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# Modelling agroecosystem nitrogen functions provided by cover crop species in bispecific mixtures using functional traits and environmental factors

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## ABSTRACT

Cover crops are used during fallow periods to produce ecosystem services, especially those related to N management such as (i) capturing mineral-N from soil to reduce nitrate leaching, and (ii) improving N availability for the next main crop (green manuring). Bispecific mixtures consisting of legume and non-legume species could simultaneously produce these two services of nitrate saving and green manuring. The magnitude of these services can be estimated from indicators of agroecosystem functions such as crop growth rate, crop N acquisition rate and the C:N ratio of the cover crop. We developed a conceptual model for each indicator which was described using general linear models. A three-step procedure was used: (1) represent the behavior of each species based on a sub-model and calibrate each species in bispecific mixtures; (2) validate the complete-mixture models, corresponding to the sum of the two species sub-models, and the proportion of each species in the whole cover, and (3) validate the generality of sub-models and complete-mixture models to predict the agroecosystem function indicators of species in mixture not used for calibration. The combined use of (i) potential agroecosystem functions measured in sole crop in non-limiting conditions, (ii) difference in leaf functional traits, as indicators of plant strategies and (iii) environmental factors, was efficient in fitting and predicting the level of agroecosystem functions provided by a cover crop species in mixture in actual conditions. The models fitted for bispecific mixtures were efficient to represent the behavior of each species in mixture and to estimate the legume proportion which expressed the species dominance. The models were evaluated as satisfactory for crop growth rate and C:N ratio for their generality in predicting the agroecosystem functions provided in mixtures by other species not used in the model calibration step, which illustrates the relevance and robustness of the approach.

## 1. Introduction

Cover crops in agrosystems are grown during the fallow period between two main cash crops to provide ecosystem services, reduce negative environmental impacts of agriculture and improve production efficiency. They can prevent nitrogen (N) losses and water pollution by acquiring mineral-N from the soil before the drainage period and thus decreasing nitrate leaching; this action is commonly called "catch crop effect" (Justes et al., 2012; Kristensen and Thorup-Kristensen, 2004). Cover crops can provide other ecosystem services, such as producing "green manure effect" which releases mineral N into the next main crop through the mineralization of cover crop residues after cover crop termination or incorporation. Biomass production and N acquisition of the cover crop influence the C:N ratio of cover crop residues, which controls the dynamics and the rate of N release from residues incorporated into the soil likely to be available for the subsequent cash crop (*e.g.*,Jensen 1991; Justes et al., 2009). A wide range of cover crop species can potentially be used to manage and recycle N in arable cropping systems. In temperate regions, cover crops are sown in mid- to late summer and must grow rapidly during late summer and autumn. Non-legume species (*e.g.*, white mustard, turnip rape, oat, phacelia) are the most efficient species for producing a catch crop function, although legumes are also able to take up mineral N in the soil and decrease nitrate leaching (Meisinger et al., 1991; Tonitto et al., 2006). Unlike non-legumes, legume cover crops fix atmospheric $N_2$ and increase soil N availability for the subsequent main crop after residue

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decomposition (*e.g.*, Tonitto et al., 2006; Touchton et al., 1984) and thus can reinforce the green manuring function (Möller and Reents, 2009). Mixing (equivalent to intercropping) legume and non-legume species as cover crops can lead to simultaneously produce "nitrate catching" and "green manuring" functions, as it has been demonstrated for some mixtures (*e.g.*, Kramberger et al., 2013; Kuo and Sainju, 1998; Möller and Reents, 2009; Tosti et al., 2012). The legume proportion of cover crop mixtures is a key factor for nutrient composition and crop N acquisition because legumes increase N content and decrease the C:N ratio of cover crop mixtures that influence mineralization and then N availability for the subsequent cash crops (Kuo and Sainju, 1998; Thorup-Kristensen et al., 2003). In a bispecific mixture, the proportion of legume and non-legume species and the level of ecosystem services provided are influenced by characteristics of the intercropped species, such as their resource-use strategy, which may impact their competitiveness, but also by environmental factors such as N availability (*e.g.*, Möller et al., 2008). To express differences in strategies between species due to resource niche differentiation, functional plant trait difference, defined as the trait distance between the target species (the species considered in the mixture) and the associated species, can be used (Chesson, 2000). It has also been demonstrated that functional trait difference is a key driver explaining the intensity of interactions between species in mixtures (Fort et al., 2014; Kraft et al., 2014; Kunstler et al., 2012). Plant functional traits are defined as the morphological, physiological and phenological features, measurable at the plant level, that impact plant performances (Violle et al., 2007). They are known to be used as a method for assessing ecosystem functions such as primary productivity and nutrient cycling, especially in grasslands (Lavorel and Garnier, 2002). They also characterize the capacity of species for competitive dominance, especially specific leaf area (SLA) and leaf dry matter content (LDMC) (Westoby, 1998; Wilson et al., 1999). For cover crop species, SLA, LDMC and leaf area (LA) were useful in characterizing the ability to grow and acquire rapidely N, even if some lack of precision was also reported (Tribouillois et al., 2015). The literature showed that leaf functional traits are robust between sites when measured under non-limiting conditions (Kazakou et al., 2014). However, under "actual" field conditions with a wide range of available resources, functional trait values and the functional trait difference are influenced by environmental factors (Fort et al., 2014; Lavorel and Garnier, 2002).

