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Rethinking Agricultural Systems in the UK

Sustainable intensification: a pivotal role for legume supported cropped systems

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Summary

Agroecology identifies nitrogen (N) use inefficiency as a major cause of the ecosystem service dysfunctions associated with modern intensive farming and the use of non-renewable resources. Agroecological insight also asserts that there are immediately available environmentally sensitive and profitable agronomic approaches that may be used to help remedy this situation. Foremost amongst these is the use of legume supported crop systems (LSCS), to provide a source of renewable nutrients and encourage natural nutrient cycling. This effort should be underpinned by the use of precision farming technologies. Specifically we highlight the importance of approaches which support the uptake of LSCS with specific regard to: 1) establishing research agendas that aim to quantify the proportion of N derived from air (%Ndfa), by legumes and understanding more fully how we may best manage (using precision farming technologies), the passage of N; 2) breeding new crop varieties (legume and non-legume), which can best exploit renewable sources of N from production methods that encourage renewable nutrient cycling; 3) developing extension services dedicated to ensuring insights are communicated effectively to farmers, and; 4) introducing policies that encourage the uptake of LSCS by farmers and strengthen the capability of the wider agrifood chain to increase the market demand for legume based products.

Key words: Legume supported crop systems, %Ndfa, renewable nutrients, renewable nutrient cycling, agrifood chain

Introduction

Numerous so-called ‘non-conventional’ approaches to agriculture are practised and may be encapsulated by terms that include ‘organic’, ‘agroforestry’ and ‘permaculture’. These approaches share a common aim to deliver a self-regulating system which is constant in its capacity to provide fertile soil, crop protection and stable yields, from an informed understanding of the interdependency of key components of farmed systems. These components and their optimal state may be identified and characterised as: 1) Productivity, of the crops and wild plants is maximised; 2) Resources, (nutrient applications, land, labour and capital) are used efficiently; 3) Inputs, of other materials from sources that are external to the production system should be minimised; 4) Diversity of the crop and wild species are optimised, and; 5) Ecosystem services are not compromised. These goals have been encapsulated by the term "sustainable-intensification", and the underpinning methods are seen as means by which we may reconcile the trade-offs that currently exist between maximising productivity and profitability whilst improving essential ecosystem services (Foresight, 2011).

It has been shown that agriculture has been a major cause of changes which have pushed the environmental tolerances beyond "planetary boundaries" (Rockström *et al*., 2009). One of the most important reasons for this is the excessive use of man-made nitrogen (N) fertilisers, which has been identified as a major cause of dysfunctions that are associated with many of today's conventional agricultural practices (Matson *et al*., 1997; Galloway *et al*., 2007; Erisman *et al*., 2008). For example, a 2-fold greater yield increase in conventional monocropped systems may be achieved with *c*. 7-fold or more increase of N fertiliser (and with 3- and 2-fold phosphorus and water use, respectively; Cassman, 2002; FAO, 2011, 2012), and despite the short term profitability of intensive inorganic fertiliser use, productivity levels per hectare decline over the long term (Ju *et al*., 2009). This is a function of depleted soil-C, -N, -Zn, -P and -K. In addition, stochastic environmental factors driven by climate change leading to a limitation of growth season, solar radiation and high temperature stress are also underpinning causal agents of yield decline (Ladha *et al*., 2003). Yield stasis and decline are therefore now real features of modern intensive agriculture in several parts of the world (Foley *et al*., 2011), including the UK.

Nevertheless, as the human population increases global food supplies must match demand within the next two decades by avoiding waste in the processing and supply chains, and by intensifying agricultural efficiency (FAO, 2009*a*). UK agriculture, including the associated extension services, is expected to play their part in this by improving nutrient use efficiency and closing yield gaps. Crops currently perform at 60% of their genetic potential. Conventional agriculture could adopt farming methods that employ the use of renewable, as opposed to non-renewable resources, and use precision agriculture to underpin management strategies that support renewable nutrient cycling (Foley *et al*., 2011). Comparing average yields of conventional and sustainably managed systems, the latter can be only 5% lower than the former provided that the management exploits renewable nutrient cycles in rain-fed systems sown with perennial-legumes on near pH neutral soils (Seufert *et al*., 2012).

