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A meta-analysis of relative crop yields in cereal/legume mixtures suggests options for management

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ABSTRACT

Intercrops of cereals and legumes are grown worldwide, both in smallholder agriculture in developing countries and in organic farming systems in developed countries. The competitive balance between species is a key factor determining productivity in mixtures. Management factors, e.g. sowing time, sowing density and rate of N fertilizer, affect the relative competitiveness and performance of intercropped species. There is a need for an overarching analysis to elucidate general principles governing the relative performance of legumes and cereals in mixtures. We therefore conducted a meta-analysis of published studies to explore how the relative yield of legumes and cereals in mixtures responds to relative sowing time, relative density and nitrogen fertilizer.

An index for relative sowing time, RST, was developed to quantify the relative difference in sowing time between the intercropped species. RST is defined as the amount of time that a species is sown earlier or later than its companion species, relative to the length of its own growing period. RST is smaller than zero if a species is sown earlier than its companion species and greater than zero if it is sown later. Relative performance of a species was characterized by its relative yield (or partial land equivalent ratio, PLER) in the intercrop compared to the yield in the sole crop.

In 409 out of 552 cases, the cereal had a greater relative yield than the legume. Sowing a species earlier than its companion increased its relative yield, and vice versa. An increase in density of a species increased its relative yield and decreased the relative yield of the companion species. The relative yield of cereals increased and that of legumes decreased with the amount of N fertilizer. The negative effect of N on the relative yield of legumes was mitigated if the legume was sown before the cereal.

The study shows how the performance of cereals and legumes in an intercrop is affected by sowing densities, relative sowing times, and nitrogen fertilizer. Growers can exploit these relationships to manage competition between cereals and legumes in mixtures and enhance species complementarity, total productivity and economic profit.

1. Introduction

Intercropping (i.e. the mixed cultivation of crop species) is a traditional agronomic practice that is widely used by smallholder farmers in Asia, Africa and Latin America (Vandermeer, 1992; Lithourgidis et al., 2011). Intercropping is also drawing increasing interest as a strategy for increasing productivity and sustainability of mechanized western crop production systems, e.g. through incorporation of legumes in cereal production systems (e.g. Dhima et al., 2007; Lithourgidis et al., 2007; Bedoussac and Justes, 2010; Pelzer et al., 2012). There are many types of intercrops, including mixtures of two cereals, mixtures of two legumes, as well as mixtures of a cereal and a legume or non-legume broadleaf species (Li et al., 2013; Yu et al., 2015). Mixtures of a cereal and a legume are by far the most common type of intercrop (Rao et al., 1987).

Cereal/legume intercrops have been shown advantageous over sole crops in many respects. Most frequently reported, cereal/legume intercrops use the land more efficiently than sole crops (e.g. Ofori and Stern, 1987a). If resource conversion efficiency of plants is equal between intercrops and sole crops, the increased land use efficiency by intercropping implies that plants in intercrops acquire more growth resources e.g. light, water or nutrients than in sole crops. Indeed, it has been reported that compared to sole crops, higher land use efficiency in cereal/legume intercrops

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was associated with greater light capture (Marshall and Willey, 1983; Watiki et al., 1993; Zhang et al., 2008; Gou et al. under review) or complementary nutrient acquisition (e.g. Hauggaard-Nielsen et al., 2009). The complementarity in nitrogen acquisition between cereals and legumes has received considerable attention in the scientific literature, though, enhanced phosphorous use efficiency has also been reported (Li et al., 2007). Cereals and legumes are complementary in their acquisition of nitrogen because legumes can fix nitrogen from air through symbionts in addition to using soil N, while cereals acquire nitrogen only from the soil (Jensen, 1996; Hauggaard-Nielsen and Jensen, 2001; Chu et al., 2004; Corre-Hellou et al., 2006). Nitrogen fixation from air is critical if there is little N available from the soil. Acquisition of soil N by the cereals may reduce the availability to the legumes and trigger the legumes to fix more N from the air (Lambers et al., 2008). Nitrogen fixation from the air is also seen as a step in making agriculture more sustainable because it circumvents the need for industrial nitrogen fixation based on fossil energy (Courty et al., 2015; Duc et al., 2015).

The different N acquisition strategies of cereals and legumes offer opportunity for complementarity, which could result in a high relative yield for each species (little reduction from competition), and a high relative yield total of the mixture. The relative yield of each species is considered a useful index for the extent to which each species has realized its potential growth, given the conditions and the competition from the other species, while the relative yield total is a useful index for the total niche realized in mixture (Vandermeer, 1992). The extent to which this relative yield total exceeds one is an indicator for complementarity.

