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Front cover:
Mixture of vetches and cereals.
Photo courtesy Jaume Lloveras.

Resource acquisition and ecosystem services provided by bi-specific cover crop mixtures

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Abstract: Multi-service cover crops are used to provide ecosystem services, particularly for nitrogen management, such as "nitrate catching" and "green manuring" effects. Sowing cover crop mixtures including legumes and non-legumes have the advantage of combining the provision of both services related to N management thanks to phenomena of niche complementarity and/or facilitation in the capture of abiotic resources. When complementarities are optimized, these species mixtures can achieve both effects similarly to those provided by the average of mono specific cover crops, especially for nitrate catching. In addition, the complementarity for the access to light thanks to species having different aerial architectures and contrasted temporal complementarities enable them to obtain services in relay, in particular in the case of the longest fallow periods over mid-Spring. However, in order to achieve the targeted services, attention must be paid to limit competition between species in particular during early stages.

Key words: Catch crop, green manure, nitrogen, intercropping, complementarity, facilitation, competition

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Introduction

Multiservice cover crops (MSCC) are sown between the harvest of a main cash crop and the sowing of the next cash crop (fallow period) to provide various ecosystem services, such as reducing nitrogen losses through nitrate leaching – the "nitrate catching" effect and supplying mineral nitrogen to the next cash crop – the "green manuring" effect. In addition, these MSCC can also protect the soil against erosion, explaining why they are so called "cover crops" (e.g. 1).

The effects of cover crops have been widely studied in the literature as monospecific crops and these effects seem to be contrasted according to the species sown (2, 3). In particular, although all species can produce ecosystem services related to nitrogen management, legume species are more efficient than other species in providing a "green manuring" effect due to their ability to acquire nitrogen through symbiotic fixation of atmospheric N_2 (e.g. 4). Because of this property, legumes are able to acquire a large amount of nitrogen, without N-fertilizer or in low soil N availability. With a low C/N ratio (high N concentration), legumes favour rapid mineralization of this nitrogen after their termination and incorporation into the soil (5, 6). On the contrary, species other than legumes, particularly crucifers, are generally more effective in catching residual mineral nitrogen in the soil – the "nitrate catching" effect – and thus can strongly reduce nitrate leaching and thus enable to mitigate aquifer pollution (7).

An interesting way of simultaneously combining the two "nitrate catching" and "green manuring" ecosystem services is to sow species mixtures including legumes and non-legumes plants (e.g. 4, 8 - 10). This practice can be seen as a form of ecological and eco-functional intensification for sustainable agricultural production (11, 12) whose principle is based on the complementary use of resources between species.

To be effective, species must not strongly compete for the same resource niche to reach complementarity as it is the case for nitrogen in legume/non-legume mixtures (13 - 16). Interactions between species are complex and evolve during the crop cycle (17). Several studies carried out on cereal–legume cash mixtures have focused on the dynamics of interactions between species and have made it possible to illustrate this complementarity resources use, whether it is a question of light interception or nutrient acquisition which ultimately explains the performance of these mixtures, particularly in terms of yield (14, 18 - 21).

In the case of MSCC whose growth duration is reduced to a few months (from 2 to 6 months), the study of these interspecific interactions in dynamics allows us to refine our understanding to ultimately optimise the species mixture according to the targeted

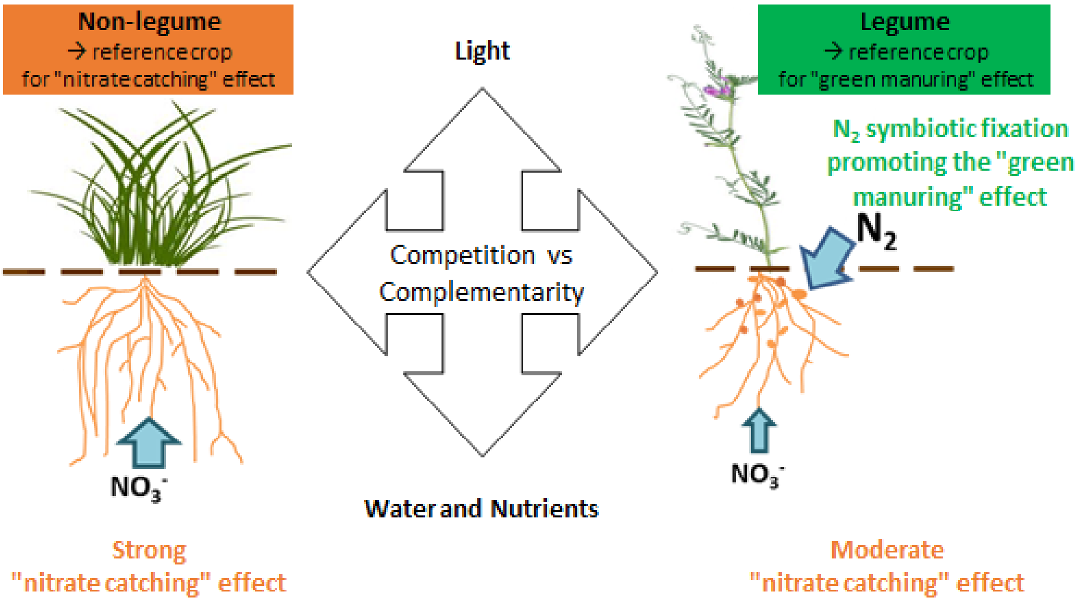

Figure 1. Diagram of interactions between species in relation to the production of nitrogen management services.

services. Indeed, these services, notably "nitrate catching" and "green manuring", will depend, among other things, on the growth duration, the date of termination of the cover crops and the selected species (5). The objective of this paper is to present what is known about the functioning of MSCC mixtures in order to better understand and predict their behaviour and performance for the production of the targeted ecosystem services.

