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Which crop model to simulate the ecosystem services provided by crop diversification in Brittany?

Louis Bourdin

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Which crop model to simulate the ecosystem services provided by crop diversification in Brittany?

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Soutenu le 26 juin 2020

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Les analyses et les conclusions de ce travail d'étudiant n'engagent que la responsabilité de son auteur et non celles d'AGROCAMPUS OUEST et l'université de Rennes 1

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Abbreviations list

agMIP: agricultural Model Intercomparison and improvement Project

ANR: Agence Nationale de la Recherche

APSIM: Agricultural Production Systems Simulator

BAP: Basic Agroecosystem Process

CCC: Concordance correlation coefficient

CICES: Common International Classification of Ecosystem Services

CMA: Conceptual modelling of an agroecosystem (

DSSAT: Decision Support System for Agrotechnology Transfer

FAO: Food and Agriculture Organization of the United Nations

INRAE: Institut national de recherche pour l'agriculture, l'alimentation et l'environnement

LAI: Leaf Area Index

LER: Land Equivalent Ratio

MBC: Microbial Biomass Carbon MBP:

DM: Dry Matter:

MWD: Mean Weight Diameter

P: phosphorus

PerfCOM: Peuplements Complexes Performants en agricultures bas intrants

RMSE: Root Mean Square Error

RothC: Rothamsted Carbon model

SOC: Soil Organic Carbon

SOM: Soil Organic Matter

SON: Soil Organic Nitrogen

STICS: Simulateur multIdisciplinaire pour les Cultures Standard

SWC: Soil Water Content

UMR SAS: Unité Mixte de Recherche Sols Agro et hydrosystèmes Spatialisation

1. Introduction

In France, over the past 50 years, farms and territories have undergone a specialisation process which turned them towards animal or crop production, with a clear decline in the number of crop-livestock farming systems (Mignolet et al., 2012). This specialisation is explained by the search for greater productivity on farms and by the desire to benefit from the economies of scale and agglomeration which can be achieved when technical progress is made and when businesses in the same sector are located in the same territory (Jouan, 2020). Moreover, the structuring of agro-industrial sectors has forced farming systems to simplify so that quality control and volumes management are optimized throughout the supply chain (Meynard & Messéan, 2014). Therefore, the number of crop species has decreased on many farms with crop choices oriented toward the most profitable species (Meynard & Messéan, 2014). Nowadays, less than 3 crop species represent about 35% of the French arable area: winter wheat, maize (grain and forage), barley (Agreste, 2020). As a consequence, crop rotations¹ are simplified (Meynard & Messéan, 2014) and landscape² heterogeneity is reduced (Mignolet et al., 2012). For example, short rapeseed-based rotations such as rapeseed / winter wheat / barley are common in the Seine basin (Mignolet et al., 2012). In addition, between 2006 and 2009, 17% of winter wheat areas are not rotated in France (Fuzeau et al., 2012).

Simplification of crop rotations has negative environmental impacts:

- increase in chemical fertilizer use and greenhouse gas (GHG) emissions following the reduction in the share of legumes in crop rotations (Pellerin et al., 2013);
- increase in pesticide use due to greater difficulty in controlling weeds and pests in short rotations and crop rotations with low diversity (Schmidt et al., 2010);
- levelling off of crop yields with the shortening of crop rotations (Bennett et al., 2012);
- loss of biodiversity due to a decrease in habitat heterogeneity (Benton et al., 2003);
- contamination of water through intensive use of fertilizers and pesticides, leading to health and water purification costs (Tilman et al., 2002).

This raises two contradictory issues: on the one hand, specialisation process – and the resulting simplification of crop rotations – is relevant for ensuring food security due to the high productivity of simplified farming systems but on the other hand, it is unable to maintain a high level of environmental quality. Current farming systems cannot meet this double challenge and Meynard et al. (2012) emphasize that new farming systems breaking with the current ones must be designed to be able to respond to this double challenge. One solution is to develop farming systems based on crop management practices that increase the level of provision of ecosystem services. Such services are defined in the Millennium Ecosystem Assessment as “*the benefits people obtain from ecosystems*” (Corvalán et al., 2005). These benefits concern food, water, timber, leisure, spiritual, etc.

These new farming systems can be built through a “*strong ecological modernization of agriculture*” (Duru et al., 2015; Horlings & Marsden, 2011) based on the development and management of on-farm biodiversity. Indeed, the functioning of an agroecosystem is based on

¹ A method of farming where different crop species are grown one after the other on a field so that the agroecosystem stays healthy and fertile (Cambridge dictionnary, 2020).

² A spatially heterogeneous geographic area characterized by diverse interacting patches or ecosystems (Wikipedia, 2020)

the interactions of two components of on-farm biodiversity (Loreau et al., 2002): planned biodiversity and associated biodiversity. These two components, which refer respectively to (i) the diversity that are intentionally chosen by the farmer and with a productive function (crops: species and cultivars; livestock: species, breeds and genotypes) and (ii) the diversity that includes all organisms that inhabit cultivated areas or colonize them from surrounding habitats (Duru et al., 2015), can be used to increase ecosystem services. Thus, with the intention of implementing a more biodiversity-based agriculture, crop diversification is a promising approach: increasing biodiversity in the fields through diversification, by choosing the most relevant planned biodiversity to foster associated biodiversity, would increase the level of provision of ecosystem services.

My internship took place at UMR SAS (Unité Mixte de Recherche Sol Agro et hydrosystèmes Spatialisation) INRAE-AGROCAMPUS OUEST and I participated in a research project whose objective is to design diversified agroecosystems and to assess, on a long-term basis, ecosystem services that can be provided by crop diversification within these agroecosystems using a modelling approach. My contribution to this project was to find the best crop model to achieve this purpose.

2. Context

a. Transition to more sustainable agriculture: redesigning agricultural systems

With nearly 9.7 billion people on Earth by the middle of the century (United Nations et al., 2019) the pressure on the food supply system is increasing, especially since the increase in the world population is accompanied by a change in food consumption (Godfray et al., 2010) linked to changes in living standards. Food security, defined by the World Bank (1986) as “*access for all people at all times to sufficient food for an active and healthy life*”, is therefore one of the major challenges of the 21st century, and agriculture plays a major role in it. Recent studies highlight that it will be necessary to produce about 50% more food to meet the growing demand (Godfray et al., 2010; TheRoyal Society (London), 2009). Using the IMPACT model³, Cassman (1999) estimates that from 1997 to 2027, agricultural production should increase by 44% for wheat, 43% for rice and by 56% for maize to satisfy world demand for these three main cereal crops.

In the past, the exploitation of new land has been used to counter food shortages and increase food production but nowadays, farmers already manage 50% of the land surface (except boreal lands, desert, rock, ice) (Tilman, 2001) and during the last 5 decades, the expansion of agricultural land has only increased by 9% (Godfray et al., 2010). New land could be brought into cultivation, but there are conflicts with the need to protect biodiversity and some ecosystem services such as carbon sequestration in tropical forests. In addition, agricultural land is being lost due to urbanization and other human uses, as well as desertification, salinization, etc (Godfray et al., 2010).

Another way to increase food production is to increase crop productivity. Licker et al. (2010) estimate for wheat, rice, and maize that it would be possible to produce 60, 40, and 50% more respectively, if yields of these crops were universally increased to 95% of their potential. However, studies on the yield gap show that there are significant differences from one world region to another (McLaughlin & Kinzelbach, 2015) and the gap between actual and potential yields allowed by genetics and best management practices is narrowing, further limiting the

³ The IMPACT model is a tool developed to calculate future food demand based on population and economic growth rates.

potential for increasing the productivity of cropping systems (Cassman, 1999; Neumann et al., 2010). In the past, a method to reduce yield gap was to act on the level and quality of inputs. This was the aim of the Green Revolution (1950-1960) in developing countries, which increased agricultural production through the adoption of high-yielding varieties and the use of chemical fertilizers and pesticides, and irrigation. However, this intensive agriculture shows its limits with a marked deceleration in yield growth, that is expected to slow to 0.7% (0.8% in developing countries) of the historical growth rate (FAO, 2009). Moreover, between 1970 and 2000 the global use of pesticides increased 12-fold all around the world, without significantly reducing the yield gap (McLaughlin & Kinzelbach, 2015). This intensification also causes many environmental and health problems (Aktar et al., 2009), and it is therefore reasonable to ask whether the increase in yield aided by intensive use of inputs is rational. In others words, there is a need to develop more sustainable cropping systems i.e. cropping systems less dependent on chemical inputs and fossil resources, more resilient and producing enough to provide people with good quality food (Duru et al., 2015). This need has given rise to two forms of “ecological modernization of agriculture” (Duru et al., 2014, 2015).

