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Perspectives of intercropping in modern agriculture

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Abstract

Intercropping is a farming practice of growing two or more crop species or genotypes, on the same field. On the fringes of modern intensive agriculture, intercropping could be one route to deliver sustainable intensification by allowing genuine yield gains without increased inputs. It has the potential to increase long term sustainability in food production. While some of the mechanisms by which they deliver agronomic benefits are understood, new knowledge from ecology and breeding offer considerable potential to improve this system. Ecological advances include better understanding of the context-dependency of interactions, the mechanism behind disease and pest avoidance and links between above and below ground system. Selecting crop combination with traits that maximize positive and minimize negative interaction and breeding especially for combination of desirable traits are two approaches for improving intercropping. Precision farming, conservation agriculture and climate smart agriculture constitutes the emerging modern innovative concepts in crop production, promoting crop diversification to build a climate resilient farming community. The biggest obstacle in adopting intercropping systems is to conceptualize the planting, cultivation, fertilization, spraying and particularly harvesting of more than one crop in the same field. Rapid improvements are also possible through the development of new agronomic practices, including mechanization of intercropping systems and improved nutrient management. Applying all of these approaches will need a better exchange of information among ecologists, environmental scientists, agronomists, crop scientists, soil scientists and ultimately social scientists, so that the full potential of intercropping as a sustainable farming system can be realized.

Keywords: Perspectives, intercropping, agriculture, ecological

Introduction

Intercropping is an ancient practice, placed on the fringes of a ‘modern agriculture’ dominated by large areas of monocultured, resource-consuming and high-yielding crops (Vandermeer, 2010) [30]. However, intercropping may be a means to address some of the major problems associated with modern farming, including moderate yield, pest and pathogen accumulation, soil degradation and environmental deterioration (Vandermeer, 1989) [31], thereby helping to deliver sustainable and productive agriculture. Intercropping has become a focus for study by a range of agricultural, ecological and environmental scientists with broad research interests, providing an opportunity for interdisciplinary syntheses combining diverse information on intercropping’s potential.

Intercropping systems involve two or more crop species or genotypes growing together and coexisting for a time. Intercropping is common, particularly in countries with high amounts of subsistence agriculture and low amounts of agricultural mechanization. Intercropping is often undertaken by farmers practising low-input (high labour), low-yield farming on small parcels of land (Ngwira *et al.*, 2012) [18]. Under these circumstances, intercropping can support increased aggregate yields per unit input, insure against crop failure and market fluctuations, meet food preference and/or cultural demands, protect and improve soil quality, and increase income (Rusinamhodzi *et al.*, 2012) [23].

Intercrops can be divided into mixed intercropping (simultaneously growing two or more crops with no, or a limited, distinct arrangement), relay intercropping (planting a second crop before the first crop is mature), and strip intercropping (growing two or more crops simultaneously in strips, allowing crop interactions and independent cultivation. Compared with their component monocrops, they are reported to deliver pest control, similar yields with reduced inputs, pollution mitigation, and greater or more stable aggregate food or forage yields per unit area (Smith *et al.*, 2013) [25].

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Competition indices in intercropping

A yield advantage of intercropping can be indicated by using different methods, among which Land Equivalent Ratio (LER) is the most commonly used to indicate the biological efficiency and yield per unit area of land as compared to mono-cropping system; an LER greater than 1.0 implies that for that particular crop combination, intercropping yielded more than growing the same number of stands of each crop as sole crops. An LER of less than 1.0 implies that intercropping was less beneficial than sole cropping (Onwueme and Sinha, 1991) [22]. Area time equivalent ratio (ATER) also provides more realistic comparison of the yield advantage of intercropping over mono-cropping in terms of time taken by component crops in the intercropping systems (Heibsch, 1980). Relative crowding coefficient (RCC or K) is another index that measures the relative dominance of one species over the other in intercropping system (De Witt, 1960) [9]. Efficiency of intercropping can also be measured by using the index called Agressivity (A), the relative yield increase in "a" crop is greater than of "b" crop in an intercropping system (McGilchrist, 1965) [17]. Competitive ratio (CR) gives better measure of competitive ability of the crops and is also advantageous as an index over K and A (Willey and Rao, 1980) [33].

