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The new Green Revolution: Sustainable intensification of agriculture by intercropping

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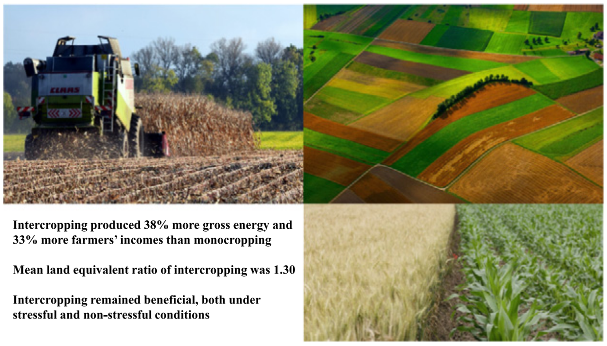
HIGHLIGHTS

- Global productivity potential of intercropping was determined using a meta-analysis.
- Global land equivalent ratio of intercropping was 1.30.
- Land equivalent ratio of intercropping did not vary through a water stress gradient.
- Intercropping increases gross energy production by 38%.
- Intercropping increases gross incomes by 33%.

GRAPHICAL ABSTRACT



Intercropping produced 38% more gross energy and 33% more farmers' incomes than monocropping

Mean land equivalent ratio of intercropping was 1.30

Intercropping remained beneficial, both under stressful and non-stressful conditions

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ABSTRACT

Satisfying the nutritional needs of a growing population whilst limiting environmental repercussions will require sustainable intensification of agriculture. We argue that intercropping, which is the simultaneous production of multiple crops on the same area of land, could play an essential role in this intensification. We carried out the first global meta-analysis on the multifaceted benefits of intercropping. The objective of this study was to determine the benefits of intercropping in terms of energetic, economic and land-sparing potential through the framework of the stress-gradient hypothesis. We expected more intercropping benefits under stressful abiotic conditions. From 126 studies that were retrieved from the scientific literature, 939 intercropping observations were considered. When compared to the same area of land that was managed in monoculture, intercrops produced 38% more gross energy (mean relative land output of 1.38) and 33% more gross incomes (mean relative land output of 1.33) on average, whilst using 23% less land (mean land equivalent ratio of 1.30). Irrigation and the aridity index in non-irrigated intercrops did not affect land equivalent ratio, thereby indicating that intercropping remains beneficial, both under stressful and non-stressful contexts concerning moisture availability. Fertilisation and intercropping patterns (rows and strips *vs.* mixed) did not affect land equivalent ratio. Although intercropping offers a great opportunity for intensification of existing agricultural lands, many challenges need to be tackled by experts from multiple disciplines to ensure its feasible implementation.

1. Introduction

By the middle of the 21st century, the global human population is projected to exceed nine billion and will continue to grow (Gerland

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et al., 2014). To meet people's needs for calories and proteins, some have predicted that crop production will have to double (100–110%) relative to its 2005 level, or roughly triple (176–238%), if the entire population were to gain access to the same *per capita* consumption enjoyed by First World inhabitants (Tilman et al., 2011). Achieving this goal with limited environmental impacts offers an unprecedented challenge to humankind. Ideally, this challenge would be met through the sustainable intensification of agriculture, *i.e.*, without harmful trade-offs between productivity and other ecosystem services (Millennium Ecosystem Assessment, 2005; Tilman et al., 2011; FAO, 2017). By increasing the yields of some cereals, the Green Revolution has so far permitted humans to cope with population growth (Khush, 2001; Pingali, 2012), and its new technologies are still central to ongoing reduction in the total number of undernourished people (FAO et al., 2015). However, improving the potential yields of staple crops is proving to be increasingly challenging in developed countries; closing yield gaps in developing countries, which are the differences between actual and potential yields, might be insufficient to ensure global food security in the future (Cassman et al., 2003). Here we argue that intercropping could push back forecasted yield ceilings in a sustainable way and may help solve the potential humanitarian crisis to come.

The yield improvement potential of intercropping has been repeatedly demonstrated (Ren et al., 2014; Aziz et al., 2015; Bedoussac et al., 2015; Yu et al., 2015, 2016; Himmelstein et al., 2017), although this response is often limited to cereal/legume intercropping systems, to their certain geographical scope, or to specific benefits, such as land sparing. Intercropping can also provide many ecosystem services, such as reducing the needs for chemical inputs to control insect pests (Letourneau et al., 2011; Iverson et al., 2014), weeds (Liebman and Dyck, 1993) and diseases (Boudreau, 2013), whilst diminishing greenhouse gas emissions that are linked to industrial N_2-fixation (Crews and Peoples, 2004). The presence of N_2-fixing legumes in intercrops could also solve the problem of N fertilisation asynchrony with crop demand, which is known to incur great losses through leaching (Crews and Peoples, 2005). This enhanced N-retention could even be accompanied by a greater potential for carbon sequestration in soils (*e.g.*, Chapagain and Riseman, 2014; Cong et al., 2015). Furthermore, micronutrient malnutrition, also called the ‘hidden hunger’, is one of the failings of the Green Revolution (Pingali, 2012), a problem to which many regions of the world are still susceptible (FAO et al., 2015), particularly under ongoing atmospheric change (Loladze, 2002, 2014). Hence, natural biofortification of food products through the mobilisation of P, Fe and Zn by cereals in intercrops is another example where intercropping could be of great utility (Zuo and Zhang, 2009; Xue et al., 2016). All of this suggests multiple win-win trade-offs between productivity and ecosystems services (Iverson et al., 2014), but much effort is still required to determine which other services are improved by intercropping (Brooker et al., 2015).