First, “*weak ecological modernization of agriculture*” aims to improve the efficiency of input use and waste recycling in order to reduce production costs and environmental impacts of farming systems. This form of agriculture, in continuity with the productivist one (Duru et al., 2014; Therond et al., 2017) is a technocentric approach (Hill, 1998) whose innovations are most often technological developments: improvement of varieties, development of less environmentally harmful inputs, development of better management practices, development of precision agriculture (Duru et al., 2015). Nevertheless, this first form of modernization of agriculture has weaknesses because it does not fundamentally challenge the principles of actual farming systems, e.g. (i) lack of diversity in cropping systems and landscapes that weakens biodiversity and (ii) uniformity of agricultural practices (Duru et al., 2015). Also, Meynard et al. (2012) further explain that approaches focusing on input optimization are not sufficient to address the above-mentioned problems of agriculture.

Secondly, “*strong ecological modernization of agriculture*” is an approach in opposition to specialized farming systems and is based on a complete paradigm shift, integrating scales ranging from fields to landscapes (Duru et al., 2014, 2015). It refers to an ecocentric approach (Hill, 1998) and aims to strongly improve ecosystem services provided by biodiversity (Therond et al., 2017), through a strong biological diversification of agroecosystems⁴ as well as an intensification of ecological interactions between components of the environment (Duru et al., 2015). Farmers can manage diversification of agroecosystems through crop diversification⁵ at different scales of space (from field to landscape) and time (cropping period). Crop diversification act on two components of biodiversity: planned biodiversity (i.e. biodiversity relating to landscape heterogeneity, intercropping and crop rotation) and associated biodiversity (i.e. biodiversity that colonizes agroecosystems from surrounding environments and that will thrive in the agroecosystem depending on its management and structure; it is composed of weed flora, soil fauna, epigenetic and aerial fauna). These two components of biodiversity promote provisioning services, of course, but also supporting services (i.e. genetic biodiversity, soil formation and structure, soil fertility, nutrient cycling, provision of water) (Duru et al., 2015; Power, 2010).

⁴ Agroecosystems are complex systems in which many species interact, with ecological processes that take place at different spatial scales, and with strong interactions between ecological and management processes (Tixier et al., 2013).

⁵ In this work, I only consider crop diversification as a way to diversify agroecosystems. So, in the rest of the manuscript, I only use the term crop diversification.

b. Crop diversification

Crop diversification is a lever to increase the sustainability of agricultural systems (Meynard & Messéan, 2014). This approach includes management practices such as:

- Intercropping i.e. the simultaneous cultivation of at least two species on the same plot of land for a significant period of time (Ehrmann & Ritz, 2014) refers to spatial diversification of agroecosystems.
- Crop rotation, previously defined, refers to temporal diversification of agroecosystems (in this document, I define crop rotation for crop diversification as not only the simple succession of crops over time, on the same field, but also the consideration of reciprocal benefits between crops when farmer chooses crop species and their succession over time).

Crop diversification within a farm, whether temporal or spatial, allows mutual benefits from one species to another, particularly about pest and disease regulation as well as mineral and water supplies notably through plant soil feedback (Vukicevich et al., 2016), ecological niche complementarity⁶, and facilitation⁷ (Brooker et al., 2015). Diversified agroecosystems also benefit from better plant health management thanks to their ability to shelter a large bank of natural enemies and reduce the transmission and development of diseases (Lin, 2011); moreover, a reduction in weed density and biomass is often observed due to competition⁸ for resources and allelopathic effects⁹ between weeds and crop species (Liebman & Dyck, 1993). In addition, increasing the number of species allows to better fulfil certain ecosystem services such as pollination and carbon sequestration (Altieri, 1999; Duru et al., 2014).

Crop diversification is also an interesting strategy for improving soil quality, defined as the capacity of soils to support biological productivity, maintain environmental quality, and promote plant and animal health (Doran & Parkin, 1994). It is important as the reduction of soil quality by erosion, chemical degradation (e.g. nutrient depletion, loss of organic matter and chemical pollution), and deterioration of physical properties (e.g. soil compaction) affects yields (D'Hose et al., 2014). Crop diversification has positive effects on the quantity of soil organic matter in the long term (Cong et al., 2015) but also on soil physical properties thanks to a better soil cover and a diversified and complementary root system (Malézieux et al., 2009). Moreover, according to Georges et al. (2012), there is a close relationship between crop diversification, productivity, and carbon storage. Finally, crop diversification allows maintaining microbial diversity in the soil, which is beneficial in terms of resilience¹⁰ of the systems to biotic and abiotic stresses (Malézieux et al., 2009), due to soil functional groups perform ecosystem functions and provide goods and services. So, maintaining the diversity of these groups can be a means of maintaining or restoring ecosystem performance in the face of climate change (Swift et al., 2004).

⁶ When plants use the same resource in a different way (in time or space) or exploit different biogeochemical forms. (Bedoussac, 2016)

⁷ A situation where the presence of one species benefits, through the creation of favourable conditions, the installation, life or survival of other species. (Stachowicz, 2001)

⁸ Occurs when the associated plants use the same abiotic resources, in the same place and at the same time. (Bedoussac, 2016)

⁹ Allelopathy is one such mechanism, in which plant interference is mediated by the addition of plant produced phytotoxins to the environment. (Bastiaans & Kropff, 2003)

¹⁰ The capacity of a system to respond to and recover from disturbance (Swift et al., 2004)

Nowadays, crop diversification is valued mainly at the level of extensive low-input systems and it is mainly found in the tropics, on small farms where it takes the form of intercropping (Brooker et al., 2015; Papademetriou, 2001). Globally in the tropics, the proportion of land cultivated with intercrops varies from 17% in India to 94% in Malawi (Brooker et al., 2015). Take the example of maize cultivation in Latin America: 60% of production is carried out using intercropping (Brooker et al., 2015). In temperate regions, crop diversification exists but it is mainly implemented for fodder production and organic farming (Ehrmann & Ritz, 2014).

In France, crop diversification interfere with obstacles that limit its development (Meynard & Messéan, 2014): there is a “*technological lock-in*” around few crop species (winter wheat, maize, barley, rapeseed), even though crop diversification relies on a large number of crop species for increasing the lengthening and the complexity of crop rotations. The concept of technological lock-in refers to a situation where a technology has become such a standard for society that it seems difficult to change it, even if there are other technologies that would better meet society’s expectations (David, 1985). Crop species that cover little agricultural land represent a small market for seed and agrochemical companies, which limits investment on their part. Such crop species suffer from slower genetic progress and a lack of registered phytosanitary products compared to major crops (Meynard & Messéan, 2014; Voisin et al., 2014). In addition, these crop species (i) benefit from less agronomical and technological knowledge, (ii) are poorly adapted to industrial processes, and (iii) do not always comply with standards recognized by the sectors and consumers (Meynard & Messéan, 2014). Furthermore, the actors that could constitute the sectors around them are not well known (Meynard & Messéan, 2014).

According to Meynard & Messéan (2014), unlocking may occur by:

- encouraging the evolution of the agri-food standard schemes with new rules as well as the evolution of training programmes for farmers and farm advisers in order to allow the development of crop diversification beyond niche markets;
- encouraging the development of sectors around crop diversification, using locally adapted references on productivity, margins and the effect of plant soil feedback.

In this respect, in France, several research projects study crop diversification. For example, the PerfCom project lasted four years and aimed to understand the functioning of intercropping-based agroecosystems with a view to better exploiting ecological processes and soil resources in order to improve the efficiency of fertiliser input use (Perfcom-ANR, 2012) The H2020 DIVERSify project, which started in 2017, focuses on the study of cereal-legume intercropping and has several objectives: (i) to gain a better understanding of plant-environment interactions, (ii) to create a decision support tool for the choice of crop species and spatial arrangements, and (iii) to identify the best technical approaches. On a larger scale, the European DiverIMPACTS project tests crop rotation and intercropping as a way to diversify agroecosystems. This project seeks to (i) evaluate diversified agroecosystems, (ii) provide farmers evidences of the technical, economic and societal benefits of diversification, and (iii) provide rural stakeholders with technical and organizational innovations likely to remove the current barriers at the farm, commodity chain and territorial levels.

So it is necessary to continue this work of acquiring knowledge about the benefits of crop diversification and at the same time, using the knowledge and the tools available, to design adapted agroecosystems scenarios i.e. virtual propositions of crop rotations and intercrops and their associated crop management systems. Especially, it is particularly interesting to extend actual studies by focusing on the relationship between diversified agroecosystems and the provision of ecosystem services over time.

c. What tools to design innovative agroecosystems including crop diversification?

According to Ertas and Jones (1996), design is “*the process of developing a system, component or process that does not yet exist and that will meet identified user needs*”. It is an active, intentional and organized process that leads to innovation and that aims to define precisely the identity of the object, i.e. what it will be, what it will do, what it will allow to be done. To design disruptive systems based on a significant increase in crop diversification, conventional step-by-step design approach may be limited. Furthermore, this continuous improvement approach, which is characterized by low risk-taking and which facilitates the learning of new systems by stakeholders, is less suitable for studying systems over long periods of time and in a variety of soil-climate contexts.