Combining nitrogen management services

Combining nitrogen management services provided by bi-specific cover crop mixtures is possible thanks to complementary resource acquisition illustrated in Figure 1. In these mixtures, the non-legume crop is expected to uptake mineral nitrogen in the soil and thus reduce nitrate leaching (7, 22), whereas the associated legume, although uptaking a part of soil mineral N, will mainly fix N_2 from the air and then would produce a "green manuring" effect by increasing the concentration and content of N in plants (23, 24).

Several studies have shown that MSCC mixtures with a legume (e.g. gramineous-legume or crucifer-legume mixtures) increase biomass production but also provide ecosystem services comparable or even higher than the best pure crops, particularly with regard to nitrogen management, allowing to provide a good compromise of services higher than the average of the two pure crops (e.g. 4, 8, 25).

In fact, certain legume–non-legume MSCC mixtures make it possible to provide a "green manuring" effect close to that of pure non-legume crops. For example, according to Ranells and Wagger (26), a mixture of rye with hairy vetch would make it possible to restore a quantity of nitrogen close to that of a pure hairy vetch crop (132 kg N ha^{-1} for the mixture 8 weeks after the termination of the cover crop, against 108 kg N ha^{-1} for vetch alone and 41 kg N ha^{-1} for rye alone). Indeed, the introduction of a legume in the mixture decreases the C/N ratio compared to pure non-legume crop, especially for ryegrass–clover, rye–hairy vetch or rye–clover mixtures (8, 10, 26, 27).

Reducing C/N ratio leads to a faster mineralisation of the residues and therefore to a faster and higher quantity of nitrogen available for the following crop. Indeed, pure non-legume crops present a risk of nitrogen pre-emption due to their higher C/N ratio, which limits the net nitrogen mineralisation of the residues. However, the effect on the following crop, especially on its yield, is highly variable and depends on soil and climate conditions, but also on cropping systems and management of the mixture, especially through the date and method of termination (24). Overall, MSCC mixtures combining a legume and a non-legume crop have a neutral or positive impact on the yields of the following crop (28 - 30) whereas pure non-legume crops often have a negative effect on the yields of the following crop (31 - 34).

This type of MSCC mixtures can also be effective in reducing residual mineral nitrogen in the soil (23) and thus the potential leaching of nitrate. These MSCC mixtures can sometimes have the same nitrogen capture ability than pure non-legume, especially in relatively low mineral nitrogen environments. This is particularly the case for mixtures of radish–vetch, radish–pea and barley–hairy vetch (25, 35). Although environmental conditions greatly influence nitrate leaching, in the case of barley–hairy vetch mixtures, the reduction in the amount of N leaching has been demonstrated during the growing cycle but also after canopy termination and incorporation (25). Mixing species with legumes limits the pre-emptive competition for mineral nitrogen, particularly when the winter is dry with low drainage and leaching (36, 37).

Assembly rules for multiservice cover crops mixtures

The dynamic analysis of the performance and interactions between mixed species is intended to help in the choice of species to be mixed according to the growing conditions (soil, climate, length of interbreeding, type of main crop succession). To this end, the results obtained by Tribouillois (38) and Couëdel (39) on various experimental sites have shown that certain bispecific mixtures such as forage shuttle–black lentil or moha–purple vetch can be effective in reducing leaching close to that of pure non-legumes, but they did not always simultaneously produce a "green manuring" effect as high as that produced by pure legumes due to the dominance of the non-legume in the mixture, and vice versa.

No MSCC mixture can simultaneously achieve the maximum level for "nitrate catching" and "green manuring" services provided by pure non-legume and legume species respectively. However, we observed that in species mixtures niche complementarity and facilitation phenomena occurred and thus made it possible to reach compromises between the two services to the extent of at least 80% for each of the two targeted services, even if sown at half density of the pure cover crop (e.g. Italian ryegrass–purple vetch or phacelia–faba beans).

In addition, some species mixtures have shown different behaviours depending on the pedoclimatic sites. Thus, for the same MSCC mixture, inversions of competition between legume and non-legume plants have been observed between sites, which leads to different performances in the compromise between "nitrate catching" and "green manuring" services (4). The choice of species to be combined must therefore be reasoned according to: 1) the type of soil, which can be more or less draining, and 2) the climate, particularly the level of rainfall, which may or may not favour drainage, but also the temperatures, which may, for example, limit the development of species or destroy those that are sensitive to frost.

