LEGUME BASED PLANT MIXTURES FOR DELIVERY OF MULTIPLE ECOSYSTEM SERVICES: AN OVERVIEW OF BENEFITS

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SUMMARY

As costs for mineral fertilizers rise, legume-based leys are recognised as a potential alternative nitrogen source for crops. Here we demonstrate that including species-rich legume-based leys in the rotation helps to maximize synergies between agricultural productivity and other ecosystem services. By using functionally diverse plant species mixtures these services can be optimised and fine-tuned to regional and farm-specific needs. Field experiments run over three years at multiple locations showed that the stability of ley performance was greater in multi-species mixtures than in legume monocultures. In addition, mixing different legume species in the ley helps to suppress both early and late weeds. Further, combining complementary phenologies of different legume species extended forage availability for key pollinator species. Finally, widening the range of legume species increases opportunities to build short term leys into rotations on conventional farms via cover cropping or undersowing.

INTRODUCTION

The demands for increasing food productivity from farmland are often seen to be in conflict with non-farmed habitats. At the same time, a similar conflict is seen to arise on farmed land itself, where crop productivity may not always easily be reconciled with the provision of other ecosystem services such as biodiversity conservation, flood amelioration, carbon storage or cultural benefits. In a three year study we asked if it is possible to design a part of the agricultural ecosystem for simultaneous optimization of productivity and other ecosystem services such as biodiversity conservation.

Our approach was to use functionally diverse species-rich leys with nitrogen fixing legumes in the rotation. Nitrogen is a key nutrient to achieve acceptable yields and crop quality (Smil, 2011). Due to globally rising costs of mineral nitrogen fertilizer and concerns over the negative environmental impact of anthropogenic nitrogen (Canfield *et al*., 2010), agricultural policy makers, farmers and scientists are increasingly paying attention to the use of leguminous plants as an alternative source of nitrogen. Legumes, through their symbiosis with rhizobacteria are able to fix aerial nitrogen and provide it in a form that is readily available to plants (Long, 1989). After growing legumes in a rotation, nitrogen accumulated in the plants' above-ground and below-ground residues is broken down by microbial activity and released for the take up by the following crop. This use of legumes for fertility-building in the rotation is adopted in farming systems where the use of mineral nitrogen fertilizer is either too expensive, or, as in organic agriculture, not permitted (Watson *et al*., 2002). Because of its function as the main nutrient provider, this stage in the rotation is of central importance for organic (and also increasingly non-organic) farming systems. Furthermore, legume-based leys provide additional benefits for soil management through soil cover and reduced soil disturbance.

Depending on climate and soil and the suitability of the land for arable production, the ley phase on organic farms can vary in duration from short term (12-18 months) to long term (around 5 years), but typically the ley is kept for about 18 months to 3 years. In Europe, organic farmers most frequently use grass-clover mixes for their leys, with white clover (*Trifolium repens*), red clover (*T. pratense*) being popular legume species, and perennial ryegrass (*Lolium perenne*) and Italian ryegrass (*L. multiflorum*) as commonly chosen grass species. Thus, currently used leys are relatively species-poor. The potential for nitrogen fixation by these leys is high but the establishment of simple grass-clover leys is often sub-optimal as a result of the cool, moist conditions required by white and red clover species.

In addition, the current practice of using mixtures of red or white clover and rye-grass in fertility building leys can lead to an asynchrony between the release of nutrients following incorporation of the green manure and the demands of the following crop. One way to improve the efficiency of the system would be to combine several legume species in a mixture, including a number of slower growing species, that would result in a more complex residue structure with a better nutrient release profile.

In a three year study across multiple locations in the UK, we studied if ley performance and the provision of multiple ecosystem services can be simultaneously improved by exploiting the functional diversity of various legume species. In particular, we studied productivity in the ley and in the following crop, weed suppression, decomposition, pollination, and the provision of invertebrate resources for farmland birds. Here we describe the general methodology of this approach and report first results.

MATERIALS AND METHODS

Set up of Replicated Field Trials

We set up replicated field trials at six sites across the UK, evaluating various legume and grass species in monocultures and in an All Species Mixture (ASM) (Tables 1 and 2). In these experiments we trialled 18 treatments. Twelve legume species and four grass species were each grown singly as monocultures; in addition, two treatments were reserved for the All Species Mixture, which was grown with and without *Rhizobium* inoculation. At all six trial locations, the experiments were sown in spring 2009 (Table 2). All trials were laid out as one-factorial randomized complete block designs with three replications. Seed lots of the four clover species, the vetch, the lucerne and one of the All Species Mix treatments were inoculated with rhizobial preparations before sowing, with 1% substrate per seed weight. The locations, plot sizes, and sowing dates are listed in Table 2. Trial sites were distributed over a large geographical area within the UK.

