ARTICLE IN PRESS

Agriculture, Ecosystems and Environment xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Sustainable intensification through rotations with grain legumes in Sub-Saharan Africa: A review

A.C. Franke[a,*], G.J. van den Brand[b], B. Vanlauwe[c], K.E. Giller[b]

[a] Soil, Crop and Climate Sciences, University of the Free State, PO Box 339, Bloemfontein 9300, South Africa
[b] Plant Production Systems, Wageningen University, PO Box 430, 6700 AK Wageningen, The Netherlands
[c] International Institute of Tropical Agriculture (IITA), c/o ICIPE, PO Box 30772, 00100 Nairobi, Kenya

ARTICLE INFO

Keywords:
Cereals
Nitrogen fixation
Phosphorus
Biotic factors
Residual benefits
Smallholder farmers

ABSTRACT

We conducted a systematic review of literature on the residual effects of grain legumes in cereal-based systems of sub-Saharan Africa (SSA) to quantify the magnitude and variability of rotational effects, to explore the importance of environmental and management factors in determining variability and to evaluate the evidence of the different mechanisms that explain rotational effects. We retrieved 44 unique publications providing 199 observations comparing continuous cereal performance with that of a grain legume-cereal rotation. The overall mean yield increase of 0.49 t grain ha^{-1}, equal to an increase of 41% of the continuous cereal yield, is highly significant, but the variability in residual effects is large. Effects were more pronounced in southern Africa, the highlands of East Africa and the Guinea savannah, and less in the humid forest/derived savannah of West Africa and the Sudano-Sahelian zone. Maize showed stronger yield responses after a legume than millet and sorghum. Agro-ecological zone and cereal type were however confounded. All grain legume types significantly improved cereal yields, with stronger residual effects observed after soybean and groundnut than after cowpea. Fertiliser N application to cereals reduces the residual effects of legumes, but the response at 60–120 kg N ha^{-1} still equalled 0.32 t ha^{-1} or 59% of the response when no N is applied. The sustained benefits with large N applications indicate the importance of non-N effects. While mechanisms for improved soil P availability after grain legumes have been studied in some detail, it remains uncertain how important these are in farmers' fields. Grain legumes are unlikely to have a major influence on the availability of nutrients other than N and P, or on soil pH. Beneficial impacts of grain legumes on soil organic matter content can occur if legumes contribute to a greater overall cropping productivity, but studies generally report no such impacts. Evidence of impacts of grain legumes on weeds is limited to striga. Studies on the impacts on nematode pressure in cereals are inconclusive, probably because legumes act as a host for some of the key nematode genera that harm maize. The impact on the pressure of other pests and diseases in cereals is probably important, but evidence on this from SSA is lacking. Future research on N_2-fixation by grain legumes and residual N benefits should focus on explaining the wide variability observed among sites. There is a clear need for more detailed mechanistic studies to assess the occurrence and relevance of non-N effects of grain legumes, particularly in relation to common pests and diseases in cereals.

1. Introduction

Diversification and intensification through inclusion of grain legumes in cereal, root or tuber based cropping systems represents a key technology in the drive towards the sustainable intensification of agriculture in sub-Saharan Africa (SSA) (Vanlauwe et al., 2014). Grain legumes fix atmospheric nitrogen gas (N_2) that can contribute to the nitrogen (N) economy of fields, provide other rotational benefits to subsequent crops, produce *in situ* high-quality organic residues with a high N concentration and a low C to N ratio, and thereby contribute to integrated soil fertility management (ISFM) (Giller, 2001; Vanlauwe et al., 2010). Their protein-rich food and feed products have a good market demand in SSA where marketing channels are available (Chianu et al., 2011). The wide range of grain legume crops and varieties with different growth durations and other characteristics suggest that legumes have a potential niche in a wide range of farming systems in SSA. Legume production may be enhanced by replacing cereals or other non-legume crops, by intensifying crop production (instead of fallowing land or including legumes as an intercrop with cereals), or by expanding the area of farmland. Quantifying the rotational effect of grain

* Corresponding author.
E-mail address: FrankeAC@ufs.ac.za (A.C. Franke).

http://dx.doi.org/10.1016/j.agee.2017.09.029
Received 29 September 2016; Received in revised form 21 September 2017; Accepted 26 September 2017

Please cite this article as: Franke, A.C., Agriculture, Ecosystems and Environment (2017), http://dx.doi.org/10.1016/j.agee.2017.09.029

legumes on subsequent crops is important for understanding the adoption potential of legume technologies as well as their impact on sustainability of production. Grain legumes often yield less and demand more labour than cereal crops due to labour-intensive manual harvesting, threshing, weeding and sowing practices (Franke et al., 2010; Ojiem et al., 2014). The rotational effects of legumes on cereal yields may nevertheless make legume-cereal rotations more attractive in terms of productivity and economic performance than continuous cereal cropping (Franke et al., 2014). However, the impact of legumes on subsequent cereals is highly variable, depending on soil fertility status, agro-ecological conditions, crop type and management, which in turn are affected by farmers' diverse socio-economic conditions (Ojiem et al., 2006). Quantifying and understanding the variability in rotational benefits will help in the tailoring of legume technologies to environments in SSA where they work best.