Most of these ecosystem services are directly linked to the biomass-enhancing mechanisms that are in place within intercropping systems, *e.g.*, dilution effects of host diversity for herbivory and disease, and facilitation effects for the acquisition of nutrients. The interactions between species that govern these mechanisms have been hypothesised to be mediated by the environment, with facilitation being more common under conditions of high physical stress relative to more benign abiotic conditions (Maestre et al., 2009). This is worth noticing, because the innovations of the Green Revolution have done well in fertile environments, but not so well in harsh ones where crop improvement programmes lag behind (Pingali, 2012). This means that positive interactions between species in intercropping systems could hypothetically exert a greater effect on marginal lands or in stressful environments.

Nevertheless, the most obvious ecological advantage of intercropping remains land sparing (Waggoner, 1996) which is the most common way to quantify intercropping benefits. Land sparing through intercropping is usually quantified by the land equivalent ratio (LER) (Willey and Osiru, 1972). The LER is the relative land area that is required under sole cropping to produce the yield that can be achieved under intercropping. A meta-analysis containing 100 different studies found a median LER of 1.17, meaning that 1 ha under intercropping produced, on average, as much as 1.17 ha under sole cropping (Yu et al., 2015). Even though LER offers the possibility to evaluate the potential for land sparing, this metric may be ill-adapted in other situations, *e.g.*, when we are concerned about a given amount of agricultural land. The relative land output (RLO) has been used less frequently, but offers a good way to assess benefits in the latter situation. By converting harvested biomass of each intercropped species into a comparable value (*e.g.*, harvested gross energy), it is possible to join their yields together. The RLO is then the comparison of total yield under intercropping with total yield under sole cropping for a given amount of land.

As promising as intercropping might seem for ecological reasons, farmers will require economic incentives for adopting this more complex practice. A meta-analysis in Africa found that intercropping benefits on yield were linked to benefits on gross incomes (Himmelstein et al., 2017). A greater independence from industrial N-fertilisers, the prices of which are highly sensitive to the energy market (Huang, 2007), is another reason why producers could consider intercropping.

In this study, our objective was to assess the benefits of intercropping in terms of harvested gross energy, farmer gross incomes, and land sparing potential. To do so, we carried out the first worldwide multifaceted assessment of intercropping benefits using available data on two intercropping species in the scientific literature. We hypothesised that intercropping was generally beneficial, whatever benefit is considered. We predicted that RLO would be larger than LER and more efficient at capturing all the benefits of intercropping. We also wanted to test the importance of the stress-gradient hypothesis (*i.e.*, benefits should be greater under harsher conditions) for explaining variability in intercropping benefits (Maestre et al., 2009). More specifically, we predicted that intercrops in arid environment would have more positive interactions between their species than intercrops under wetter conditions. Also, following the stress-gradient hypothesis, we predicted that irrigated and fertilised agricultural lands would benefit less from intercropping than non-irrigated and non-fertilised lands. Given the well-known ability of leguminous species to fix nitrogen, we also verified if the presence of this taxonomic group affected the performance of intercropping systems through facilitative interactions. Finally, we tested the importance of intercropping patterns by comparing mixed intercropping to row/strip intercropping, because they potentially have consequences for the degree of interaction between the intercropped species.

2. Methods

2.1. Data collection

We searched the literature published between 1975 and 2014 using the following electronic databases: CAB Abstracts, Biological Abstract, Scopus and Google Scholar. Titles, abstracts and keywords were searched using these keywords: “intercropping,” “intercrop,” “mixture,” “polyculture,” “land equivalent ratio,” and “relative yield.” Intercropping data that were considered appropriate for analyses satisfied the following criteria: 1) intercrops contained only two species; 2) yields for both species in the intercrop were available, as well as yields in their sole crops; 3) yields were expressed in terms of the marketable part of crops, and not their whole biomass; and 4) intercrops and corresponding sole crops received the same agricultural treatments, *i.e.*, irrigation, fertilisation and pest management. During this process, we estimated that in roughly 60% of all studies data did not include any sort of variance estimate (*i.e.*, standard deviation, standard error or variance). We evaluated that removal of these studies would be more detrimental to the accuracy of our statistical estimates than the lack of a formal