Interactions in intercropping

Competition and complementarities are the two most important interactions in intercropping. Willey (1979) [34] suggested three broad categories of competitive relationships in intercropping: 1) when the actual yield of each species is less than expected, termed mutual inhibition, 2) where the yield of each species is greater than expected (mutualism); and 3) the most common situation, where one species yields less than expected and the other more; termed compensation. Complementarity is a key feature of intercrops and natural vegetation. According to Willey (1979) [34], yield advantage in multiple cropping occurs when component crops differ in their use of growth resources in such a way that when they are grown in combination they are better able to complement each other and so make better overall use of resources than when grown separately in terms of competition. The component crops are not competing for exactly the same resources (in space or time) and intercrop competition is less than intracrop competition.

Temporal and spatial complementarities can be differentiated from one another (Willey 1979) [34]. In temporal complementarities, growth patterns differ in time (typically at least 30-40 days maturity difference); crops use water at different times, particularly where the system is moisture limited. It involves a time displacement that results in the capture of more resources by the intercrop rather than a change in the efficiency of utilization. Spatial complementarity is the combined leaf canopy or root system of an intercrop that makes better use of available resources when grown together, such as total light interception, water and nutrient uptake because component crops exploit different soil layers or canopy heights in intercropping. Component crops differ in their nutrient requirements, the form of nutrients which they can readily exploit and their ability to extract them from the soil. One crop exploits a greater volume of soil. Where the total quantities of resource captured is relatively similar, the efficiency of utilization of the resources captured is increased in intercrops compared to the sole crops.

Resource-use efficiency in intercropping systems

In 79% of biodiversity experiments, biomass production in species diverse systems was, on average, 1.7 times higher than in monoculture (Cardinale *et al.*, 2007) [7]. Enhanced biodiversity can increase productivity and other ecosystem functions through replacement and complementarity effects. Replacement (or selection) effects result in dominance of mixtures by single, very productive crop species or genotypes: the dominating species increase yields in mixtures relative to expected yields (calculated from monoculture averages of the component species), but not because of beneficial interactions between neighbouring plants (Huston, 1997) [12]. Complementarity effects occur when intercropped plants with complementary traits interact positively to increase productivity, and here genuine yield gains are possible both direct facilitation and niche complementarity enable mixtures to yield more than expected from their corresponding monocultures (Trenbath, 1974) [26].

Liebig's 'law of the minimum' suggests that crop production is determined by the lack of a single critical resource – the limiting factor. If a cropping system increases the availability of a limiting resource then yield should increase. Common limiting factors are light, water, oxygen (in waterlogged soils), temperature, or any one of 14 essential mineral elements (Marschner, 2012) [16]. In many agricultural systems, the limiting factors are nitrogen (N), phosphorus (P) or water availability, whilst cropping season length is often restricted by daylight and temperature extremes.

Root development, nutrient dynamics and rhizosphere processes in arable multi-cropping production systems enable facilitative processes during later plant development stages (theoretical example of a pea, wheat, maize intercrop). Early interplant competitive pressures enable facilitation in the later stages of plant development. Black arrows indicate interconnections and direction ofsupport/enhancement in downward order, arrows represent physical (brown), bio-chemical (red; e.g. biological N fixation (BNF)), and ecological rhizosphere processes which enable direct and indirect resource facilitation (green; e.g. root colonisation by mycorrhizal fungi (MF) and common mycorrhizal networks (CMN). Interspecific competition promotes root growth. Early root development determines the spaces and volumes of soil occupied. Soil N depletion by wheat, increases biological nitrogen fixation (BNF). Plants have different mechanisms by which rhizosphere pH levels are altered and nutrients mobilized. Competitive pressures and host plant diversity encourage colonisation by mycorrhizal fungi (MF), through which plants can access greater soil nutrient and water pools in exchange for carbon. Root systems may be complementary in architecture (e.g. tap roots vs. other roots) and spaces occupied, or essentially may occupy the same space over time, such as maize, which recovers once wheat has been harvested, and extra nutrients are mobilized. Through BNF legumes and cereals utilize different pools of nitrogen. While cereals deplete soil N pools, legumes rely on atmospherically fixed N. In intercrops plants can use different mechanisms to utilize different soil P forms and sources, which ultimately leads to nutrient complementarity and transfer. Nutrient transfer may occur directly or indirectly, over time and space. Excess nutrients via BNF or mobilisation may be transferred to neighbouring plants directly (if rhizospheres can interfere), or indirectly, via common mycorrhizal networks (CMN). Upon plant decay excess nutrients become available and are transferred via said mechanism.