Meynard et al. (2012) put forward another approach that opens up the field of possibilities and aims to design farms that break away from existing systems: “*de novo*” design approach. This approach mainly relies on computer modelling as a tool for a dynamic description of cropping system functioning and performances (Le Gal et al., 2010; Martin et al., 2013). Such a tool is capable of assisting the representation of biophysical, technical and decision-making processes, but also of assessing ex ante the multiple impacts of innovations on the system, a step that is difficult to achieve using an experimental approach (Le Gal et al., 2010). It can be used to simulate very broad combinations of factors over the long term, such as the combined effect of a change in fertilizer rate, cultivars, and sowing density on yield. It is also possible to represent the interactions between the components of a farm and the interactions between the farm and its physical, economic and social environment (Le Gal et al., 2010).

Crop models focus mainly on biophysical aspects with detailed descriptions of the processes and relationships that may exist between the physical and biological components (soil, water, plant, crop, etc.) of the system under consideration. They are an appropriate way to test new scenarios of agroecosystems based on crop diversification and to estimate variables related to ecosystem services. Among crop models, main ones are:

- APSIM (Agricultural Production Systems Simulator) was originally designed as an agricultural systems simulator that accurately estimates production in response to manure and can provide long-term predictions of farming practices on the land (Keating et al., 2003);
- DSSAT (Decision Support System for Agrotechnology Transfer) was developed to integrate knowledge on climate, soil, crops and their management, in order to facilitate the transfer of production methods in places where the soil or climate differed (Jones et al., 2003);
- STICS (Simulateur multIdisciplinaire pour les Cultures Standard) developed since 1996 (Brisson, 2008; Brisson et al., 2003) has three main objectives: (i) to accurately predict yields under the influence of environmental practices and conditions, (ii) to summarize the knowledge acquired in ecophysiology and agronomy, and (iii) to serve as a basis for adapting technical itineraries according to pedoclimates (Brisson, 2008; Brisson et al., 2003; Jones et al., 2003; Keating et al., 2003).

They are all computer models developed from independent modules which through a set of equations represent ecophysiological processes (e.g. phenological development, leaf growth, radiation interception and photosynthesis, yield and quality development, root growth, water balance, soil nitrogen transformations, water and nitrate transfers). In this way, the addition and creation of new modules is simplified, which facilitates the subsequent evolution of these models. They can simulate the growth and development of many crops as well as the dynamics

of water, carbon and nitrogen on a daily scale. They are initialized by input variables accessible to researchers (Brisson et al., 2003) i.e. variables concerning climate, soil and cropping system (sowing date, sowing density, fertilization, water availability, etc.). According to the publications that use these models, they are rather suitable for the design of agroecosystem that seek to optimize the efficiency of input use. For example, APSIM was recently used in a project to model the effects of tillage on productivity, soil water dynamics and evapotranspiration in a maize / winter wheat / soybean rotation in China (Yang et al., 2018). In parallel, the STICS model is being used in an integrated protection design project. To this end, it has been encapsulated in a bio-aggressor model and a decision model in order to integrate an economic and epidemiological analysis (Bergez et al., 2014). However, despite all the power of these models, they remain open to criticism and it is essential to check whether they adapt well to the pedoclimatic context in which we wish to simulate crop diversification scenarios.

3. Issue

Current farming systems have many issues, particularly related to their negative impacts on the environment. Crop diversification, which acts on planned biodiversity as well as associated biodiversity, is a solution for designing disruptive sustainable farming systems, able to provide several ecosystem services.

Designing such farming systems including various levels of crop diversification via crop rotation and intercropping needs crop modelling because it allows assessing ecosystem services provided by a wide range of virtual systems, on different climate-soil contexts, on a long-term basis. Consequently, my work was to define detailed characteristics that a crop model should have to simulate crop diversification and its consequences on various ecosystem services relevant in Brittany region. Indeed, it is a region where specialized intensive agricultural systems dominate and have an impact on the environment with water contamination, greenhouse gas emissions or declining soil quality (Lemaire et al., 2014). Furthermore, my work aimed to select the best crop model according to the detailed characteristics I proposed and to test its relevance in Brittany region.

The main objective of my work was to test a crop model capable of representing a diversified agroecosystem, in various pedoclimatic contexts, and capable of simulating various variables related to the provision of ecosystem services over time. To this end, it was first questioned what were the main and essential characteristics that such a crop model should have. Through a conceptual agroecosystem modelling approach (Lamanda et al., 2012) and according to our expectations, an “*ideal*” system was established. Subsequently, 3 crop models (APSIM, DSSAT and STICS) were compared to the conceptual model in order to identify which of these crop models is best suited to implement this ideal system. Finally, in order to use one of these models for a larger study, an analysis of the accuracy of the chosen crop model was carried out.

4. Materials and methods

a. Conceptual modelling of an agroecosystem (CMA) based on crop diversification

To define detailed characteristics a crop model should have to simulate crop diversification and its consequences on various ecosystem services, I decided to use the protocol described by Lamanda et al. (2012). I used it as a guideline to propose a conceptual representation of an agroecosystem that includes (i) crop management practices related to crop diversification and

(ii) processes related to ecosystem services. The protocol of Lamanda et al. (2012) is organized in four steps.

The first step is the **structural analysis** of the system. It consists in defining the limits of the system, its components, and its environment:

- The limits of the system are most often conceptualized “*as a volume defined by a soil area, a soil depth and a canopy height*”.
- The components of the system, called the Basic Agroecosystem Process (BAP) (Launay, 2017), are biophysical entities (e.g. plants), basic crop processes (e.g. photosynthesis) or sub-systems. They interact with each other and with the environment and are characterized by one or more attributes (i.e. one or more state variables and parameters). BAPs are chosen sparingly, taking into account available knowledge and data. Only those with the greatest influence on the system are retained.
- The environment of the system includes biophysical, economic, social, or institutional aspects. Environment is breaking down into active and passive environments. The active environment corresponds to “*the elements from other systems that act on the system related to the problem (e.g. the climate and the technical system used by the farmers)*”. The passive environment includes the outputs of the system, which can be indicators of its performance (e.g. energy use efficiency) as well as the services it provides to other systems (e.g. habitats for wildlife).

The second step is the **functional analysis**: the main hypotheses on the relationships between the BAPs as well as between the BAPs and the environments are identified. According to Lamanda et al. (id), these relationships are represented as (i) flows of materials (e.g. water, nitrogen, phosphorus), energy (e.g. light) or information (e.g. root to shoot signals), and (ii) actions (e.g. impact of tillage on soil structure, influence of pest and disease on production).

The third step is the **dynamic analysis**: it provides a dynamic dimension to the system: this involves studying how the structure and relationships are modified over the life of the system. This step can lead to modify the previous ones by removing or adding BAP's or relationships that appear essential (or not) at a given moment in the life of the system.

Finally the last step is a step which allows to validate the consistency of our system. It is important to check that all elements are correctly represented and linked to the system.

To build a conceptual model adapted to the problem we defined, I decided to go through a literature review to select the most relevant BAPs and their relationships. The decision rules presented in Figure 1 allowed me to classify, according to whether they are relevant or not, the information found in the bibliography concerning effects of agroecosystems and their management on ecosystem services.

b. Crop simulation model comparison

In this second part of my research work, I verified that some existing crop simulation models (i) include management practices listed in the *active environment* of the conceptual model I proposed, (ii) represent relationships included in the conceptual model I proposed, and (iii) simulate outputs listed in the *passive environment* of the conceptual model I proposed.

Three crop simulation models were pre-selected using the agMIP platform (agricultural Model Intercomparison and improvement Project, a structure that aims to improve agricultural models and scientific and technological capabilities): APSIM, DSSAT, and STICS. They were chosen because they are widely used and included many crops and parameterization in their formalism.