Finally, our results show that the choice of species mixtures must also be reasoned according to the fallow management method and in particular the date of termination of the cover crops. From an operational point of view, the following key results can be retained to design bispecific MSCC mixtures, here with examples for Southern France:

In the case of a short fallow period with early termination (between Mid-October to Early-November) followed by sowing of a winter crop or before deep tillage (in the case of clay soils), both species must develop very rapidly to avoid a strong dominance of one species over the other. In this case, a mixture of forage turnip–faba bean or white mustard–purple vetch can be used. It should be noted that the choice of crucifer could have possible allelopathic effects on the legume even if it has not been fully demonstrated yet (40).

In the case of a long fallow period with termination before winter (by End-December), preference should be given to a mixture composed of species that develop sufficiently rapidly but not necessarily synchronously. In this case, the slower growing species should not be sensitive to frost and low temperatures in order to be able to maintain a "nitrate catching" effect and increase the "green manuring" effect throughout the autumn. In this case, a mixture of ethiopian mustard–common vetch could be planted, for example.

In the case of a long fallow period with termination at the beginning of spring, it is desirable to provide both nitrogen management services while maintaining a vegetative soil cover to avoid soil erosion or structure degradation. In this case, species must be resistant to winter conditions (low senescence and/or good frost tolerance), i.e. a mixture of ryegrass–red clover can be chosen. One may also want to have a succession of these N services thanks to a temporal complementarity for access to resources, starting with an efficient "nitrate catching" effect at the beginning of the cycle followed by a "green manuring" effect in a second stage. In this case, a mixture associating a non-legume plant with early development in autumn can be sown to enhance the nitrate catching very early

Figure 2: Example of the evolution of the moha–clover mixture to provide "relay" ecosystem services through early moha development and then maintenance of winter cover with frost-resistant clover. Photographs taken: a) 4th October 2012 and b) 8th January 2013.

during autumn. This non-legume plant should be very sensitive to frost (from -1 or -2°C) to be destroyed naturally as soon as the first frost occurs, leaving the place for the legume to grow later. This is for example the case for tropical crops such as moha, fodder sorghum, nyger or buckwheat. The latter must therefore be tolerant to frost and winter conditions with a significant capacity for growth and nitrogen acquisition in late autumn and during winter in order to provide a later "green manuring" effect while maintaining soil protection (38). This behaviour was observed, for example, in the case of moha–clover and sorghum–clover mixtures (Figure 2).

Conclusion

The performance of MSCC mixtures depends on the complementarity between species, particularly with regard to the capture of resources. The dominance of one species in relation to another will determine the level of ecosystem services produced and their temporal provision. However, when complementarities are optimised, MSCC mixtures combining legumes and non-legumes crops can achieve performances close to those provided by the best pure crop and always higher than the average of the corresponding pure crops in terms of "nitrate catching" and "green manuring" services.

This effectiveness of the MSCC mixtures in combining the two effects is due to niche complementarity and/or facilitation in the capture of abiotic resources. Similarly, complementarity in terms of access to light thanks to species with different aerial architectures and contrasting temporal growth dynamics makes it possible to obtain effective MSCC mixtures to provide services in "relay" (temporal complementarity), particularly in the case of long fallow period. However, to obtain the expected effects, attention must be paid to limit competition between species for the same niche resources.

For this purpose, there are many species of MSCC that are contrasted in terms of growth capacity, frost sensitivity or maintenance of winter growth, which make the choice of the species to be mixed difficult but nevertheless essential for the success of the cover crop. Another difficulty is that the intensity of ecosystem services provided varies according to the date of termination and the pedoclimate context, requiring trade-offs between the targeted services. MSCC mixtures may have other interests than those related to nitrogen, such as improving soil protection through longer and faster soil cover, improving sulphur management, storing carbon and reducing greenhouse gas emissions (41). Finally, from a practical point of view, MSCC mixtures reduce the risk of bad sowing thanks to a diversity of sensitivities to sowing conditions. Thus these mixtures represent a form of security for achieving the targeted services (36, 40).

The choice of species must be adapted to the pedoclimate and the cropping system. In a situation with high residual mineral nitrogen in soil at harvest, or after a grain legume, it will be preferable to choose a mixture favouring the "nitrate catching" effect or a pure non-legume crop, in particular if the soil is filtering and/or the winter climate is usually very rainy. On the other hand, in a situation of a low residual mineral nitrogen, with incorporation of crop residues, and moreover in conditions of poor drainage, a mixture favouring the "green manuring" effect is recommended to avoid a nitrogen pre-emption effect for the next cash crop.

There are many factors influencing the performance of MSCC mixtures. Among them, the choice of species, the number of species to be combined and their seeding densities are probably essential factors that need to be studied further. Finally, the effects of MSCC mixtures have yet to be studied for many services, which opens up a vast field of research to be explored further. In particular, this shows the limits of classical experimentation and suggests the possibilities offered by crop models to explore this rich diversity of practices and services.

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