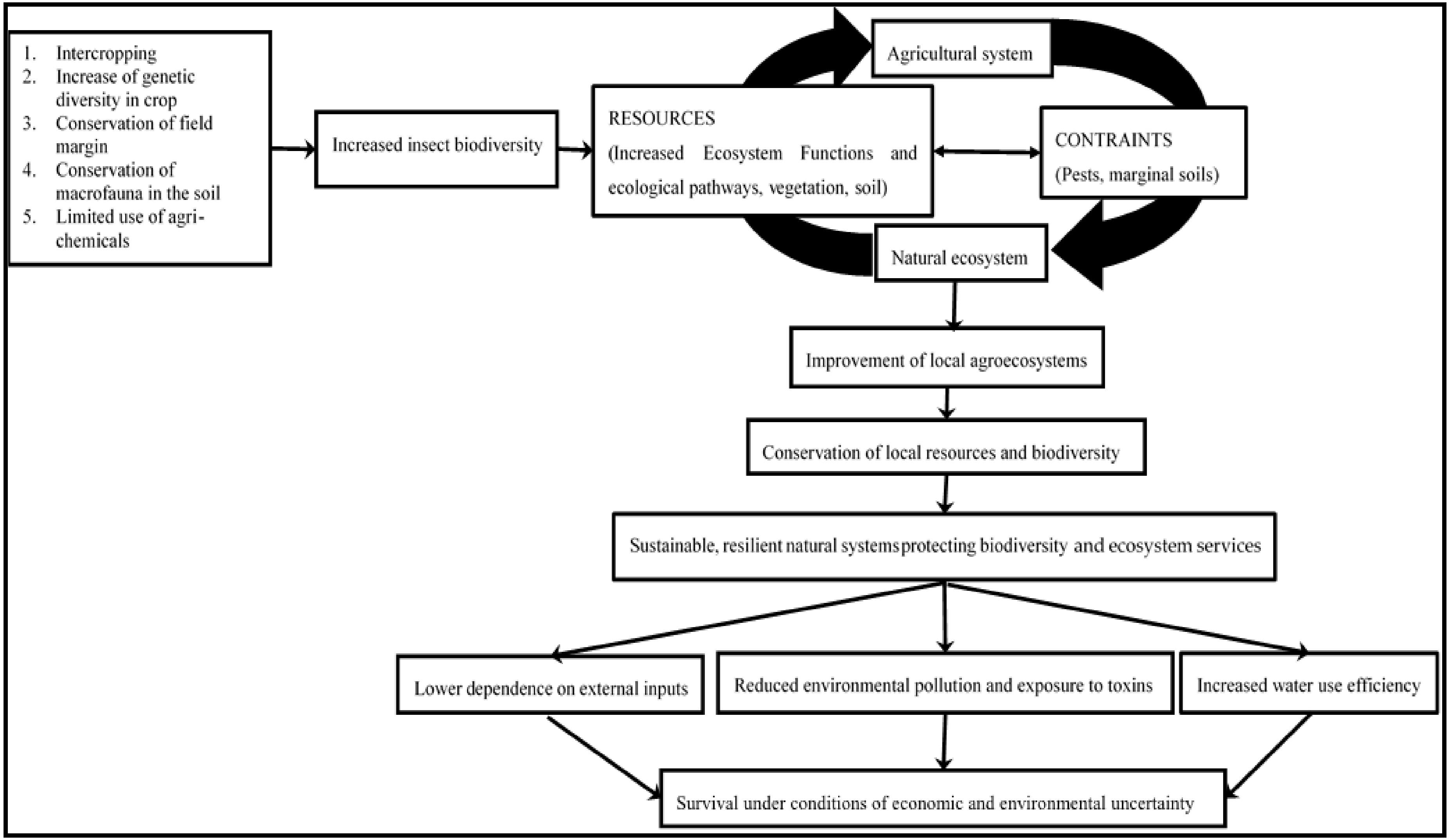

Fig. 2: Model for the redesign of a sustainable and resilient agricultural crop ecosystem

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