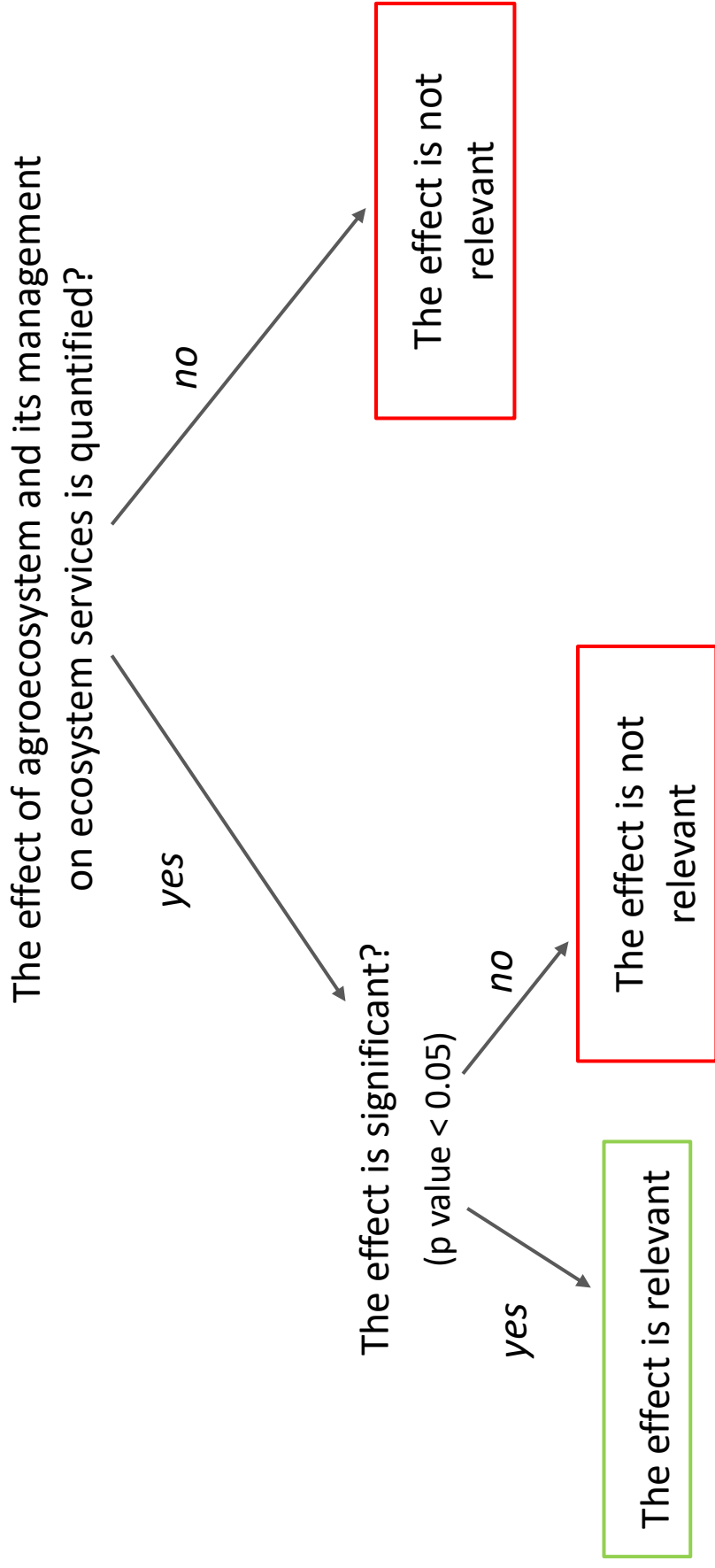


Figure 1: Decision tree allowing to rank the effects related to agroecosystems and its management known in literature. In green the effects of agroecosystem and its management has to be taken account in the construction of the conceptual-model; in red the effects of agroecosystem and its management are not necessary for the construction of conceptual-model. Management of the agroecosystem includes farmer practices such as the choice of crop rotations and crop management systems.

APSIM (Keating et al., 2003) consists of (i) a set of biophysical modules that simulate at a daily time step biological and physical processes in agricultural systems, (ii) management modules that allow users to specify the expected management rules that characterize the simulated scenario and control the simulation process, and (iii) a simulation engine that drives the simulation process and controls all information passing between the modules. The different crop modules allow users to simulate growth and development of about 30 crop species (it includes grassland and forest systems). The simulation of multi-species mixtures (intercropping) is also included.

DSSAT integrates soil, climate, crop and management knowledge with the capacity to simulate a system at a daily time step. It optimizes the transfer of production technologies from one area to another where soils and climates differ. In addition, DSSAT facilitates decision-making by reducing the time and human resources required to analyse complex alternative solutions. It also provides a framework for scientific cooperation to integrate new knowledge and apply it to research questions (Jones et al., 2003).

STICS simulates growth and development of a crop, as well as the water and nitrogen balances, at a daily time step. It is recognized for its robustness and its plasticity thanks to a large choice of options in the formalisms and its large number of integrated crops (Brisson, 2008; Salo et al., 2016). The model is adapted to 32 crop species, annuals, perennials, herbaceous or woody. The input variables required for its operation concern the soil, the climate, the crop management system and the crop itself. Output variables are related to yield, environment (quantity of nitrates leached, nitrous oxide emission, etc.) and some dynamic soil characteristics (e.g. soil organic carbon, soil organic nitrogen, etc.). In 2004, a version integrating intercrops was made available (Brisson et al., 2004).

c. Scenarios of cropping systems for the selected crop simulation model

The last part of my research work focussed on the most appropriate crop model to represent the conceptual model I proposed. It consisted in:

- validating that the selected crop model works for some crops and climate-soil context of the Brittany region;
- studying how outputs related to ecosystem services are simulated over time in this crop model;
- defining the accuracy required for the input data, in particular those relating to the soil description.

The last two steps have been studied in order to be able to use the model to assess on a long-term basis, effects of crop diversification scenarios, designed with expert knowledge (therefore with variable data accuracy), on various ecosystem services.

Regarding the model validation, the EFELE experiment (Le Rheu, France) was chosen as a reference to compare some crop model outputs with field observations (crop yields measured at harvest; volumetric water content at 15-cm depth, measured daily; soil organic carbon content and soil organic nitrogen content measured at 0-25 cm depth in March 2012 and March 2016). Data from this experiment was also used for the two other steps.

EFELE is an experiment dedicated to the long-term characterization of the effect of repeated applications of organic products from livestock farms (slurry, manure, compost, digestates) on soil, water, and air quality. Experimental monitoring began in 2012 and the crop rotation studied is Maize / Wheat / Mustard (as a cover crop during the fallow period). Two trials are carried out on the EFELE experiment; data from the trial “TS/MO” was used. This trial focuses on the

interaction between tillage (ploughing, reduced tillage) and type of fertilizer (mineral fertilizer, cattle manure) on the dynamics of the soil organic matter and the micropollutants.

Based on the climate-soil context (Appendix 1) and the crop management systems of the “TS/MO” trial, four runs will be implemented on the selected crop model (Table 1). The separation of the simulations in successive steps is explained by the fact that I did not routinely manipulate any of the 3 crop models. Thus, this approach will allow me to progressively understand the functioning of the chosen model.

Table 1: Short description of the simulation runs. From 2012-2019, crop rotation on the EFELE experiment was Maize / Wheat / Mustard.

Name of the simulation run	Run number	Crop rotation	Climate year	Output variable
Monocropping	1	Maize	2012-2014-2016-2018	yield, biomass
	2	Wheat	2013-2015-2017-2019	yield, biomass
Rotation 1	3	Maize / Wheat / Fallow	2012 to 2019	yield, biomass, SWC, SOC, SON, P, N ₂ O, CO ₂ , N leaching, soil losses
Rotation 2	4	Maize / Wheat / Cover crop	2012 to 2019	yield, biomass, SWC, SOC, SON, P, N ₂ O, CO ₂ , N leaching, soil losses

Abbreviations: SWC soil water content; SOC soil organic carbon content ; SON soil organic nitrogen content; P phosphorus content; N₂O nitrous oxide content; CO₂ carbon dioxide content; N nitrate

The first two runs simulated the growth of a single crop (maize, wheat) over the climatic year corresponding to the real period of presence of the crops on the EFELE experiment. So, these are not continuous simulations over the 8 years. These first two runs served as the basis for the simulation of the next two runs and aimed to take control of the software by simulating simplified runs with very basic outputs. The third run was closer to the reality with the implementation of a Maize / Wheat / Fallow rotation; outputs related to ecosystem services (CO₂ and N₂O emissions, erosion, and nitrate leaching) and to soil organic matter dynamics were calculated. Yields at harvest, soil water content dynamics, and soil organic matter dynamics were compared to EFELE’s data (simulated vs. observed data; Piñeiro et al., 2008). Finally, the last run aimed to represent as much as possible the cropping pattern on EFELE with the establishment of a cover crop during the fallow period.

Regarding the accuracy required for the input data, I tested soils with a level of description of the soil layers degraded with respect to the initial soil : first, the initial soil was layered in two horizons (0-25 cm; 25-90) then in one horizon (0-90 cm)

Crop management systems of the EFELE experiment are detailed in Table 2. Main characteristics of the soil and climatic years are presented in Table 3 and Figure 2.

The statistical parameters used to evaluate the crop simulation model performances are as follows (Tedeschi, 2006): observed and simulated mean and standard deviation, root mean square error (RMSE) and correlation coefficient of concordance (CCC).

