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REVIEW ARTICLE

Legume ecosystemic services in agro-ecosystems: a review

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ABSTRACT

Legumes are a pivotal component of the agro-ecosystems and sustainable agriculture worldwide and are of immense importance for providing food to the ever-growing population. Legumes are also a significant source of fodder and are grown on a large scale in the semi-arid tropics including Africa, Asia and Latin America. They deliver several important services to societies as sources of oil, fiber, and protein-rich food and feed while supplying nitrogen to agro-ecosystems via their unique ability to fix atmospheric N_2 in symbiosis with the soil bacteria rhizobia, thus stimulating the productivity of the associated or following crops. They contribute efficiently to agro-ecosystems services through low reliance on synthetic N fertilizers, reduced greenhouse-gas emissions, increased diversification of crop rotations with concomitant increases in above- and below-ground biodiversity, soil fertility, carbon storage and changes in weed, pest, and disease pressures. This review examines how the inclusion of legumes in redesigned cropping and forage systems might assist in reducing the environmental risk associated with the need to further increase the production of food, forage, and fiber while addressing the current reliance on N fertilizer to maintain high crop yields in most of the planet's agro-ecosystems.

Highlighted Conclusion

Legumes fix the atmospheric nitrogen, release in the soil high-quality organic matter and facilitate soil nutrients' circulation and water retention. Based on these multiple functions, legume crops have high potential for conservation agriculture, being functional either as growing crop or as crop residue.

INTRODUCTION

Sustainable agriculture implies to refer to nature as a model for designing farming system. In most natural ecosystems, the greater the diversity the more resistance to change and better ability to recover from disturbances. In an agricultural ecosystem, the so-called agro-ecosystem, disturbance is much more frequent, regular and intense. The ecological concepts of disturbances and their recovery through succession play an important role in agro-ecosystems management. Thus, agro-ecosystems are undergoing disturbances in the form of cultivation, soil preparation, sowing, planting, irrigation, fertilization, pest management, harvesting, pruning, and burning. The diversity and intensity of agro-ecosystems in developing- (Kassam et al. 2009) and developed- (Izaurralde et al. 2003) countries have been changing over time in response to a number of interacting biophysical and social factors at the local, regional and global levels. The impact of spatio-temporal climate variability on is likely to increase with climate change, which will disrupt many agro-ecosystems functions, altering their capacity to provide goods and other services, and rendering them more susceptible to degradation whereas the security of food supply to an increasing population has turned into a pressing issue worldwide (Friend 2010). Sustainable food production can be achieved by avoiding excessive disturbance and allowing successional processes to generate greater agro-ecosystems stability.

Leguminous crops provide a range of agro-ecosystemic services for humans including: (1) N (protein)-rich foods, feeds and green-manures; (2) a lowering of the need for fertilizer N to support crop and pasture production as the result of contributions of symbiotic dinitrogen fixation (SNF) to the growth of the legume host, and the subsequent improvement of soil fertility through inputs of legume organic residues; (3) improvements in soil structural characteristics; (4) direct impacts on soil biology by reducing the incidence of cereal root pathogens, and/or encouraging beneficial microorganisms; (5) diversification of species grown in rotations reducing the requirement for pesticides and other agro-chemicals, encouraging systems resilience and biodiversity; (6) deep-rooted perennial legumes reducing the risk of groundwater contamination by nitrate, or the development of dryland salinity, due to their ability to grow and extract water all year round; and (7) the revegetation and reclamation of degraded or cleared lands. Even though legumes obtain N through SNF rather than through fossil energy-derived N fertilizer, they are generally not considered as a mitigation option. Also, they are usually not regarded as particularly relevant feedstock in bio-refinery for the production of bio-fuel and/or bio-materials (Brehmer et al. 2008). The combination of agro-ecosystems services related to legume production provides internal and external effects and raises of the following questions for value chain developers: what are the effects for farmers? what are the innovation challenges? and how can changes in farming systems be achieved? This review discusses the potential new roles of legumes for agro-ecosystems services and the sustainable development of agricultural systems.