The various rotational effects of grain legumes on subsequent crops can be divided into 'N-effects' and 'non-N-effects', also known as 'other rotational effects'. Nitrogen effects refer to the improved N nutrition of a subsequent non-legume crop and the associated reduction in N-fertiliser demand as a result of the N_2-fixing capabilities of legumes. The amount of N_2 fixed depends on the genetic potential of the legume, the rhizobia and the symbiosis, and on the ability of legumes to establish their symbiosis which depends on the environment and management (Giller, 2001). In case where most of the fixed N_2 is removed at crop harvest, the field N balance of a legume crop is close to zero or even negative. Nevertheless, in such a situation more N may be available for the subsequent crop than after a cereal. This can be due to an N-sparing effect (the absence of soil N depletion compared with a cereal grown without sufficient N input) or reduced N immobilisation of soil mineral N due to the lower C-to-N ratio of legume residues (Chen et al., 2014). N-effects from legumes depend on the amount of N fertiliser applied to the subsequent crop and in general are more pronounced in N-poor than in N-rich environments. Comparing the nitrogen budget of a non-legume crop following a legume with that of continuous non-legume crops where little N is applied allows estimation of the N-effect in terms of additional yield or N uptake (Giller, 2001). However, this approach tends to overestimate the N effects, and it often remains impossible to assign an increase in yield or N uptake of a non-legume crop after a legume to an increase in N availability or to other rotational effects, or their interaction. Isotope dilution methods may be used to directly estimate the N carry-over to subsequent crops, but these approaches are open to multiple interpretations (Chalk et al., 2014).

'Non-N-effects' of legumes refers to impacts mediated by biotic factors such as the occurrence of pests, weeds and diseases, and abiotic factors such as changes in the availability of water or nutrients other than N, changes in soil pH, or changes in soil organic matter and soil structure. While many studies in SSA assessed N dynamics in legumes by measuring N_2-fixation rates, legume field N balances and N uptakes by subsequent crops, the non-N-effects effects are often neglected. Nevertheless, the non-N-effects may be of great importance. For instance, in environments with intense striga pressure (*Striga asiatica* or *S. hermonthica*), a non-host legume crop can drastically reduce the striga seedbank leading to lower striga densities and strong yield increases of cereals in rotation relative to continuous cereal cultivation (Franke et al., 2006; Rusinamhodzi et al., 2012). Also in temperate climates, the impact of legumes on biotic factors can be as important as the N effects where soil N is limiting (Kirkegaard et al., 2008). However, the question remains how widespread such strong impacts of legumes on biotic constraints of subsequent crops are. Apart from biotic stresses, legumes may influence the activities of other rhizosphere organisms that stimulate or suppress plant growth or available nutrients. The biotic impact of pests and diseases occurring belowground are hard to quantify, which explains why they receive little attention in field studies. An additional complexity to quantify some of the non-N-effects of an abiotic nature is the slow rate at which they change. Impacts of crop rotations on soil fertility parameters such as soil organic matter contents, soil structure and water holding capacity are typically only visible in longer-term experiments including several cropping cycles, which are scarce in SSA.

We are unaware of any recent studies that synthesise and structure the knowledge on the rotational benefits of grain legumes in the (sub-) tropics. Given that much less fertiliser is used in SSA than in other regions of the world, the contributions of N_2-fixation are particularly important (Giller et al., 2013). Here we review the literature on the rotational effects of grain legumes, with a specific emphasis on SSA. Cropping systems in SSA outside the humid forest zone tend to be dominated by cereals, particularly maize, millet, sorghum and rice, combined with root and tuber crops where rainfall is adequate (Dixon et al., 2001). Specifically we: 1) Quantified the magnitude and variability of rotational effects of legumes on subsequent cereals; 2) Explored the importance of environmental and management factors in determining variability in rotational effects; and 3) Evaluated the evidence of the different mechanisms that explain rotational effects of legumes on subsequent crops.

2. Methods

2.1. Literature search

We systematically searched the Web of Science with the terms "legume* AND maize AND rotation", "legume* AND sorghum AND rotation*", "legume* AND millet AND rotation*", "legume* AND rice AND rotation*" and "legume* AND rotation* AND Africa" and selected publications on experiments in SSA. Checking the references of the papers retrieved yielded six more papers. We also included a study from the current special issue. Only publications presenting primary source data from on-station or on-farm field experiments were included in the subsequent analysis. Legume-cereal mixed cropping experiments were excluded for two reasons: i) they are difficult to compare with monocrops of legumes and cereals and ii) the impacts on crop productivity depend strongly on spatial and temporal crop patterns. A requirement for inclusion of a study was that the cereal crops belonged to the same variety across treatments and were managed in the same way (including nutrient application rates). Where experiments were unbalanced, results from treatments were selected in such a way to ensure that treatments with cereal after cereal and cereal after legume were comparable. Where publications described experiments replicated across countries, districts representing different agro-ecologies, or different legumes or cereals, each comparison was considered separately. Similarly, if rotational cycles were repeated or N fertiliser treatments were applied to the cereal, results from individual cycles and N treatments were used. Results were averaged in case studies were conducted in multiple locations within the same districts or agro-ecology, or when studies included additional treatments such as different soil cultivation types or fertiliser applications to legumes. To compose the scatter graphs in Fig. 1 however, all individual treatments that could be extracted from the publications were used. To assess impacts per region, we divided studies from West Africa into three broad agro-ecological zones (AEZs): the humid forest/derived savannah (> 1200 mm rain, > 250 growing days per annum), the drier Guinea savannah (700–1200 mm rain, 150–250 growing days per annum), and the arid Sudano-Sahelian zone (< 700 mm rain, < 150 growing days per annum). Studies from Southern and East Africa were too few to be divided. A search on the Web of Science using the terms "tuber AND legume AND Africa" yielded few publications on legume-tuber mixed cropping, supporting the choice to focus our study exclusively on legume-cereal rotations.

To disentangle the different types of rotational effects of grain legumes on cereals, we extended our literature search with terms such as "N nutrition OR P nutrition", "N fertiliser replacement", "pest", "weed", "disease", "soil structure", "organic matter", "pH", "nematodes" in combination with "cereal* AND legume*". Again, we focused on studies