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (X_{obs,i} - X_{model,i})^2}{n}} \quad CCC = \frac{2\sigma_{XY}}{\sigma_{XX} + \sigma_{YY} + (\mu_X - \mu_Y)^2}$$

The CCC varies between -1 and 1 and combines (i) precision through Pearson’s correlation coefficient, which represents the proportion of the total variance in the observed data that can be explained by the selected crop model, and (ii) accuracy by bias which indicates how far the regression line deviates from the line (1:1). A value of $CCC = +1$ corresponds to perfect positive agreement. A value of $CCC = -1$ corresponds to perfect negative agreement. A value of $CCC = 0$ corresponds to no agreement. The crop model performance can be evaluated according to the following limits: “*very good*” when $CCC > 0.90$, “*satisfactory*” when $0.90 < CCC < 0.80$, “*acceptable*” when $0.80 < CCC < 0.70$ and “*poor*” when $CCC < 0.70$ (Ojeda et al., 2018). RMSE and CCC calculations were performed using R Core Team (2019).

Table 2 Crop management systems of the EFELE experiment for the plots with conventional tillage and mineral fertilizer supply.

Tillage	N mineral fertilisation	P mineral fertilisation
Deep plowing to a depth of 25 cm	N applied as ammonium nitrate, with a mean dose of 92 kg N/ha on maize and 118 kg N/ha on wheat	Annual input of 50 kg of P ₂ O ₅ /ha

Table 3: Main characteristics of the simulated soil created with EFELE data: depth, soil water content (SWC) at three pressure heads (near saturation (-3.2 kPa), field capacity (-31.6 kPa) and permanent wilting point (-1585 kPa)), percentage of organic carbon (OC), pH, quantity of nitrate (NO₃) and ammonium (NH₄).

Depth (cm)	Bulk density	SWC			OC (%)	PH	NO ₃ (ppm)	NH ₄ (ppm)
		-1585 kPa	-31.6 kPa	-3.2 kPa				
0-15	1.266	0.114	0.376	0.432	1.11	6.1	3.5	2.7
15-25	1.310	0.115	0.362	0.430	1.06	6.1	1.7	1.1
25-60	1.465	0.110	0.330	0.420	0.62	6.3	2.1	0.3
60-90	1.540	0.110	0.330	0.410	0.33	7	3.3	0.3

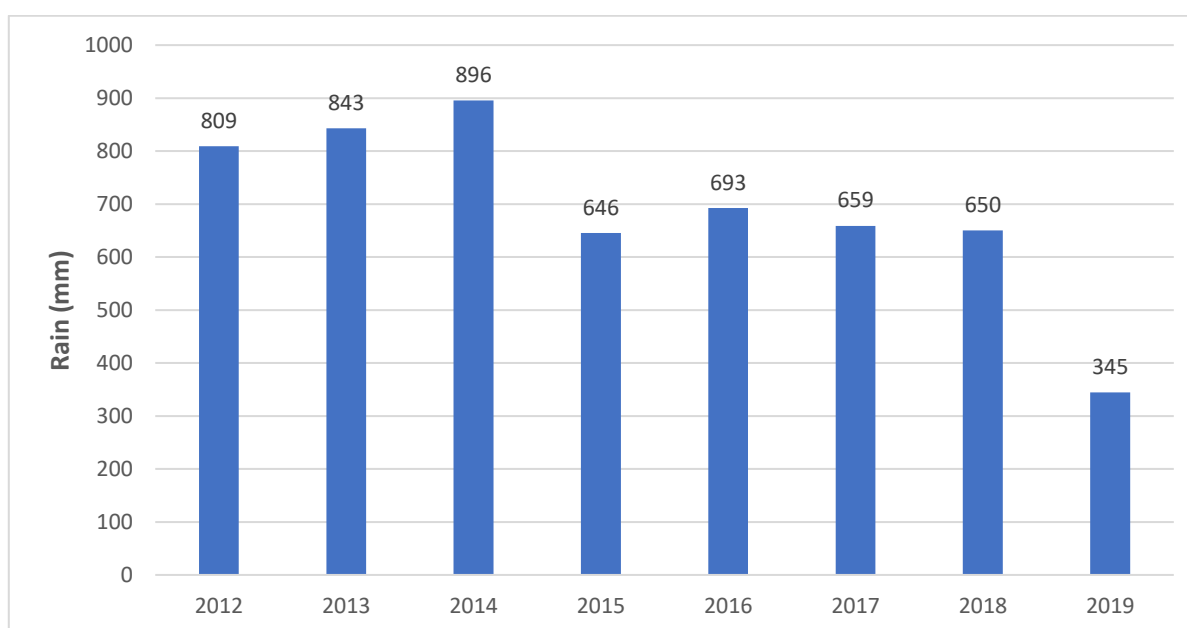


Figure 2: Annual rainfall at EFELE (Le Rheu, France). For 2019, this is not the total rainfall, but rainfall between January and August.

5. Results

a. A conceptual model of an agroecosystem based on crop diversification

Structural analysis

The system to represent was defined as a field consisting of its soil profile and its aerial environment (Figure 3).

The passive environment, containing the conceptual model outputs, provides variables informing on ecosystem services, classified by the CICES V5.1 as provisioning, regulation, and maintenance services (Haines-Young & Potschin, 2017): production, regulation of greenhouse gases, control of erosion, soil water quality and supply, carbon storage, and nitrogen and phosphorus regulation (Table 4).

The active environment contains elements that act on the system: climate, crop management system and crop rotation (i.e. the cropping system), and environmental properties. In the active environment, climate includes air temperature, rainfall, radiation and gases. The cropping system is described by the tillage, the fertilisation, the crop diversification (sole cropping/intercropping/rotation), the sowing and harvesting, and the different other farmer practices (pesticides use, irrigation, liming) that take place during one year in the field. Environmental properties are represented by the type of soil as well as the landscape elements that border the system.

It was chosen to represent BAPs as subsystems, in the field, that interact between them. These subsystems evolve under the influence of the agroecosystem and its management and intervene in the provision of ecosystem services. So, the conceptual model consists of eight main BAPs:

- soil organic matter, subdivided into 3 pools called “*Fresh*”, “*Labile*”, and “*Stable*”;
- soil mineral pool, subdivided into “*Nitrogen*”, “*Carbon*”, and “*Phosphorus*”;
- soil structure;
- water availability;
- biological activity;
- crop;
- weeds;
- pests and diseases.

Each BAP is described by variables that characterize its state over time. Whereas the type of crop diversification (intercropping/crop rotation) is in the active environment, crop species and their development are considered as a BAP; it allows interaction with weeds and pests and diseases BAPs to represent biotic pressures that may limit production.

Functional analysis

Bibliographic analysis allows me to identify the main relationships that occur in the system of the conceptual model; they are presented in detail Appendix 2. In the context of this work, these relationships mainly concern the elements of the active environment related to crop diversification (Figure 3). These relationships reflect effects that may exist between the elements of the active environment and the BAPs, and between the BAPs themselves; these relationships also reflect effects of the BAPs on the elements of the passive environment i.e. on the variables that represent ecosystem services.

System: field

soil profile + aerial environment

<p>Active environment</p> <p><i>Climate</i></p> <ul style="list-style-type: none"> - temperature - rain - radiation - gases <p>Cropping system</p> <ul style="list-style-type: none"> - Tillage <ul style="list-style-type: none"> o depth o frequency - Fertilization <ul style="list-style-type: none"> o organic / mineral o dose o frequency - Intercropping / sole cropping <ul style="list-style-type: none"> o species / cultivars o number of species o % species - Rotation <ul style="list-style-type: none"> o length o diversification index - Sowing - Harvesting - Pesticide use - Irrigation - Liming <p>Environmental properties</p> <ul style="list-style-type: none"> - Type of soil <ul style="list-style-type: none"> o texture, pH - Other elements <ul style="list-style-type: none"> o slope o trees / hedges o neighboring crop o boundaries

Crop
aerial / roots traits

Weeds
% coverage
biomass

Pests and diseases
severity and incident rate

SOM		
Fresh pool	Labile pool	Stable pool
C : N residues	C : N microbial labile carbon	C : N humus humified carbon

Structure
bulk density
mean weight diameter

Mineral pool		
N	C	P
NO ₃ ⁻	dissolved inorganic carbon	orthophosphate ions
NH ₄ ⁺		particulate / organic phosphorus

-	<p>Passive environment</p> <p>Production</p> <ul style="list-style-type: none"> o yield o land equivalent ratio <p>Greenhouse gases regulation</p> <ul style="list-style-type: none"> o nitrous oxide emissions from soil o carbon dioxide emissions from soil <p>Erosion control</p> <ul style="list-style-type: none"> o soil loss <p>Water quality</p> <ul style="list-style-type: none"> o nitrate leaching <p>Water supply</p> <ul style="list-style-type: none"> o soil water status <p>Carbon storage</p> <ul style="list-style-type: none"> o soil organic carbon <p>Nitrogen and phosphorus regulation</p> <ul style="list-style-type: none"> o available phosphorus content o soil organic nitrogen
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Figure 3: Conceptual model of an agroecosystem based on crop diversification. In the center part of the figure, the BAPs are represented. Variables that characterize each BAP are shown in italics, below the corresponding BAP's. Variables influencing the system are listed in the active environment. Variables that are outputs of the system are listed in the passive environment. Elements of the active environment related to crop diversification are bold.