LEGUME ECOSYSTEMS SERVICES FOR AGRO-ECOLOGICAL PRACTICES

Agro-ecosystems are among the most important ecosystems, accounting for 11.2% of the total land area and 12.9% of annual total value of ecosystem services across the planet. Agro-ecosystems have such important services as sustaining agricultural production, maintaining water quality and volume, regulating climate, conserving soils, recycling nutrients, and conserving biodiversity (Figure 1). They store or sequester 18–24% of the planet's carbon stocks, in both soil and vegetation. They provide 94% of the protein and 99% of the calories consumed by humans. Although the use of high-input technologies and agricultural practices can sustain the supply services of agro-ecosystems to a certain extent, they weaken regulation services such as carbon sequestration, water purification, and greenhouse gas regulation, ultimately compromising the supply of grain and fiber (Huang et al. 2015). A deeper appreciation of how to mitigate such undesirable trade-offs as decreasing grain yield and increasing N loss, through a multiplicity of agro-ecosystem services is needed to achieve sustainable agricultural development (Andreotti et al. 2018). Many studies have looked at agro-ecosystem services and explored ways to optimize their use including the general assessment of agro-ecosystems services, the characterization of trade-offs and causal factors, the evaluation of the scale effects of on ecosystemic services, and the optimization strategies for agro-ecosystem services trade-offs (Verhagen et al. 2018).

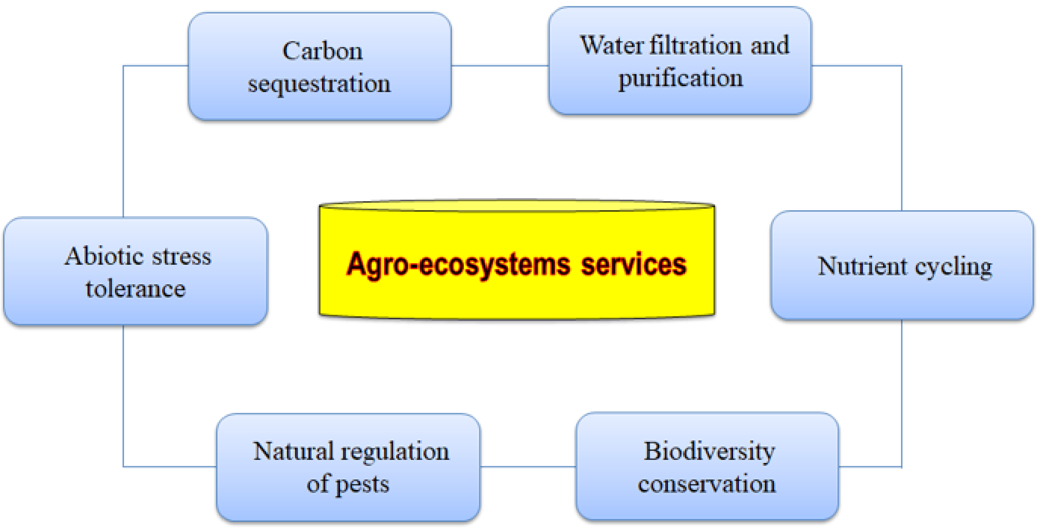

Figure 1. Agroecosystem services as a basis for agro-ecological practices.

Thus, agricultural practices and agro-ecosystems services should be interlinked to provide important ecosystemic services to human societies. These inter-linkages should incorporate both the expected societal benefits and the impacts on other existing ecosystemic services, which might harm the overall ecosystem performance. Power (2010) concluded that farmers obtain many benefits from a wide range of agro-ecosystems services, while society is either benefiting or being harmed by agricultural management. Since these inter-dependencies are presently unclear. Rositano et al. (2018) suggested further studies to deepen the relationship between agricultural management and agro-ecosystems services to introduce options for sustainable agricultural land uses.