In intercropping systems with restricted N supply, legumes can increase agricultural productivity (Altieri *et al*., 2012) [1]. Legumes are pivotal in many intercropping system, and of the top 10 most frequently used intercrop species listed by Hauggaard-Nielsen & Jensen (2005) [10], seven are legumes. Increased N availability in legume intercrops occurs because competition for soil N from legumes is weaker than from other plants, or the nonlegumes obtain additional N from that released by legumes into the soil or via mycorrhizal fungi (Van der Heijden & Horton, 2009).

Soil organic carbon

Organic matter inputs are closely related to soil fertility and soil organic carbon (SOC) contents. SOC provides the energy to enable all rhizosphere processes. In plant-soil systems enzymes, derived from microorganisms, plant roots and plant and animal residues play a significant role in organic matter decomposition and nutrient cycling. Multi-cropping, with different plant species and specific functional groups, such as N-fixing legumes, affect the abundance, activity and composition of soil enzymes and decomposer communities (Zarea *et al*. 2009) [36]. Values of SMB-C (soil microbial biomass carbon) were strongly influenced by the type of land, management practices, rather than by SOC (Oelbermann and Echarte, 2011) [21].

Nitrogen transfer

There are two ways in which N is transferred from an N-fixing crop to a non-N-fixing component crop, namely via Indirect and direct routes. Indirect transfer occurs when N, in form of ammonium, amino-acids or sloughed-off cells and leaf litter, is deposited in the rhizosphere by the legume and subsequently transformed by microorganisms, making it available to the component crop. Indirect N transfer via leaf litter significantly contributed to the total N uptake of the component crop (Kurdali *et al*. 1990) [14].

Phosphorus uptake

Mechanisms by which P cycling and plant uptake is affected by multiple-crop arrangements include complementary P use and P facilitation (Li *et al*. 2007) [15]. By complementary phosphorus use component crops accessing different P pools due to organic acid exudation reduce interplant competition within the system. Such effects have been found in white lupine-wheat (Cu *et al*. 2005) [8] and wheat and common bean (Li *et al*. 2008) intercrops. P facilitation describes mechanisms by which one plant may enhance P uptake by another plant. Mechanisms of P facilitation in intercrops include: rhizosphere acidification; exudation of carboxylates and other P- mobilising compounds; secretion of phosphatase; release and activation of enzymes; and association with microorganisms (Betencourt *et al*. 2012) [5].

Potassium uptake

Subsoil K uptake in spring cereals can account for up to 50% of total K uptake and up to 55% in ryegrass and clover mixtures (Witter and Johansson 2001) [35]. Hence, it is possible that, due to the deeper root systems generally found in multiple-crop systems, such subsoil K resources can be utilised more effectively, when crops are subjected to interspecific competition.

Nutrient uptake of chilli with frenchbean as intercrop was significantly superior to that of chilli with amaranth as intercrop and pure crop of chilli. The uptake of N, P and K of chilli-frenchbean system was 86, 86 and 117% more than the nutrient uptake of chilli in chilli-amaranth system. Better uptake of nutrients by chilli in chilli-frenchbean system is due to poor competition for nutrients between chilli and frenchbean because of the difference in duration and variation in the rooting habit of chilli and frenchbean. Poor nutrient uptake of chilli in chilli-amaranth intercropping system might be due to the aggressive nature of amaranth compared with frenchbean and in chilli-amaranth system both chilli and amaranth are transplanted crops (Anitha and Geethakumari., 2003) [2].

Designing and breeding for intercropping systems

Plant selection and breeding offer two approaches for improving intercropping systems that, to date, have rarely been considered. The first is selecting crop species and/or cultivar combinations with traits that maximize positive, and minimize negative, interactions.

The second is breeding specifically for combinations of desirable traits. Both approaches are promoted through new knowledge concerning the mechanisms underlying intercropping benefits, but also by our increasingly detailed understanding of trait variation within crop germplasm collections.

The ideotype required of a particular crop is likely to differ for monocropping and intercropping. In monocropping, traits in the chosen crop exploit the environment exclusively for that crop, and focus on increasing the availability and acquisition of limiting resources (White *et al*., 2013) [32]. By contrast, traits for a component of an intercrop are those that optimize complementarity or facilitation traits can be combined from different crops to overcome resource limitations, resource requirements for each crop can be separated temporally, and the cycling of resources can be optimized during the growing season.