A Pivotal Role for Legumes

In natural systems legumes are often "pioneer plants" which occur most commonly in soils of low nutrient status due to their capacity to fix inert atmospheric di-N gas into biologically useful ammonia initially, and then more complex nitrogenous compounds; the performance of legume crops reflects their functional history. However, empirical data on the proportion of N derived from air (or "%Ndfa") for legume crops in the UK are lacking. Estimates from mathematical models suggest that globally an estimated 100 million tonnes of fertiliser N is industrially fixed per year by the Haber-Bosch process. Additionally, it is estimated 50–140 million tonnes of N is fixed per year by crop-plant associated biological N fixation (BNF; Unkovich *et al*., 2008). We should, therefore, aim to increase the N provided by BNF at the expense of Haber-Bosch-derived N, and ensure that a significant quantity of the biologically derived N is made available for non-legume crop growth. Other countries have embraced legume supported crop systems to the benefit of their environment and their economies. For example, pasture legumes are estimated to have contributed 80% of the N input into Australian agriculture (Angus, 2001; Angus & Peoples, 2013). In Brazil, 13 million ha of cropped (nodulated) soybean translates into an annual direct saving on fertiliser of $2.5 billion (Alves *et al*., 2003). This value will increase if the pre-crop effects are taken into account: i.e. subsequent non-legume yield increases and reductions in inorganic chemical applications on the subsequent non-legume crop.

Modelling gross margins for crop-rotations across the various pedoclimatic regions of Europe showed that that average gross margins of cereal followed by cereal was +3€ ha^{-1}, and +226€ ha^{-1} if cultivated after grain legumes; this was mainly due to the pre-crop yield effect and reduced mineral fertiliser application (Reckling *et al*., 2013). Aggregated gross margins across the whole crop-sequences were +34 to +110€ ha^{-1} for legume supported rotations, and this range was related to soil character as it increased from sand to loam, respectively (Reckling *et al*., 2013). However, the evaluation has still to take into account the added economic potential of reductions in the cost of pesticide applications (compared to monocropping a single species succession), improvements in attempts to close yield gaps, and other benefits of ecosystem services that may be provided over the longer-term.

The legume, therefore, relies on its capability to respond to N deficiency by increasing its growth and BNF. Indeed, legume growth is not only unrestricted by N limitation, it may even be enhanced, as indicated in Table. 1: where N limitation and reliance on BNF caused increases in shoot (1.5-fold), plus root and grain (both 2-fold; *P*<0.001, ANOVA).

Table 1. *Average dry weight data (g ± SE, plant^{-1}), for shoot, root and grain at harvest for pot-grown faba bean varieties*

Plant Part	N Source	
	BNF	Inorganic
Shoot	15.55 ± 2.75	10.53 ± 2.22
Root	5.72 ± 1.38	2.88 ± 0.76
Grain	18.45 ± 0.10	9.79 ± 2.80
R:S Ratio	0.42 ± 0.10	0.28 ± 0.06

(n = 14; eight spring and six winter types from the Processors Growers Research Organisation Recommended List for 2012). The root medium consisted of sterile perlite:sand (50:50 [w/w]). Plants were either rhizobium-inoculated to acquire nitrogen (N) from biological N fixation (BNF), or were fertilised with inorganic N (equivalent to a steady state provision equivalent to 0.15 kg N ha^{-1} as KNO_3 for the whole of the life-cycle). The N-containing medium was pH regulated to match the micronutrient-only provision given to the N-fixing plants. Average data of all cultivars was used as there was no significant difference between cultivars. 'R:S', denotes root to shoot ratio.

Varieties, and especially the legume varieties, should be matched to suit practices that utilise renewable source of nutrients and which encourage natural nutrient cycling. Recent work at the Centre for Sustainable Cropping at the James Hutton Institute assessed faba bean (*Vicia faba* L.) grain N levels (Table 2). This showed that grain N is derived mainly (*c*. 85% of the total N on average) from air. However, the greatest N levels were found for three cultivars (highlighted as grey shaded cells in Table 2), when they were grown under a sustainable management that used only renewable sources of N, as this resulted in a greater capacity for both BNF and assimilation of soil N.