This study aimed to provide conceptual models to express and predict three main indicators of agroecosystem functions (AEF) for N management (nitrate capture and green manuring) provided by cover crop in mixture during an autumnal fallow period. Three indicators of AEF (AEFi) were chosen and analyzed, such as: (i) crop growth rate (CGR), (ii) crop N acquisition rate (CNR) and (iii) the C:N ratio of the cover crop. We tested the hypothesis that the combination of three types of information, such as (i) potential AEFi of sole crop species, (ii) functional trait differences and (iii) environmental factors, could be sufficient and relevant input variables to express the AEFi produced by bispecific cover crop mixture and to predict species dominance. To this end, we applied a three-step approach for each AEFi assessed: (1) calibration of two independent sub-models to represent the behavior of each species in the bispecific mixture under actual limiting conditions (with possible water and N stresses); (2) validation of the ability of the complete model, corresponding to the sum of both sub-models, to predict AEFi of the entire bispecific mixture and its ability to predict the legume proportion in the mixture; (3) validation of the generality of the sub-models and complete models for predicting the AEFi of a wide range of cover crop mixtures that include species not used in the calibration step. We intend to make these models applicable to a wide range of cover crop species associated in bispecific legume/non-legume mixtures to provide AEF related to N management, explaining why we tested lot of species and

**Table 1**
Experimental site description and growth conditions of the five field experiments. Variables in bold were used as input variables in models.

| Site location | Exp. 1 Auzeville | Exp. 2 Auzeville | Exp. 3 Bignan | Exp. 4 Auzeville | Exp. 5 Auzeville |
|---|---|---|---|---|---|
| Data use | Measurement of input co-variables | Sub-model calibration and whole model validation | Sub-model calibration and whole model validation | Sub-model calibration and whole model validation | Sub-model and whole models validation for species generality |
| Treatments | 34 sole crops | 25 mixtures | 25 mixtures | 16 mixtures | 81 mixtures |
| Plot size ($m^2$) | 14 | 14 | 25 | 18 | 11 |
| Sowing date | 16/08/12 | 16/08/12 | 17/08/12 | 22/08/13 | 16/08/12 |
| Sampling date | 12/10/12 | 26/10/12 | 13/11/12 | 22/10/13 | 29/10/12 |
| Soil texture | Clay loam | Clay loam | Silt loam | Loam | Clay loam |
| Soil pH | 7.9 | 7.8 | 5.8 | 7.9 | 7.7 |
| $C_{org}$ ($g\,kg^{-1}$) | 7.43 | 7.28 | 19.8 | 7.73 | 7.01 |
| N total ($g\,kg^{-1}$) | 0.87 | 0.81 | 2.1 | 0.88 | 0.79 |
| Organic matter ($g\,kg^{-1}$) | 12.9 | 12.6 | 34.0 | 13.4 | 12.1 |
| **Mineral N availability ($kg\,ha^{-1}$) (AvN)** | **44** | **53** | **112** | **44** | **45** |
| Irrigation at sowing (mm) | 170 | 60 | 0 | 50 | 60 |
| Rainfall (mm) | 44 | 80 | 323 | 82 | 80 |
| PET (mm) | 210 | 237 | 159 | 193 | 237 |
| Water at wilting point (mm) | 132 | 132 | 87 | 132 | 132 |
| Water in soil at sowing (mm) | 179 | 179 | 281 | 166 | 180 |
| Water available at sowing (mm) | 197 | 47 | 194 | 34 | 48 |
| **Water availability (mm) (AvW)** | **69** | **−50** | **358** | **−27** | **−49** |
| Daily mean temperature (°C) | 19.1 | 19.1 | 13.5 | 18.4 | 19.1 |