Metagroforestry

Influence of the management and spatial arrangement of agroforestry systems on nitrogen recycling: a meta-ecosystem modeling approach

Métaprogramme BIOSEFAIR

Project report: 2024 - 2026

January 2026

Agroforestry systems (AFS) combine trees, crops and/or pastures in order to optimise agricultural production while improving the provision of ecosystem services. Their functioning is based on complex interactions between plant and soil subunits, the intensity of which depends closely on the spatial organisation of the system and the associated agricultural practices. Among the key processes governing these interactions, the nitrogen cycle plays a central role in plant productivity, soil fertility and the sustainability of AFAs.

This project was based on the hypothesis that the spatial arrangement of the sub-units of an agroforestry system, combined with management practices, is a major lever for influencing nitrogen flows, distribution and conservation within the system, via mechanisms of complementarity and transfer between sub-units. The main objective was to develop a modelling framework to jointly analyse the effects of spatial organisation and agricultural practices on nitrogen dynamics and to assess their consequences on plant production and system fertility.

To achieve this objective, the project employed a modelling approach based on the concept of a meta-ecosystem, explicitly representing the various sub-units that make up an agroforestry system (trees, crops, herbaceous cover) and the nitrogen flows that connect them. The SAF is thus described as a set of ecosystems interconnected by material flows, the intensity of which depends on both spatial configuration and management practices.

A dynamic mathematical model, based on a system of differential equations, was constructed to describe nitrogen stocks and flows within each sub-unit and between sub-units. The spatial parameters of the model correspond to the relative areas of the subunits and their functional overlap zones, defined by the spatial distribution of tree litterfall and the horizontal and vertical distribution of tree root systems. These overlaps determine the intensity of nitrogen transfers between subunits, particularly via litter inputs and competition for soil resources.

The model also incorporates the presence of deep tree roots, representing a 'safety net' effect whereby trees can capture nitrogen that has leached into deeper horizons and contribute to its redistribution to surface layers via litter. Agricultural practices (sowing, harvesting, fertilisation, residue management, tree pruning) are incorporated in the form of disturbances to stocks and flows, in order to represent the managed and temporally structured nature of SAFs.

The model was applied to a Mediterranean agroforestry system studied at the DIAMs (Mauguio) experimental site. Its parameterisation was based on existing data, supplemented by new field measurements of the nitrogen content of different plant biomasses in the system's subunits. These measurements provided information on the nitrogen content of the system's various plant components and enabled the orders of magnitude to be integrated into the model.

The results show that the spatial organisation of the SAF, in interaction with agricultural practices, strongly structures the distribution of nitrogen stocks and flows between sub-units, with consequences for plant production and the system's ability to limit nitrogen losses through leaching. Beyond the case study, the project provides a generic and transferable modelling framework for exploring scenarios for the management and spatialisation of SAFs, contributing to a better understanding of the biogeochemical functioning of these complex agroecosystems.

Detailed results

The project aimed to analyse the role of spatial organisation and management practices in the functioning of agroforestry systems, using an approach explicitly focused on nitrogen recycling dynamics. It was based on the development of a modelling framework based on the concept of a meta-ecosystem, designed to explicitly represent the relationships between the spatial organisation of the sub-units of an agroforestry system, the nitrogen flows that connect them and their effects on plant production and nitrogen conservation within the system.

The main result of the project is the development of a dynamic mathematical model describing nitrogen stocks and flows within an agroforestry system, explicitly integrating its spatial structure and agricultural practices. The model is currently implemented in R; the code is functional and allows dynamic simulations to be carried out, although some functions are still being finalised, particularly those relating to residue management and the representation of symbiotic nitrogen fixation. The model is based on a representation of the agroforestry system as a set of interconnected sub-units (trees, crops, grass strips), between which nitrogen flows circulate.

The spatial parameters taken into account correspond to the relative areas of the subunits and their functional overlap zones, defined on the basis of the spatial distribution of tree litterfall and the horizontal and vertical distribution of tree root systems, which determine the intensity of nitrogen transfers between subunits.

The presence of deep tree roots is incorporated to represent a ‘safety net’ effect, whereby trees can capture nitrogen that has leached into deep horizons and contribute to its redistribution to the surface layers of the soil via litter inputs. Agricultural practices (sowing, harvesting, fertilisation, residue management, tree pruning) are represented as disturbances to nitrogen stocks and flows, allowing the managed and temporally structured nature of agroforestry systems to be taken into account. Different simulations can be produced from the model, allowing comparison of spatial organisation scenarios and management practice scenarios. These simulations make it possible, for a given set of parameters, to systematically explore the system's responses and identify configurations likely to optimise various performance criteria, by analysing the trade-offs and synergies between the system's overall crop production, the production of each of the sub-units (trees, crops, grass strips), and nitrogen conservation and use within the system.