It may also be argued that legumes are not equal in their pre-crop effect and a life cycle analysis for faba bean has demonstrated that services (additional to N provisions by BNF) include provision of high quality protein (suitable for humans and aquaculture industries: see www.beans4feeds.net), mobilisation of phosphorus, increased provisions to pollinators and other beneficial insects, reduced tillage intensity, reduced energy use and greenhouse gas emissions, and offset of food miles from the importation of foreign grain legumes (Köpke & Nemecek, 2010). Additionally, a comparative analysis of different grain legumes showed that faba bean had a significantly greater

Table 2. *Quantities (kg N ha^{-1} yr^{-1}), and sources of nitrogen (N) in faba bean grains harvested from field halves that were managed either sustainably (Sus.) or conventionally (Con.) at the James Hutton Institute Centre for Sustainable Cropping (2012)*

N Source		Total (BNF + soil)		BNF		Soil	
Treatment		Con.	Sus.	Con.	Sus.	Con.	Sus.
Cultivar	Fuego	160 ± 19	111 ± 15	131 ± 14	86 ± 11	29	25
	Pyramid	229 ± 24	198 ± 18	220 ± 13	145 ± 29	9	54
	Ben	146 ± 20	310 ± 30	142 ± 27	276 ± 36	4	34
	Tattoo	252 ± 26	207 ± 28	199 ± 27	218 ± 11	53	89
	Maris Bead	229 ± 23	280 ± 25	210 ± 14	210 ± 16	18	70

N derived from biological N fixation (BNF) was determined using the 15N natural abundance technique (Unkovich *et al*., 2008). N assimilated from soil was estimated by deduction from total N levels.

effect than others on the yield of subsequent cereal grain crops (Wani *et al*., 1991; Hauggaard-Nielsen *et al*., 2009, 2012). Also, faba bean varieties possess vigorous tap roots that deliver benefit throughout the soil profile, thus improving soil structure, stabilising soil aggregates and improving root proliferation of subsequent crops (Rochester *et al*., 2001, 1998). Such pre-crop benefits of grain legumes are generally achieved without the use of a catch crop and yet for maximum utility it is important that the N mineralised from the legume residues are not lost over winter. However, the use of a relay-crop sown to act as a cover or catch-crop to mitigate this loss is not used by UK

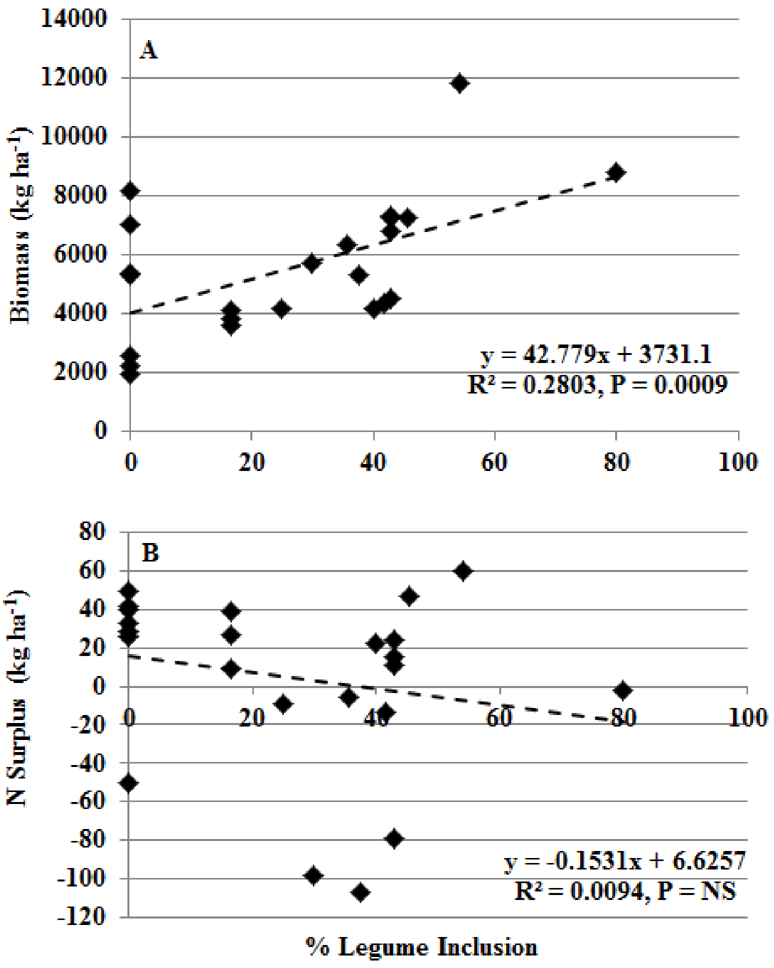

Fig. 1. A comparative analysis of crop rotations which did (n=22) or did not (n=7) include legumes. Trends in response to the level of legume inclusion (%) are shown for: A, yield, as biomass (t ha^{-1} yr^{-1}), and; B, N-surplus (kg ha^{-1} yr^{-1}).

grain-legume producers. Such an approach would be especially useful to many UK farmers who must harvest so late in the growing season that establishing a follow-on winter crop is not feasible. Beyond the conservation of nitrogen, additional benefits from catch crops include improved soil structure, increased organic matter content, reduced soil erosion and weed densities (Hartwig & Ammon, 2002). An analysis of historical data gathered from countries throughout Europe, and for crop rotations which were, or were not, supported by legume-based crop-rotations has also demonstrated that as the proportion of legume inclusion within the crop rotation increases yield (as biomass) increases (Iannetta *et al*., 2012; Fig. 1A). In addition, N-surplus remained adequate as it was not significantly reduced by increasing the proportion legumes included within the crop rotation (Fig. 1B).