To assess the after-effects of the legume species in the rotation, i.e. after incorporation of the ley plots into the soil, a cereal was grown at two sites for yield assessment (winter wheat, sown in autumn 2010 at Rothamsted and spring wheat, sown in spring 2011 at Wakelyns).

Table 1: Details of replicated trials: locations, plot sizes and sowing dates

	North	West	Altitude (m)	Plot size (m x m)	Sowing date (2009)
Barrington Park	51°49'52.2"	1°40'12.3"	150	1.5 x 10	20/04
Duchy	50°13'38.2"	5°18'23.0"	42	1.5 x 5	24/04
IBERS	52°25'48.1"	4°01'22.1"	29	2 x 8	23/04
Rothamsted	51°48'38.6"	0°22'02.4"	114	2 x 5	15/04
SAC Aberdeen	57°11'05.6"	2°12'45.1"	109	1.5 x 12	13/05
Wakelyns	52°21'36.7"	-1°21'09.2"	51	1.2 x 10	29/04

Table 2: Legume and grass species included in the trials: Latin and common name; seed rate (in kg/ha), seed weight (Thousand Kernel Weight, TKW in g) and seed rate in the monoculture plots (Monoc.) and in the All Species Mix (ASM)

			Seed rate (kg/ha)		
Abbrev.	Latin name	Common name	Monoc.	ASM	TKW
AC	*Trifolium hybridum*	Alsike clover	10	1.25	0.7
BT	*Lotus corniculatus*	Birdsfoot trefoil	12	2.5	1.2
BM	*Medicago lupulina*	Black medic	15	2.5	1.6
CC	*Trifolium incarnatum*	Crimson clover	18	2.25	3.1
IR	*Lolium multiflorum*	Italian ryegrass	33	1	2.9
LT	*Lotus pedunculatus*	Large birdsfoot trefoil	12	2.5	1
LU	*Medicago sativa*	Lucerne	20	2.5	2.4
MF	*Festuca pratensis*	Meadow fescue	25	1.25	2.14
MP	*Lathyrus pratensis*	Meadow Pea	75	3.25	153
PR	*Lolium perenne*	Perennial ryegrass	33	2.5	2
RC	*Trifolium pratense*	Red clover	18	2.5	1.8
SF	*Onobrychis viciifolia*	Sainfoin	80	5	19.2
TY	*Phleum pratense*	Timothy	10	0.5	0.32
WC	*Trifolium repens*	White clover	10	1.5	0.5
SC	*Melilotus alba*	White sweet clover	18	0	2.3
WV	*Vicia sativa*	Winter vetch	100	0	41

Measurements and Assessments

At all sites a number of eco-physiological traits was measured several times during the first growing season (2009), including height, C:N ratio, and relative growth rate. In addition, at one site, Rothamsted Research, the number of pollinators and phytophagous insects supported by the different species was also recorded. Yield of the following cereals was quantified on 1 m^2 per plot.

Modelling: Competition Model

A simulation model of inter-plant competition was used to predict the performance of the legumes when grown in different species mixtures. The model used daily weather data to calculate the radiation intercepted by each species in the canopy and temperature dependent photosynthesis and growth rates. The model was validated using external datasets and was used to predict the biomass of possible legume mixtures as well as the biomass proportions of their component species.

Modelling: Determining Functionality of Mixtures

Using regression analyses, plant traits were related to various functions (Violle *et al*., 2007); these were weed suppression, yield of the following crop, regrowth, soil fertility, and biodiversity value. The competition model was then used to predict the community weighted mean of different plant traits for various mixtures; this aggregated trait of the mixture is the weighted average of the traits of individual mixture components. The weights are generated by the competition model (see above) by calculating the different species' proportions in the mix. Community weighted means of the traits can then be used to predict the function values of any mixture. Finally, an aggregated function of agronomic productivity was calculated as the harmonic mean of the values for weed suppression, yield of the following crop, regrowth, soil fertility.

RESULTS

Performance of All Species Mixture in Relation to Monocultures

The stability of ley performance was greater in the ASM (multi-species mixture) than in legume monocultures (Figure 1). The All Species Mix also showed higher weed suppression than the average of the monocultures (Döring *et al*., 2012).