As a first step to assessing genotypes for intercropping, diverse germplasm of major crops could be trialled in intercropped and monoculture systems to identify traits delivering favourable yield/quality in one or both systems. Breeding companies are starting to do this (e.g. KWS breeding programme for intercropping bean and maize; Schmidt, 2013) [24]. Breeding of plants with traits that benefit a companion crop could also be undertaken, for example by selecting for production of volatiles that deter pests. Finally, the complex interactions that drive resource capture and distribution in intercropped systems could be better understood through resource-based modelling to explore how specific traits can be optimized for complementarity (Trinder *et al*., 2012) [27].

The outline of the breeding programme is indicated. The starting point in this process consists of exploiting fully the interspecific diversity available in *Phaseolus*. In the past, breeders concentrated their efforts on the characterization and utilization of *P. vulgaris* landraces and wild forms in genetic improvement programmes. Nevertheless, within the common bean primary gene pool, insufficient genetic variation has been found to overcome several major production constraints (Baudoin *et al*., 1995). Better sources of resistance to these constraints have been identified in alien germplasm, mainly the secondary gene pool. The latter is composed of the two species *P. coccineus* and *P. polyanthus*, better adapted to highlands (above 2000 m) and combining useful agronomic traits (e.g. plant architecture, rusticity, diseases resistance, cold and acid soil tolerance) poorly or not expressed in *P. vulgaris*. In the genetic improvement of beans for multiple cropping systems, these two food legumes could be bred as a distinct crop or utilized in the interspecific hybridizations with the common bean (Baudoin *et al*., 1992).

Plant-soil interaction in intercropping

Recent plant–soil organism interaction studies have also highlighted possibilities for improving intercropping systems. Specific mechanisms, such as the transport of allelochemicals through common mycorrhizal networks (CMNs), with CMNs possibly acting as ‘superhighways’ directly connecting plants below ground, allow for systemic signalling across plant populations and directed allelochemical delivery to target plants. Increasing plant diversity helps to maintain soil organism diversity and increasing soil organism diversity leads to increased plant productivity with, for example, a > 50% increase in shoot biomass observed with increasing mycorrhizal species number (Van der Heijden *et al*., 1998). Experimental studies have indicated that below-ground organisms can increase the attraction of herbivore enemies, decrease herbivore fitness, increase pollinator visits and protect against pathogens. Understanding these networks of interactions provides insights into how soil microbial communities might be managed to improve crop production, and also indicates that increased crop diversity – for example, that arising in intercrop as opposed to monocrop systems – could play an important role in this management process. Furthermore, recent applications of structural equation modelling to complex ecological networks could be highly relevant to untangling these complex webs of interactions, and distinguishing clearly which processes are related to final changes in system function (including crop production).

Crop production on acidic soils is often limited by P availability or Al toxicity (White *et al*., 2013) [32]. Roots of plants adapted to acidic soils, such as peanut, cowpea, potato, sweet potato, maize, beans and brassica, secrete organic acids and phosphatases into the rhizosphere, thereby increasing soil P availability and improving the P nutrition of beneficiary plants. The release of organic acids can also protect roots of beneficiary plants from Al toxicity.

Crop production on alkaline and calcareous soil is often limited by the availability of P, Fe, Zn, Mn or Cu (White *et al*., 2013) [32]. Crops tolerant of mildly alkaline soils, such as brassica, maize, beet and squash, acidify their rhizosphere and secrete organic acids and phosphatases into the soil, thereby increasing P, Fe, Zn, Mn and Cu availability and the mineral nutrition of beneficiary plants. In addition, cereals and grasses that release phytosiderophores can improve the acquisition of cationic micronutrients, such as Fe, Zn, Mn and Cu, by those intercropped plants that possess the capacity for metal-phytosiderophore uptake (Zhang *et al*., 2010) [37].

Correlation between rhizosphere soil Olsen P and nodule dry weight of common bean grown as sole crop (filled circle) or intercrop (opened circle) under S1 (P deficient) and S2 (P sufficient) conditions: The increase in the EURS of intercropped legumes in intercropping can be explained by interspecific competition for nitrogen use by the dual intercropping. Field research studies show a significant increase in N_2 fixation by common bean, as a result of competition with either durum wheat or with maize.