Legumes and Intercropping

The positive picture for mono-cropping with legumes may be improved further if we were to also consider intercropping. In nature, legumes rarely exist in pure stands but as a naturally occurring community with non-legumes, often grasses. In an agronomic context, legumes need not be considered as monocrops. Intercropping is often the most efficient farm practice to maximise food production as determined by the land equivalent ratio (or LER), under conditions of low inputs, whatever the limiting input(s) may be (Vandermeer, 1992). Though additionally, there is a lack of understanding of the specific (soil) environment conditions and plant traits that underpin LER > 1: .Nevertheless, intercropping can deliver yields which are higher and more stable, as yield losses due to environment, weeds, pests and pathogens are mitigated. This is achieved as intercropping exploits a fundamental phenomenon of natural systems by exploiting functional diversity, competition and facilitation via rhizodeposition (Fustec *et al*., 2009; Köpke & Nemecek, 2010).

Collectively, the agroecological evidence serves to highlight the multifunctional nature of the various legumes types. It also highlights how their potential can be realised by informed management practices which focus upon optimising the natural cycle of nutrients from renewable sources. However, optimising this realisation in field is inhibited by the neglect of extension services that could be dedicated to ensuring that agroecological research insight gained from the study of legume supported crop systems (LSCS) and precision-farming-based is communicated effectively to farmers. Additionally, crops (legumes and non-legumes), can and should be bred to access renewable sources (BNF and farm yard manure), rather than inorganic sources of soil N (Dawson *et al*., 2008), and in intercropped systems. Yet, and despite this evidence, there are as yet no formal UK plant breeding programmes to help realise this.

LSCS and Precision Farming

The efficacy of LSCS is largely dependent on spatial and temporal structuring of a range of variables, particularly pH (Weisz *et al*., 2003; Adamchuk *et al*., 2004), phosphate concentration (Weisz *et al*., 2003; Marques da Silva *et al*., 2008; Serrano *et al*., 2011*a*), rainfall (Ginting *et al*., 2003), and topography (Ginting *et al*., 2003; Marques da Silva *et al*., 2008). Effective management of soils and the environmental impact of fertilisers have gained attention in recent years, but the adoption of appropriate technologies to monitor and mitigate these effects within British farming has been slow. For example, the proportion of farms in England using GPS autosteer and guidance, soil mapping, and variable rate application (VRA) has been estimated at 22%, 20% and 16% respectively (Defra Farm Practices Survey, 2013). The range of available equipment varies from capacitance probes to measure dry yield of field biomass of diverse swards, to high resolution methods requiring ground-truthing and correction, e.g. spectral reflectance/field spectrometry, vegetation indices (VI), maximum likelihood classification (MLC), and remote-sensed satellite imagery, in addition to the more conventional yield monitors. The abundance of precision assisted technologies (PATs) has created the potential for rapid and accurate quantification of legume inputs into a range of farming systems, e.g. pasture biomass (Marques da Silva *et al.*, 2008; Biewer *et al.*, 2009; Serrano *et al.*, 2011*a*,*b*); cereal-legume rotations and intercrops (Ginting *et al.*, 2003; Weisz *et al.*, 2003; Adamchuk *et al.*, 2004; Griffin *et al.*, 2008; Färe *et al.*, 2009; Fuerst *et al.*, 2010; de Castro *et al.*, 2012); and undersown with cereals in vineyards as a weed suppressant and supplementary nitrogen source (Panten *et al.*, 2010). The growth of the precision market is estimated to reach $3.72bn globally by 2018, at an estimated compound annual growth rate (CAGR) of 13.36% from 2013 to 2018 (MarketsandMarkets, 2013). With the rise of PATs for farming it is now possible to measure, quantify, and target farm activities to improve resource use efficiency, reduce environmental impacts, and maximise profitability.