The land equivalent ratio (LER) is widely used to characterize the land use efficiency in intercropping. LER is calculated as the sum of the relative yields of intercropped species in an intercrop, as compared to their sole crops (Mead and Willey, 1980). The value of LER may be interpreted as the land area required to produce the same yields in sole crops as obtained from a unit area of intercrop. An LER greater than one implies that intercropping makes a more efficient use of the land than sole cropping. The partial land equivalent ratio (PLER) is the relative yield of an intercropped species compared to its yield in a sole crop (Ofori and Stern, 1987a). PLER can be interpreted as a measure for the contribution of each species to the efficiency of land use by the system as a whole.

In older literature (e.g. Mead and Riley, 1981), a distinction is made between relative yield (total) and (partial) land equivalent ratio. The premise is that relative yield total should be measured in experimental settings with replacement designs in which the relative density total is one (e.g. De Wit's replacement series; De Wit, 1960), whereas land equivalent ratios are measured in experimental settings with a much wider set of designs, including additive designs with a relative density total of two, and augmentative designs that have a relative density total between one and two. Relative yield (RY) is calculated in the same way as partial land equivalent ratio, while the relative yield total (RYT) is calculated in the same way as the land equivalent ratio. Therefore the distinction between RY and PLER, and between RYT and LER is nowadays seldom made, and we consider it unnecessary and obsolete.

According to the stress gradient hypothesis (SGH) (Brooker et al., 2008), plant–plant interactions depend on the environmental context with negative interactions (competition) dominating under favorable conditions, and positive interactions (facilitation) prevailing under unfavorable conditions. The SGH predicts that at high doses of nitrogen fertilizer, interspecific competition would be dominant in intercrops, whereas at low nutrient inputs, complementary use of N would be dominant. In cereal/legume intercropping, under low nitrogen input conditions, the complementary acquisition of nitrogen from different sources would be dominant (Jensen, 1996) while at high nitrogen input, interspecific competition would lead to a dominance of cereals in the mixture due to the stronger competitiveness of cereals as compared to the companion legumes (Ofori and Stern, 1987a).

The competitiveness of individual species in mixtures might be affected by differences in sowing date. The first-sown species will get a competitive advantage while the second-sown species is likely to have a competitive disadvantage. However, if the sowing delay of the second species is very large, such that its growth period is to a large extent after the growth period of the first species (as in relay intercropping), the suppression on the second species might be minor or transient (Zhang and Li, 2003). The strength of interspecific competition could also be determined by relative plant densities of the mixed species (Ofori and Stern, 1987a; Vandermeer, 1992). Increased density of one intercropped species is likely to increase its competitiveness in the intercrop, and suppress the performance of the associated species (De Wit, 1960; Braakhekke, 1980; Gardiner and Craker, 1981; Fawusi et al., 1982). Although the effects of these agronomic practices (rate of N fertilizer, sowing time and sowing density of intercropped components) on competitiveness of the species in mixtures have been reported, there is a large variation in these effects across studies. There is a lack of quantitative assessment across studies of the extent to which these agronomic practices can influence the performance of individual species in mixtures. Besides, it is not clear how species performance in mixtures is affected by the interplay between these factors.

In this study we conduct a meta-analysis to investigate how performance of cereals and legumes is affected by sowing time, sowing density, rate of N fertilizer and the interactions between these factors in cereal/legume intercrops. PLER is taken as a measure of performance of intercropped species. As PLER is the ratio of yield of one species in an intercrop over yield in the respective sole crop, low yields in sole crops might result in high PLERs. We therefore also explore whether high PLERs are associated with low yields of the sole crops.

2. Materials and methods

2.1. Paper and data selection

Data on yields in cereal/legume intercrops used here are a subset of records from a database built by Yu et al. (2015). From the original database, all data records of cereal/legume intercrops (552) were extracted, representing data from 144 experiments out of 77 publications. Each data record provides the PLER of both the cereal and the legume. An experiment was defined as a unique combination of site and year. Within experiments, data records were defined by treatment, including crop species combination, sowing dates, rate of fertilizer application and crop densities. Data were entered into the database using identifiers for the publications and the experiments, and listing all relevant inputs and outputs (Appendix: Table A1). Among the 552 data records of cereal/legume intercrops, 485 were grain cereal/grain legume intercrops, 14 were combinations of grain cereal/fodder legume, and 53 were fodder cereal/fodder legume intercrops. Not all data records reported all variables mentioned in Table A1. There were some missing values for density of crops (5 out of 552 records) and rate of N fertilizer (92 out of 552 records; Table A1). Data records with missing values of a variable were excluded only from those analyses that required that variable.

2.2. Response and explanatory variables

In all analyses, partial land equivalent ratio (PLER), was taken as response variable. PLER is defined as:

$$\text{PLER} = \frac{Y}{M} \quad (1)$$

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