The model was applied to a Mediterranean agroforestry system of the ‘alley cropping’ type studied at the DIAMs experimental site (Mauguio). Its parameterisation was based on existing data, supplemented by a significant effort to acquire new data: approximately 1,000 plant biomass samples were analysed for their nitrogen content using CHN. These data provided information on the orders of magnitude of the nitrogen content of the various plant components of the system and improved the consistency of the plant compartments of the model in relation to the observations made on site. On the scientific front, a publication is currently in preparation, and two M2-level internship reports have been produced by students who contributed to the construction, parameterisation and analysis of the model.

The project objectives have been partially achieved. The main objective of developing a modelling framework integrating spatial organisation, agricultural practices and nitrogen recycling dynamics has been achieved in conceptual and methodological terms, and the model makes it possible to explore the influence of spatial parameters and management practices on nitrogen stocks and flows, with satisfactory consistency with the observations made at the DIAMs site. However, the model has not yet reached a level of maturity that would allow it to simulate a wide range of spatial configurations beyond the parameters currently implemented, nor has it reached a form that can be directly exploited by an external user. The exploration of different types of agroforestry systems has not been carried out, as the work has focused on an alley cropping system, and some of the tasks initially planned, such as the development of a typology of agroforestry systems, the acquisition of nitrogen flux measurements and the use of isotopic tracing, have not been carried out. The project chose to rely on existing data from the experimental site and to supplement it with targeted measurements of nitrogen content in plant biomass.

During the project, the scope of work was adjusted to focus efforts on building, formalising and stabilising the model, which helped consolidate the conceptual and mathematical framework and strengthen the internal consistency of the tool developed. Several difficulties were encountered, particularly in integrating symbiotic nitrogen fixation in a realistic manner, notably in representing the inhibition of fixation as a function of mineral nitrogen availability in the soil. Some key parameters of the model were not directly available in the literature or in existing datasets and were estimated using sensitivity analyses. Furthermore, the model's behaviour proved to be sensitive to certain parameters related to nitrogen uptake, requiring iterative adjustment and validation. Finally, the simulations carried out using the model are numerically complex and require relatively long calculation times, which currently limits the exhaustive exploration of the scenario space and is a point of attention for future developments.

The project's outcomes are mainly methodological and conceptual. The modelling framework developed allows for an integrated analysis of the effects of spatial organisation and management practices on the nitrogen cycle and recycling in agroforestry systems, highlighting the importance of the spatial distribution of subunits, areas of functional overlap and the potential role of deep roots in limiting nitrogen losses through leaching. The model thus provides a basis for formulating general recommendations for a given system, identifying management and spatial organisation scenarios that are favourable to both crop production and nitrogen conservation. In the longer term, it could be made more generic and adapted to other agroforestry systems, so that it can be used by other teams and in other soil and climate contexts, opening up prospects for the development of tools to aid the design and management of agroforestry systems based on a mechanistic understanding of how the nitrogen cycle works.

Scientific outlook

This work has opened up several scientific avenues, both conceptual and methodological, raising new research questions about the modelling of agroforestry systems and the functioning of the nitrogen cycle and recycling.

One perspective concerns the adaptation and extension of the modelling framework developed to other spatial configurations and other types of agroforestry systems. The model was designed and applied in the context of an alley cropping system in a Mediterranean environment, but its application to temperate or tropical systems with contrasting spatial structures, tree densities and growth dynamics would broaden the scope of analysis. Such an extension would offer the possibility of examining the robustness of the mechanisms represented and identifying the parameters that structure the functioning of the nitrogen cycle according to soil and climate contexts..

A second perspective concerns the explicit integration of climate change and the seasonality of processes into modelling. Taking into account changes in the duration and timing of the growing season, in line with changing climatic conditions, combined with a more detailed representation of the seasonality of processes such as organic nitrogen mineralisation or nitrogen losses, would make it possible to analyse their effects on plant production, nitrogen recycling dynamics and interactions between sub-units of agroforestry systems. This approach would also offer the possibility of exploring the time lags between nitrogen availability, crop demand and environmental conditions in a context of climate change.

Finally, the framework developed paves the way for the integration of other ecosystem services associated with the presence of trees and grassed areas. The addition of services such as carbon sequestration, water regulation, pollination, pest and pathogen control, erosion protection and biodiversity maintenance would make it possible to analyse the trade-offs and synergies between these services, crop production and those related to the nitrogen cycle. This perspective is part of a more integrated approach to assessing the performance of agroforestry systems and raises research questions about how to jointly represent crop production and ecosystem services in spatially heterogeneous and managed agroecosystems.