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LEGUME BENEFITS FOR AGRICULTURE SUSTAINABILITY

Legumes have traditionally been used in cropping systems, as part of crop rotations or inter-cropping especially with cereals. The key benefits of legumes include the SNF through the symbiotic relationship with soil bacteria collectively referred to as rhizobia (Lazali et al. 2016; 2018). Furthermore, legumes play an important role in reducing greenhouse gas emission (GHG), due not only to their SNF capability that would alleviate N fertilization based on fossil energy, but also for carbon sequestration and biomass production (Jensen et al. 2012). Moreover, legumes provide multiple agro-ecosystems services such as biological control of pests, pollination, and nutrient cycling (Figure 2). Indeed, legumes have great potential to diversify farming systems to restore associated biodiversity in agro-ecosystems, and serve as break-crops which help to reduce weeds, pest and disease associated with short rotations. Legume crops may also increase yields of subsequent cereals by about 29 % on average. Finally, legumes are a sustainable source of protein for healthy human and animal diets, as well as dry matter production (Voisin et al. 2013).

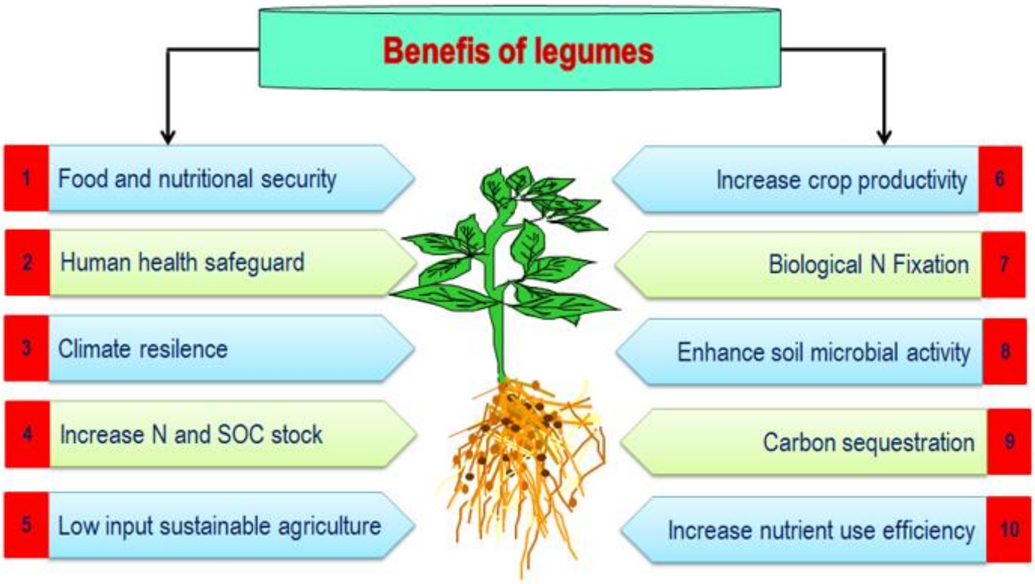

Figure 2. Services of legumes to agricultural production system.

Soil quality. Conservation-farming practices are increasingly practiced in several regions on a global scale, primarily in response to improved recognition of soil degradation, quality, health, and sustainability. Legumes play a key role in maintaining natural resource base through soil stabilization, reduced soil degradation and by preventing soil erosion particularly in small and marginal areas (Srinivasarao et al. 2012). Legumes act as soil amendments and have positive effect on soil health (Hauggaard-Nielsen et al. 2007). Forage legumes are much more effective in improving soil physical properties because of their large and deep root system, long growth period and great capacity for SNF. They improve the soil structure by binding soil particles into aggregates and form more pore space. Hence, as a result of this soil becomes less erosive and holds more water. Incorporation of legume residues in the soil enhanced the soil pH as a result of decomposition and mineralization of organic residues by micro-organisms (Macharia et al. 2011). This provides a beneficial soil environment for plant growth as a result of such nutrients as carbon, nitrogen, phosphorus, potassium, calcium, magnesium and sulphur availability for plant use increased (Jensen et al. 2012). Legumes high quality organic matter as a result of added atmospheric nitrogen favorably affects the soil C/N ratio. Deep rooted legumes facilitate the nutrient solubilization by root exudates and enhance their uptake as well as water infiltration into the soil.