An increase in EURS (mostly during low P availability) indicating a tight relationship between legume N_2 fixation, growth and total grain yield. However, detecting differences in EURS between legumes grown in both sole and intercrops may offer an important clue in investigating key processes that influence P availability under P deficiency, where legume’s reliance to N_2 fixation presumably increased in parallel to a number of rhizosphere-induced changes (proton release, organic acids exudation, acid phosphatases, etc.) that contributed to increase P availability and growth. Recent studies were reported a high EURS of cowpea and common bean among intercrops treatment compared to corresponding EURS as sole crop, the increase in EURS by intercropping was significantly observed under low P conditions in either alkaline or calcareous soil (Latati *et al*., 2016).

Regulation of pest in intercropping

The regulation of pests provides an excellent example of where a better understanding of fundamental ecological processes can have direct benefit for the improvement of intercropping and crop production in general. Globally, pests are estimated to destroy more than 30% of crop yield annually, while declining insect pollinator abundance could limit the productivity of insect-pollinated crops worldwide (Kremen *et al*., 2002) [13]. There are numerous examples of the benefits in intercropping systems that arise because of pest and pollinator regulation, but only recently have the mechanisms behind these benefits been understood. For example, by providing a more complex habitat with a greater diversity of resources for beneficial organisms (Potts *et al*., 2003) [20], intercropping systems have the potential to reduce the apparency of crop plants to pests and increase the abundance and diversity of pollinators and natural enemies of crop pests. Furthermore, increased natural enemy activity can lead to reductions in crop damage in intercropped systems a 50–100% increase in predator species richness and abundance relative to herbivorous pests has been detected in apple orchards interplanted with aromatic herbs (Beizhou *et al*., 2012) [4].

Results showed that groundnut harboured significantly less population of leaf hoppers when intercropped with cluster bean (6.2 to 9.3 hoppers/5 sweeps) and sunflower (7.1 to 9.7 hopper/ 5 sweeps) as compared to other intercrops during both the years of study at 30, 45 and 60 DAS. Highest leafhopper population was observed in sole groundnut (upto 19.3 hoppers/ 5 sweeps). Nath and Singh, (1998) reported that the population of leafhopper was highest in groundnut + pigeonpea intercropping system.

In case of thrips, intercropping of groundnut with soybean (upto 57.0 hoppers/ 5 sweeps) and pigeon pea (upto 44.7 hoppers/ 5 sweeps) increased the thrips population in groundnut. Similarly, Singh *et al.* (1991) reported that intercropping groundnut with pigeonpea increased the incidence of *C. indicus*. (Prasad and Gedia, 2011) [19].

Disease suppression in intercropping

Disease suppression is also widely found in intercropping systems, with 73% of documented studies reporting reduced disease incidence in intercrops compared with crop monocultures, commonly in the range of 30–40% (but upto80% in some systems; Boudreau, 2013) [6]. Disease suppression can result from a variety of factors, including decreased host plant availability, altered dispersal by rain, wind and vectors, and microclimatic effects on pathogen establishment (Boudreau, 2013) [6]. However, increased vegetation diversity does not always translate into increased yield, or improved pollination and biocontrol services (Cardinale *et al.*, 2012). As discussed with respect to the SGH, understanding this context dependency may be crucial in tailoring intercropping systems to spatial and temporal variation in environmental conditions.

Disease suppression in intercropping system by: physical barriers to spread of aerial pathogens or their vector- "fly paper effect" (Trenbath, 1997), trapping, altered microclimate –shading, altered microclimate- relative humidity, spacing and host- pathogen interaction induced resistance.

Conclusion

Intercropping systems clearly have the potential to increase the long-term sustainability of food production under low inputs in many parts of the world. Whilst some of the mechanisms by which they deliver benefits are understood, there is considerable potential to improve intercropping systems to gain either greater yield (or other benefits) with the same inputs, or sustained yield with reduced inputs based on new knowledge from both ecology and agronomy, and the interface between the two disciplines. In the short term, perhaps the most straightforward approach is simply to trial new combinations of crops to exploit beneficial mechanisms that have already been identified, for example, new combinations of cereals and legumes (a widespread focus for current research). Rapid improvements are also possible through the development of new agronomic practices, including the mechanization of intercropping systems and improved nutrient management, but again such efforts can be taken forward using existing knowledge and experimental approaches.

On a longer timescale, increasing resource-use efficiency of intercrops through plant breeding is likely to be the most effective option. However, breeding programmes should explicitly consider multiple traits that would benefit mixed cropping and not simply those traits known to raise the yield of monocrops. These breeding efforts, as well as the development of management practices tailoring intercropping systems to the local environment, can be guided by the new understanding derived from ecological research into organismal interactions.

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