Table 4: Variables of the passive environment ordered according to (i) the CICES V5.1 classification (Haines-Young & Potschin, 2017) and (ii) the time scale necessary for the variables of the active environment to have an effect on them. References for this ordering are listed. About the CICES V5.1 classification: the highest level are the categories, called "Services", used in the Millennium Ecosystem Assessment (2005), "provisioning", "regulation and maintenance". Below these "Services" are a series of "Divisions", "Groups" and "Classes".

Output	Code CICES	Services	Division	Group	Class	Time scale	Reference
Production	1.1.1.1	Provisioning	Biomass	Cultivated terrestrial plants for nutrition, materials or energy	Cultivated terrestrial plants (e.g fungi, algae) grown for nutritional purposes	Crop cycle to pluri-annual	<ul style="list-style-type: none"> Lehman RM, Osborne SL, Duke SE (2017) Diversified no-till Crop Rotation Reduces Nitrous Oxide Emissions, Increases Soybean Yields, and Promotes Soil Carbon Accrual. <i>Soil Sci Soc Am</i> 181:76–83. Li C, He X, Zhu S, et al (2009) Crop diversity for yield increase. <i>PLoS One</i> 4:e8049. Nunes MR, van Es HM, Schimelbeck R, et al (2018) No-till and cropping system diversification improve soil health and crop yield. <i>Geoderma</i> 328:30–43. Paul R, Sabatier R, Tchamitchian M (2020) Modelling crop diversification and association effects in agricultural systems. <i>Agric Ecosyst Environ</i> 288:106711.
Greenhouse gases regulation	2.2.6.1	Regulation and maintenance	Regulation of physical, chemical, biological conditions	Atmospheric composition and conditions	Regulation of chemical composition of atmosphere	Infra-annual to pluri-annual	<ul style="list-style-type: none"> Buragienė S, Šarauškus E, Romaneckas K, et al (2019) Relationship between CO2 emissions and soil properties of differently tilled soils. <i>Sci Total Environ</i> 662:786–795. Dyer L, Oelbermann M, Echarte L (2012) Soil carbon dioxide and nitrous oxide emissions during the growing season from temperate maize-soybean intercrops. <i>J Plant Nutr Soil Sci</i> 175:394–400. Huang J, Su P, Gao W, Chen Y (2019) Effects of Maize-Soybean Intercropping on Nitrous Oxide Emissions from a Silt Loam Soil in the North China Plain. <i>Pedosphere</i> 29:764–772. Lehman RM, Osborne SL, Duke SE (2017) Diversified no-till Crop Rotation Reduces Nitrous Oxide Emissions, Increases Soybean Yields, and Promotes Soil Carbon Accrual. <i>Soil Sci Soc Am</i> 181:76–83.
Erosion control	2.2.1.1	Regulation and maintenance	Regulation of physical, chemical, biological conditions	Regulation of baseline flows and extreme events	Control of erosion rates	Infra-annual to pluri-annual	<ul style="list-style-type: none"> Bogunovic I, Perera P, Kusic I, et al (2018) Tillage management impacts on soil compaction, erosion and crop yield in Stagnosols (Croatia). <i>CATENA</i> 160:376–384. Laloy E, Bielders CL (2010) Effect of Intercropping Period Management on Runoff and Erosion in a Maize Cropping System. <i>J Environ Qual</i> 39:1001–1008. Wall GJ, Pringle EA, Sheard RW (1991) Intercropping red clover with silage corn for soil erosion control. <i>Can J Soil Sci</i> 71:137–145. Personal communication with Christian Walter (L'Institut Agro – AGROCAMPUS OUEST).
Water quality	2.2.5.1	Regulation and maintenance	Water	Water conditions	Regulation of the chemical condition of freshwaters by living processes	Infra-annual to pluri-annual	<ul style="list-style-type: none"> De Notaris C, Rasmussen J, Sørensen P, Olesen JE (2018) Nitrogen leaching: A crop rotation perspective on the effect of N surplus, field management and use of catch crops. <i>Agric Ecosyst Environ</i> 255:1–11. Maneviski K, Børgesen CD, Andersen MN, Kristensen IS (2015) Reduced nitrogen leaching by intercropping maize with red fescue on sandy soils in North Europe: a combined field and modeling study. <i>Plant Soil</i> 388:67–85. Personal communication with Patrick Durand (INRAE).
Water supply	4.2.2.2	Provisioning	Water	Ground water for used for nutrition, materials or energy	Ground water used as a material (non- drinking purposes)	Infra-annual to pluri-annual	<ul style="list-style-type: none"> Bordovsky JP, Lyle WM, Keeling JW (1994) Crop Rotation and Tillage Effects on Soil Water and Cotton Yield. <i>Agron J</i> 86:1–6. Chen G, Kong X, Gan Y, et al (2018) Enhancing the systems productivity and water use efficiency through coordinated soil water sharing and compensation in strip-intercropping. <i>Sci Rep</i> 8:1–11. Personal communication with Patrick Durand (INRAE).
Carbon storage	2.2.4.2	Regulation and maintenance	Regulation of physical, chemical, biological conditions	Regulation of soil quality	Decomposition and fixing processes and their effect on soil quality	Annual to pluri-annual	<ul style="list-style-type: none"> Cong W-F, Hoffland E, Li L, et al (2015a) Intercropping enhances soil carbon and nitrogen. <i>Glob Change Biol</i> 21:1715–1726. Cong W-F, Hoffland E, Li L, et al (2015b) Intercropping affects the rate of decomposition of soil organic matter and root litter. <i>Plant Soil</i> 391:399–411. Pellerin S, Bamière L, Lamay C, et al (2019). Stocker du carbone dans les sols français. Quel potentiel au regard de l'objectif 4 pour 1000 et à quel coût ? Résumé du rapport d'étude, INRA (France), 114 p. Yang Y, Tilman D, Furey G, Lehman C (2019) Soil carbon sequestration accelerated by restoration of grassland biodiversity. <i>Nat Commun</i> 10:1–7.
Nitrogen and phosphorus regulation	2.2.4.2	Regulation and maintenance	Regulation of physical, chemical, biological conditions	Regulation of soil quality	Decomposition and fixing processes and their effect on soil quality	Infra-annual to pluri-annual	<ul style="list-style-type: none"> Cong W-F, Hoffland E, Li L, et al (2015a) Intercropping enhances soil carbon and nitrogen. <i>Glob Change Biol</i> 21:1715–1726. Laitati M, Blavet D, Alkama N, et al (2014) The intercropping cowpea-maize improves soil phosphorus availability and maize yields in an alkaline soil. <i>Plant Soil</i> 385:181–191. Li C-J, Li Y-Y, Yu C-B, et al (2011) Crop nitrogen use and soil mineral nitrogen accumulation under different crop combinations and patterns of strip intercropping in northwest China. <i>Plant Soil</i> 342:221–231. Lukowiak R, Grzebisz W, Sassenrath GF (2016) New insights into phosphorus management in agriculture — A crop rotation approach. <i>Sci Total Environ</i> 542:1062–1077.

As far as possible, I tried to select studies where the pedoclimatic conditions are similar to those observed in Brittany to design the conceptual model. To resume the bibliographic synthesis (detailed in Appendix 2), the main type of diversification described concerns intercropping. The second most frequently described type of diversification after intercropping is the implementation of crop rotations. Generally, these systems are compared with monocropping. If the relationship between an ecosystem service and a type of diversification is not described, the relationship between the ecosystem service and crops that could be used to promote diversification was investigated. For example, with respect to erosion, aggregate stabilization was described by species. Cover crops and catch crops are involved in temporal diversification and they have direct influence on erosion and leaching. So, their effects on ecosystem services were included in the synthesis. Then, to complete the influence of our system on the provision of ecosystem services, the effect of some crop management practices other than crop diversification was included in the analysis.

Dynamic analysis

The system evolves over times, and the intensity of relationships mentioned in the functional analysis may decrease (even disappear) or increase (detailed scheme of the dynamic analysis is attached in Appendix 3).

Following Lamanda et al (2012), and to improve understanding of dynamic analysis, each relationship was expressed as an assumption between two elements of our conceptual modelling (variables of the active environment, BAPs, variables of the passive environment). These assumptions explain why the elements of the active environment are related to the BAPs (HAE, hypotheses active environment), how the BAPs are related to each other (HBAP, hypotheses BAP) and how these BAPs are related to the passive environment (HPE, hypotheses passive environment).