Decomposition and incorporation of legumes as a green manure has a solubilizing effect on both macro (N, P and K) and micro (Zn, Fe, Mn and Cu) nutrients in the soil. Soil analysis at beginning and end of introduced forage legume experiment revealed that soil pH, carbon, nitrogen and potassium increased while calcium decreased significantly from the soil by end of the experiment. The biomass and diversity of microorganism in the soil are good indicators of soil quality. Legumes contribute to an increased diversity of soil flora and fauna lending a greater stability to the total life of the soil. Inclusion of legume in cropping system favours the microbial activities in the soil because rhizo deposits of legumes are higher in substrate quality with low C/N ratio (Nair and Ngouajio 2012). Increased microbial population and activity in the soils containing alfalfa might be due to release of better-quality substrate from alfalfa roots as compared to grasses (Dhakal and Islam 2018).

Nutrition and food security. Food insecurity is a reality for millions of people and households, especially in poor and developing countries. Recent data reveals that over 2 billion people around the world do not have regular access to safe, nutritious and sufficient food, including eight percent of the population in Northern America and Europe. Indeed, more than 950 million people in the world were still hungry in 2030. Such living conditions increase the risk of malnutrition and ultimately impair the health of populations. It is recognized that lack of protein-energy intake, as well as micronutrient deficiencies, are major under-nutrition triggers, both frequently associated with more severe food insecurity states. Grain legumes could be part of the solution for these problems, although over time they have been significantly depreciated within human diets, and legume crops are yet greatly under-cultivated. In fact, legumes are relatively invisible actors of agro-food systems whereas they provide solutions to the double burden of inadequate dietary intake (under-nutrition) and excess food intake (over-nutrition) in an unequal world which is not widely considered or understood.

Legumes may already be leading a green-food revolution, because they have been identified as critical to provide nutrients and balanced diets for nutritional security with minimal use of resources, as well as to facilitate social-eating when cultivated in small areas within backyards or home-, school- and community- gardens (Keatinge et al. 2012). Their high protein content (17-30%) associated with relevant nutritional richness, turns grain legumes into better affordable nutritive options, comparatively to more expensive animal-based protein food sources, such as meat or dairy products, which may be less achievable among food insecure contexts. Legumes are also important food sources of slowly digested complex carbohydrates (~50–65%) and fiber (~30/100 g) with low glycaemic index, as well as nutrients like magnesium, iron, potassium, phosphorus or zinc, several complex B vitamins, namely B1, B6, and B9, and health-protective bio-active compounds (Singh et al. 2016). On the other hand, they possess low energy density in terms of fat (1.3 kcal/g cooked), providing mostly mono- and poly-unsaturated fats. Last but not least, grain legumes hold versatile technological and cooking properties providing excellent opportunities among food industry to be used in the production of several convenience value-added food products, like flours, snacks, infant or sports foods (Asif et al. 2013).

Greenhouse gas emissions. The introduction of legumes into agricultural rotations helps in reducing the use of fertilizers and energy in arable systems and consequently lowering the GHG emissions. N fertilizer savings across Europe, in rotations including leguminous crops, average around 277 kg ha^{-1} of CO_2 per year (Jensen et al. 2012). It has been reported that half of the CO_2 generated during NH_3 production would be reused if the NH_3 were converted to urea. This is, however, only a time shift of CO_2 release in the atmosphere since, once the urea is applied to the soil, the hydrolyzation activity by urease will release CO2 originally captured during urea production. Considering an efficiency of 2.6–3.7 kg CO_2 generated per kilogram of N synthesized, the annual global fertilizer leads to a release of 300 Tg of CO_2 into the atmosphere each year (Jensen et al., 2012). Some studies indicate that at global scale, the amount of CO_2 respired from the root systems of N_2-fixing legumes could be higher than the CO_2 generated during N-fertilizer production (Jensen et al. 2012). However, it is important to emphasize that the CO_2 respired from nodulated roots of legumes comes from the atmosphere through the photosynthesis activity. Conversely, all the CO_2 released during the process of N-fertilizer synthesis derives from fossil energy, thus determining a net contribution to atmospheric amount of CO_2 (Jensen et al. 2012). N_2O represents about 5-6% of the total atmospheric GHG, but it is much more active than CO_2. Agriculture represents the main source of anthropogenic N_2O emissions, due to both animal and crop production. A majority of these emissions result from the application of nitrogen fertilizers (Reay et al. 2012): every 100 kg of N fertilizer about 1 kg of N is emitted as N_2O (Jensen et al. 2012), although different amounts depend on several factors including N application rate, soil organic C content, soil pH, and texture (Rochester 2003). Denitrification processes are the most important source of N_2O in most cropping and pasture systems. Jeuffroy et al. (2013) demonstrated that legume crops emit around 5-7 times less GHG per unit area compared with other crops. Measuring N_2O fluxes, they showed that peas emitted 69 kg N_2O ha^{-1}, far less than winter wheat (368 kg N_2O ha^{-1}) and rape (534 kg N_2O ha^{-1}). Nevertheless, it is important to highlight that the influence of legumes in reducing N_2O emissions depends also on the management of agro-ecosystems in which they are included. When faba bean was grown as mono cropping, it led to threefold higher cumulative N_2O emissions than that of unfertilized wheat (441 vs 152 g N_2O ha^{-1}, respectively); conversely, when faba bean was mixed with wheat (intercropping system), cumulative N_2O emissions fluxes were 31% lower than that of N-fertilized wheat (Senbayram et al., 2016). Anyway, the benefits derived from the introduction of legumes in crop rotations become significant when commercially relevant rates of N fertilizer are applied.