Model Output

A number of significant relationships between plant traits and different agronomic and ecological functions were quantified using regression analysis: numbers of phytophagous insects and rate of re-growth were related to specific leaf area (leaf area/leaf weight), abundance of pollinators to flowering traits and weed suppression to height and seed size. Winter wheat yield was significantly related to biomass of the previous legume species.

These relationships were used to predict the agronomic function and biodiversity function of the individual legume and grass species and of different mixtures. Preliminary analyses show that mixes containing both lucerne and white clover score highly regarding the agronomic productivity function. The additional inclusion of crimson clover in such a legume-based mix will then increase the value for pollinators because of its early flowering time. In addition, this species offers to reduce early weed growth (Döring *et al*., 2012). Importantly, the growth pattern of crimson clover as an annual species is complementary to lucerne and white clover so that a mix of these species increases resource use efficiency and reduces interspecific competition. Finally, crimson clover emerged as a species with relatively high C:N ratio. When combined with lucerne or white clover that show lower C:N ratios, crimson clover can thereby potentially contribute to a more spread-out N supply.

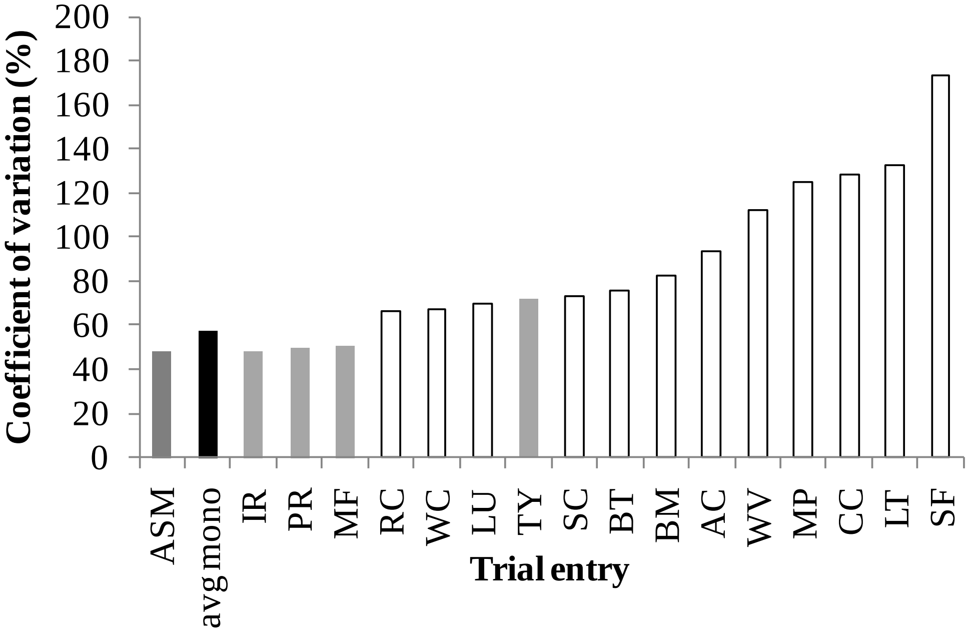

Figure 1: Coefficient of variation (CV, %) on biomass over six trial locations (Table 1). Abbreviations of trial entries see Table 2; grasses are shown with light grey columns, legumes with white columns. The CV of the All Species Mix (ASM, dark grey column) is lower than the average CV of the monocultures (not shown) and it is also lower than the CV of the average biomass of the monocultures (avg mono, black column)

DISCUSSION

Mixing different legume species in the ley has several advantages: it suppresses both early and late weeds (Döring *et al.*, 2012); it extends forage availability for key pollinator species (Brown *et al.*, 2012); and it increases stability of performance (see Figure 1). In addition, mixing species may help to increase the reliability of establishing the ley; further, by producing residues with different carbon to nitrogen ratios mixtures also provide opportunities for modifying decomposition rates to improve the synchrony between nitrogen release following incorporation and crop nitrogen demand. Finally, widening the range of legume species increases opportunities to build short term leys into rotations on conventional farms.

The simulation model used in this study has shown the potential to generate a range of optimal mixtures that deliver multiple functions. This includes new varieties of legumes, or even new species; if their plant traits are measured, their functions can be determined and their performance in potential mixes can be predicted. Therefore, the combination of the simulation model and relationships between plant traits and ecosystem functions provides a powerful tool for exploring the performance of a large number of mixtures in terms of the delivery of multiple services.

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