Most of the relationships, e.g the influence of climate on crop, occur at an infra-annual level, during the first year of cultivation; for example, among the 15 relationships represented in the dynamic analysis regarding the effect of crop diversification on production only 4 occur over longer periods of time (Appendix 3). However, some relationships have an effect on the passive environment only on a multi-year scale. For example, according to the bibliography, changes in soil organic matter and rate of mineralization are only perceptible on a 7-year scale for sandy loam soil and changes in the stock of labile phosphorus are only visible after 4 years (Table 4).

Finally, changes over time in some relationships will depend on the type of crop diversification (sole cropping / intercropping / crop rotation). If one compares a scenario with bare soil during the winter period vs a scenario with a cover crop during the winter period, there is an immediate effect on erosion regulation and nitrate leaching (personal communication, Christian Walter, L'Institut Agro – AGROCAMPUS OUEST). However, the comparison between a poorly diversified plant cover and a diversified plant cover suggests a significant effect on erosion only on the scale of several years.

b. Comparison of crop simulation models using our conceptual model of an agroecosystem based on crop diversification

Three crop models – APSIM, DDSAT, and STICS – were compared in their capacity to retranscribe (i) the elements of the active and passive environments of our conceptual model, (ii) the BAPs, and (iii) the main relationships between active environment, passive environment, and BAPs.

At the model output level (Table 5), each crop model is able to simulate and provide indicators on yield, carbon dioxide emissions from soil, nitrate leaching, soil water status, soil organic carbon and soil organic nitrogen contents. However, erosion and phosphorus mobilization processes are not taken into account in the STICS formalism (Brisson, 2008; Brisson et al., 2003). Concerning DSSAT, the description of nitrous oxides fluxes and soil losses are not yet available in the current versions of the model (Jones et al., 2003; Porter et al., 2010).

Table 5: Outputs of conceptual model that APSIM, DSSAT and STICS can simulate

	Production	GHG regulation		Erosion control	Water quality and supply		C storage	N and P dynamics	
	Yield	CO ₂	N ₂ O	Soil loss	Water status	Nitrate leaching	SOC	SON	Available P
APSIM	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
DSSAT	Yes	Yes	No	No	Yes	Yes	Yes	Yes	Yes
STICS	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	No

GHG, greenhouse gases; C, carbon; N, nitrogen; P, phosphorus; SOC, soil organic carbon; SON, soil organic nitrogen

Unlike STICS, a soil phosphorus module exists in DSSAT but it is poorly documented. Only APSIM is capable of simulating each of the outputs of our conceptual model with well-described modules (Keating et al., 2003; O’Leary et al., 2016).

As far as BAPs of our conceptual model are concerned, some are not able to be represented by the models. This is notably the case for the biological activity of the soil. Then, only APSIM and DSSAT have modules to represent the weed competition and its effects on soil water and nutrient resources. DSSAT presents a pest module (Jones et al., 2003). It allows users to input field observations on insect populations or damage, disease severity, to simulate the effects of specified pests and diseases on growth and yield. However, this aspect of the impact of pests and diseases and weeds will be left aside because their consideration in the formalism of the cited models remains simplistic and could complicate, at this stage, the validation step for the selected crop model. For the rest of the BAPs, soil organic matter is simulated in a similar way between the 3 crop models with 3 pools. Each of the models used “*tipping bucket*” approach for soil water balance. Nitrogen loss due to denitrification was modelled as a function of soil temperature and water content in all models. Mineralization of soil organic matter was controlled at least by soil temperature and moisture, and in addition with STICS soil clay content and soil calcium contents were used as control variables for organic nitrogen mineralization. APSIM and STICS include the process of phenological response to nitrogen stress. The bulk density is considered in the soil organic matter processes and is used in the water movement calculations in all models (Brisson et al., 2003; Jones et al., 2003; Keating et al., 2003; Porter et al., 2010; Probert et al., 1998; Salo et al., 2016).

As far as the active environment is concerned, the 3 crop models can simulate crop rotations and intercropping. However, with STICS, for the moment only one barley-pea intercropping is available. APSIM seems to be the most developed model on this point with the possibility to simulate more species mixture for intercropping (Chimonyo et al., 2016; Dimes et al., 2011; Knoerzer et al., 2011). The management modules of these 3 models make it possible to carry out several farm practices: sowing, mineral and organic fertilisation, irrigation, soil tillage, harvesting. The effects of tillage on soil bulk density and compaction of ploughed soil due to subsequent precipitation are both considered by DSSAT and STICS. (Maharjan et al., 2018).

Concerning the quality of these models, a recent study tested 11 crop simulation models including APSIM, DSSAT and STICS, using spring barley dataset under various nitrogen

fertiliser rates from three experimental years in Finland (Salo et al., 2016). The models were calibrated using data from 2002 to 2008. Thus, in 2008, concerning the calibration of yield, STICS showed good performance with low RMSE values and index of agreement values close to 1 in relation to other models. On the other hand, DSSAT was one of the models with the worst performance for the grain yield. Calibration results for phenology did not correspond perfectly with the observed data; however, the 3 models were among those with the lowest RMSE for anthesis and maturity dates. Other information that emerges from this study was that the models that perform best in their LAI estimation with all N rates like APSIM, did not perform better in crop yield estimation.

Thus, by its capacity to simulate all the outputs of the conceptual model and its quality which remains suitable compared to other models, APSIM was chosen for the rest of the work.

c. Simulations with APSIM

APSIM validation for maize and wheat in a temperate climate and for a silty loam soil (EFELE experiment)

As APSIM does not have a mustard crop module to simulate the cover crop of the EFELE experiment, I used a rapeseed crop module to simulate a mustard-like cover crop. In the same way, the maize cultivars sown on the EFELE experiment were not available on APSIM: following Morel et al. (2018), a cultivar was created. For wheat, a cultivar registered in the catalogue of cultivars of the European Union was used (Claire; *EU Plant variety database* (v.3.2.1), 2020). Finally, as the rapeseed module of APSIM does not take into account the phosphorus the simulation of phosphorus in rotation 2 was not possible.

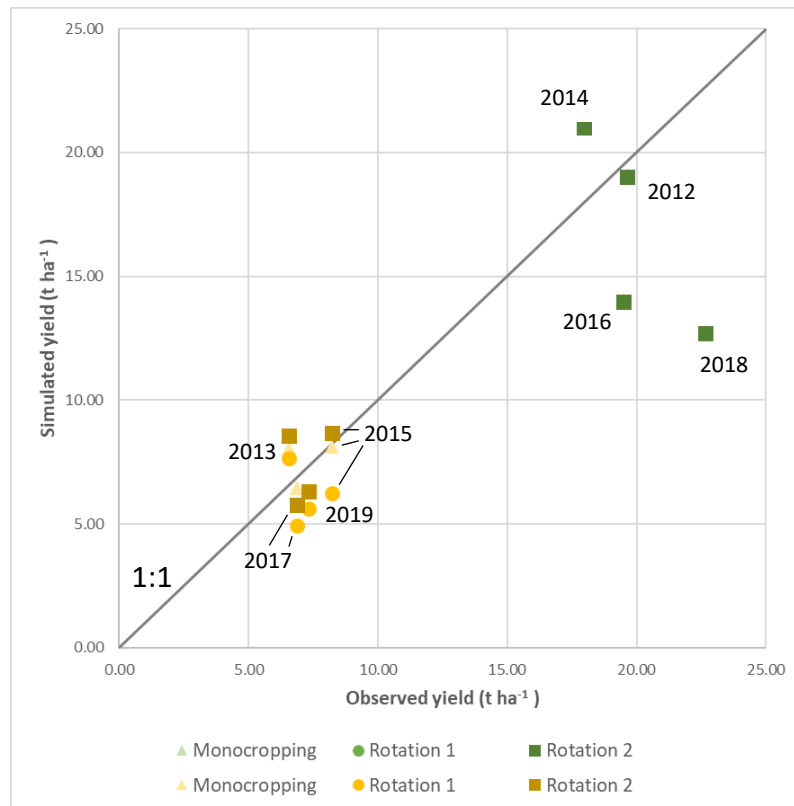


Figure 4: Observed vs. simulated dry matter (DM) yield for maize and wheat in the EFELE experiment (“TS/MO” trial; “conventional tillage/mineral fertilizer” treatment) in 2012-2019. Monocropping simulations correspond to runs 1 and 2; rotation 1 (run 3) is Maize / Wheat / Fallow; rotation 2 (run 4) is Maize / Wheat / Cover crop. Wheat crop is represented by yellow marks and maize crop by green marks.