Crop productivity. Crop rotation is also a strategy for increasing productivity and sustainability in insensitive crop production systems, such as thorough inclusion of legumes in cereal production systems (Latati et al. 2016). Benefits of a well-managed crop rotation are breaking plant pest cycles, improving yields, reducing chemical fertilizer inputs, improving soil fertility, increasing biological diversity of the agro-ecosystems, and controlling soil

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erosion. Leguminous plants provide a high biomass in rotation that improves the soil organic carbon stock and maintains a high amount of active carbon in soil, which are important factors to soil health management (Lazali et al. 2021). Legume-based crop rotations that include grass produce more biomass and contribute to improving the soil organic carbon stock and can be adapted to any legume-based cropping system. The legume-based green manure crops are also part of the crop rotation in many sustainable land development systems. Leguminous cover crops are also grown in a rotation primarily to improve soil fertility and prevent soil erosion.

Legume cover crops are included in the system because of their SNF and high biomass production ability (Lazali et al. 2017). When the legumes are used strategically in a crop rotation, it can provide N to the succeeding crop. The quantity of N_2 fixed by this association between legumes and rhizobia varies according to plant species and cultivars, the crop management, climate, the soil type, and duration of the crop (Chu et al. 2004). The quantity of N that a legume crop provides to succeeding crops depends not only on the quantity of N_2 fixed but also the maturity of the legume crop, when it is incorporated into the soil, whether as a whole plant or only as the plant's root system that remains in the field, and the ecological conditions that govern the speed of decomposition (Addo-Quaye et al. 2011).

CONCLUSION

Legumes either as growing crop or as crop residue in farming systems may contribute to major ecosystemic services of great agricultural and societal value, although their role for the mitigation of climate change has been scarcely addressed. N_2-fixing legumes can (1) lower the emission of GHG such as CO_2 and N_2O by decreasing the requirement for mineral N fertilization, (2) release of high-quality organic matter in the soil to increase carbon sequestration, nutrients' circulation and water retention, and (3) reduce the overall fossil energy inputs in the farming systems. Due to their environmental and socioeconomic benefits, legumes could be competitively introduced in modern cropping systems to increase crop diversity and reduce external inputs. They do perform well in conservation-, intercropping- and agroforestry systems which are important among others, in low-input farming systems, especially for developing countries.

Based on these multiple functions, legume crops have high potential for conservation or sustainable agricultural systems although they may require novel solutions of plant management and breeding for producing bio-fuels, materials and chemicals as options in climate change mitigation. One of the key paradigms for future sustainable agriculture is multifunctionality of the same piece of land in order to supply several services with the key principle of diversity in crop species over time and space. Thus, legume species, with their multiple functions for potential agro-ecosystemic services, including their ability to reduce GHG emissions and increase soil carbon sequestration, should be given careful consideration as important components of future sustainable food, fiber, and energy production systems for human prosperity.

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