However various factors present challenges for quantifying costs *versus* benefits, most importantly a high level of site heterogeneity, a lack of accessible spatial analysis tools for field-scale experiments, and the paucity of UK-based experiments to investigate the efficacy of PATs within legume-based systems. Two major weaknesses impeding progress in the UK have also been identified as a 'fragmented research base' and 'depletion of applied science capacity' (ESP-KTN: Precision Farming, 2013).

Applied research agendas compound these shortcomings. For example, key documents aimed to influence UK agricultural policies do not recommend any legumes as priority crops for UK research agendas (e.g. see Royal Society, 2009, recommendation 2). The model legumes (*Lotus* and *Medicago*) are useful for academic purposes. However these crop species sit in a relatively small and distinct phylogenetic clade and while they may be related to existing crop legumes, they are not representative of the cropped species themselves or their behaviour *in situ*. Moreover, biotechnological approaches to improve N use efficiency are targeted at non-legumes rather than on legumes and their symbionts (e.g. John Innes Centre, 2012). At the recent 10th European N Fixation Congress Munich (2012) only one article (James *et al.*, 2012), actually quantified the N derived from air by legumes (Giller *et al.*, pers. comm.). Such situations have arisen despite warnings by Unkovich *et al.* (2010), that the application of mathematical models to estimate N fixation should not be used as a substitute for direct measurement.

Biological Nitrogen Fixation by Trees and Shrubs should also be Exploited

BNF in intercropped systems should be extended to the use of perennial N fixing shrub and tree species. Among the shrubs are *Ulex* and *Cytisus* spp. (gorse and broom, respectively), which can fix large quantities of N (Drake, 2011). In addition, there are tree species, such as alder (*Alnus* spp.), that form a symbiosis with the N fixing actinomycete *Frankia*, and this association leads to generally high %Ndfa values compared to legumes (Andrews *et al.*, 2011). Such species are being used in conjunction with non-N-fixing tree crops in alley-cropping systems farmed in an organic-agroforestry based approach (http://www.organicresearchcentre.com/), though the potential benefits remain to be quantified accurately in terms for both N resource and financially (*cf.* Munroe & Isaac, 2013). Biological control is facilitated by structurally complex landscapes (Thies & Tscahrntke, 1999), and the grassy margins and habitats such as those that grow around the base of trees and hedgerows can act as reservoirs of crop pest predators (Thomas *et al.*, 1992) which can disperse into crops (Oaten *et al.*, 2007; Hoff & Bright, 2010). Analysis of FAO data has also indicated that the negative impacts of pesticides on pollinator-dependent vegetable production is mitigated in areas of sufficient forest cover (Basu *et al.*, 2011), a finding that indicates the potential and commercial importance of maintaining sufficient agroforestry area. Agroforestry can improve soil-quality and -carbon sequestration, biodiversity conservation, and air and water quality (Jose, 2009), and we would therefore argue that agroforestry in the form of alley cropping should be deployed as part of, and not separate to, diversified cropped systems that aim to improve pest management and increase crop yield (*cf*. Letourneau *et al*., 2011).

Closing Comments

The wider points presented here are that there are externalities of conventional agriculture that are not reflected in the value of the product, and that there are agronomic approaches that may be pursued immediately to underpin the UK's agricultural capacity for sustainable intensification. The reduced yields from certified-organic practices are mainly due to pests and diseases in legumes (de Ponti *et al*., 2012), and so using BNF by legumes in conjunction with management strategies which encourage natural nutrient cycling and conventional pest and disease control measures (informed by precision farming), could and arguably should, bring the best of both worlds together, and in the short-term. The challenge is then one of economics, specifically ensuring improved and stable yields with increased gross-margins for those farming novel legume-based systems, as well as other challenges including influencing farmer preference away from high input monoculture systems. Farm subsidies could present long-term encouragement of crop systems that optimise renewable nutrient use and more sustainable economic improvement on farm, and could be achieved via two key policies which support: 1) the development of dedicated extension services to ensure the communication of effective strategies for renewable nutrient cycling; 2) the collective action of food-technologists, -processors and -retailers along-side public-health and marketing specialists to provide new markets for legume-based products. After all, the human health benefits of grain legume-derived food products are already proven, and include lowering blood cholesterol, and the consequences of coronary heart- and cardiovascular-disease (Kushi *et al*., 1999; Nagura *et al*., 2009). In addition, a global analysis has shown that GDP growth originating from agricultural improvements are at least twice as effective as growth generated in non-agricultural sectors in benefiting the poorest of a country's population (FAO, 2009*b*).

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