Simulated crop yield ranged from 12.7 to 21.2 t ha⁻¹ for maize and from 4.9 t ha⁻¹ to 8.7 t ha⁻¹ for wheat while observed crop yield ranged from 18.0 to 22.7 t ha⁻¹ for maize and from 6.6 to 8.2 t ha⁻¹ for wheat (Figure 4). The difference between simulated and observed crop yields was higher for maize than for wheat; consequently, better model accuracy for predicting crop yield was highlighted for wheat, with lower RMSE values and increasing CCC values (Table 6). Better model accuracy was obtained with monocropping simulations whereas rotation 1 simulation presented the worst statistical parameters. According to Ojeda et al (2018), the performance of the crop model for yield simulation is in the “*poor*” category (CCC < 0.70).

Table 6: Statistical summary on the accuracy of APSIM to simulate crop dry matter yield for maize and wheat in the EFELE experiment (“TS/MO” trial; “conventional tillage/mineral fertilizer” treatment) in 2012-2019.

	Monocropping		Maize / Wheat / Fallow		Maize / Wheat / Cover crop	
	Maize	Wheat	Maize	Wheat	Maize	Wheat
No. Obs	4	4	4	4	4	4
Observed data - mean (t ha ⁻¹)	19.95	7.24	19.95	7.24	19.95	7.24
Simulated data- mean (t ha ⁻¹)	16.78	7.23	16.71	6.11	16.67	7.32
Observed data - SD (t ha ⁻¹)	1.96	0.72	1.96	0.72	1.96	0.72
Simulated data- SD (t ha ⁻¹)	4.03	0.98	4.03	1.15	3.98	1.50
RMSE (t ha ⁻¹)	5.90	0.91	5.93	1.71	5.91	1.27
CCC	-0.38	0.25	-0.37	-0.01	-0.37	0.23

No. Obs, number of observations; SD, standard deviation; RMSE, root mean square error; CCC, concordance correlation coefficient.

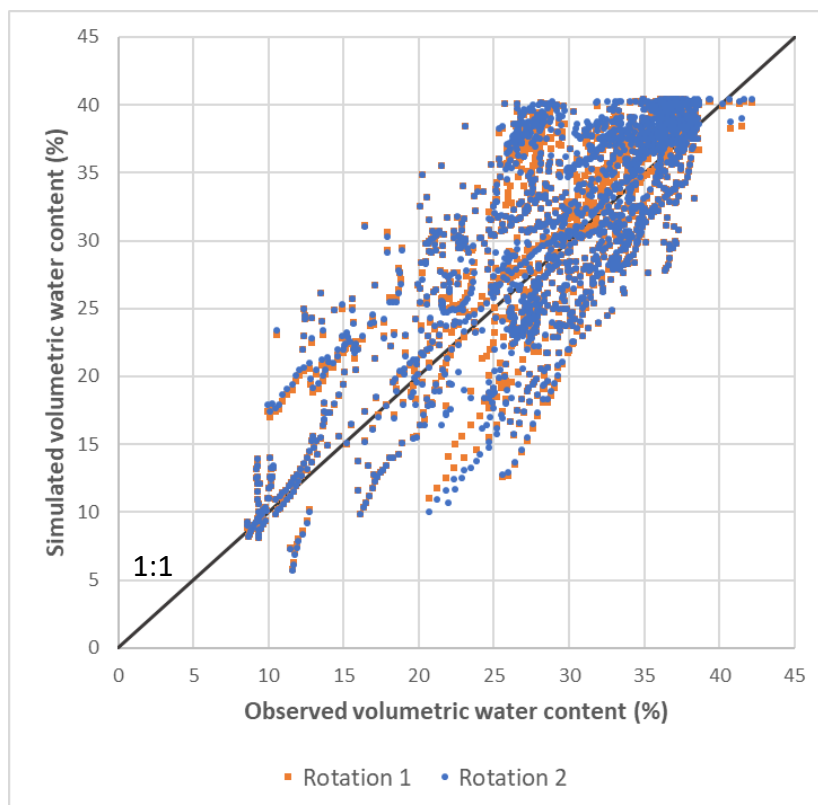


Figure 5: Observed vs. simulated volumetric water content (%) at 15-depth cm in the EFELE experiment (“TS/MO” trial; “conventional tillage/mineral fertilizer” treatment) in 2012-2019. Rotation 1 (run 3) is Maize / Wheat / Fallow; rotation 2 (run 4) is Maize / Wheat / Cover crop.

Regarding data on volumetric water content, good agreement between observed and simulated data was found for both rotation simulations (Figure 5), with values that indicate acceptable crop model accuracy: CCC values were 0.79 and 0.78 for rotations 1 and 2, respectively (Table 7). However, rotation 2 simulation had an RMSE value 0.25 point higher than rotation 1 simulation, with an overestimation of volumetric water content at 15 cm greater in 2016 and 2018 (Figure 6).

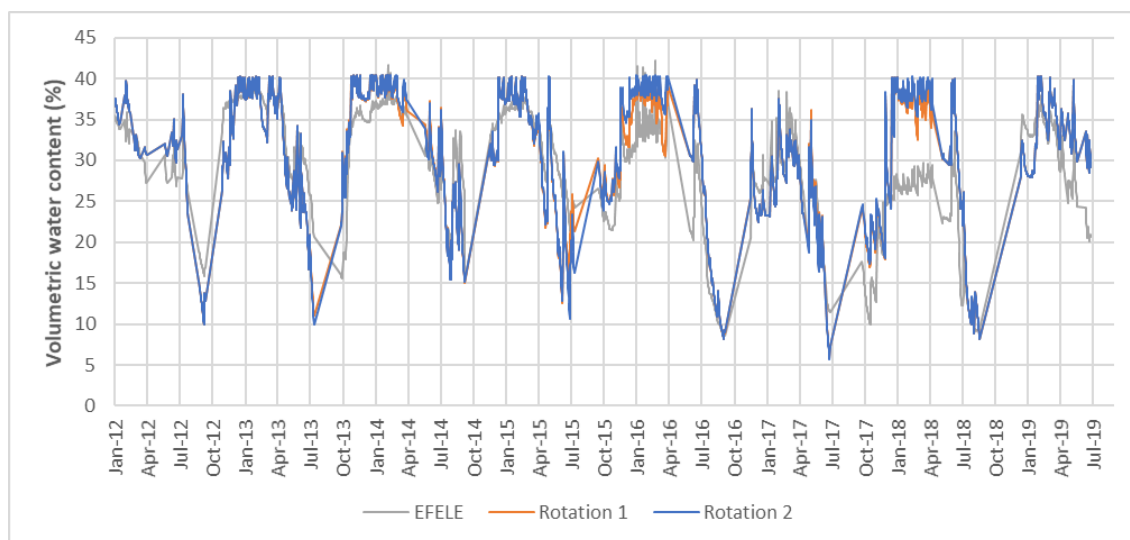


Figure 6: Evolution over 8 years (2012-2019) of volumetric water content (%) at 15-cm depth for rotation 1, Maize / Wheat / Fallow, rotation 2, Maize / Wheat / Cover crop, and on EFELE experiment (“TS/MO” trial; “conventional tillage/mineral fertilizer” treatment).

Table 7: Statistical summary on the accuracy of APSIM to simulate volumetric water content (%) at 15-cm depth in the EFELE experiment (“TS/MO” trial; “conventional tillage/mineral fertilizer” treatment) in 2012-2019. Rotation 1 (run 3) is Maize / Wheat / Fallow; rotation 2 (run 4) is Maize / Wheat / Cover crop.

	Rotation 1	Rotation 2
No. Obs	1840	1840
Observed data - mean (%)	29.00	29.00
Simulated data mean (%)	30.42	30.55
Observed data - SD (%)	7.37	7.37
Simulated data- SD (%)	7.90	8.01
RMSE (%)	4.93	5.18
CCC	0.79	0.78

No. Obs, number of observations; SD, standard deviation; RMSE, root mean square error; CCC, concordance correlation coefficient.

As far as amount of soil organic carbon and amount of soil organic nitrogen were concerned, differences between rotation 1 and rotation 2 simulations appeared during the year 2016 with higher values for rotation 2 simulation than for rotation 1 simulation (Figure 7). Whatever simulations, periods of high soil organic carbon increase correspond to the simulated incorporation of crop residues into the Fresh Organic Matter pool by tillage. To evaluate APSIM accuracy for soil organic carbon and soil organic nitrogen data, simulated data were compared with observed data measured on March 15, 2012 and March 16, 2016 in the EFELE experiment. Simulated data of soil organic carbon and soil organic nitrogen was similar to

observed data in the EFELE experiment, particularly for soil organic nitrogen for rotation 2 in March 2016. The amount of soil organic carbon and soil organic nitrogen increased for both observed and simulated data, with a difference of a few points for soil organic carbon (rotation 2: 2.13 t ha⁻¹; rotation 1: 2.31 t ha⁻¹) but negligible in terms of carbon storage.

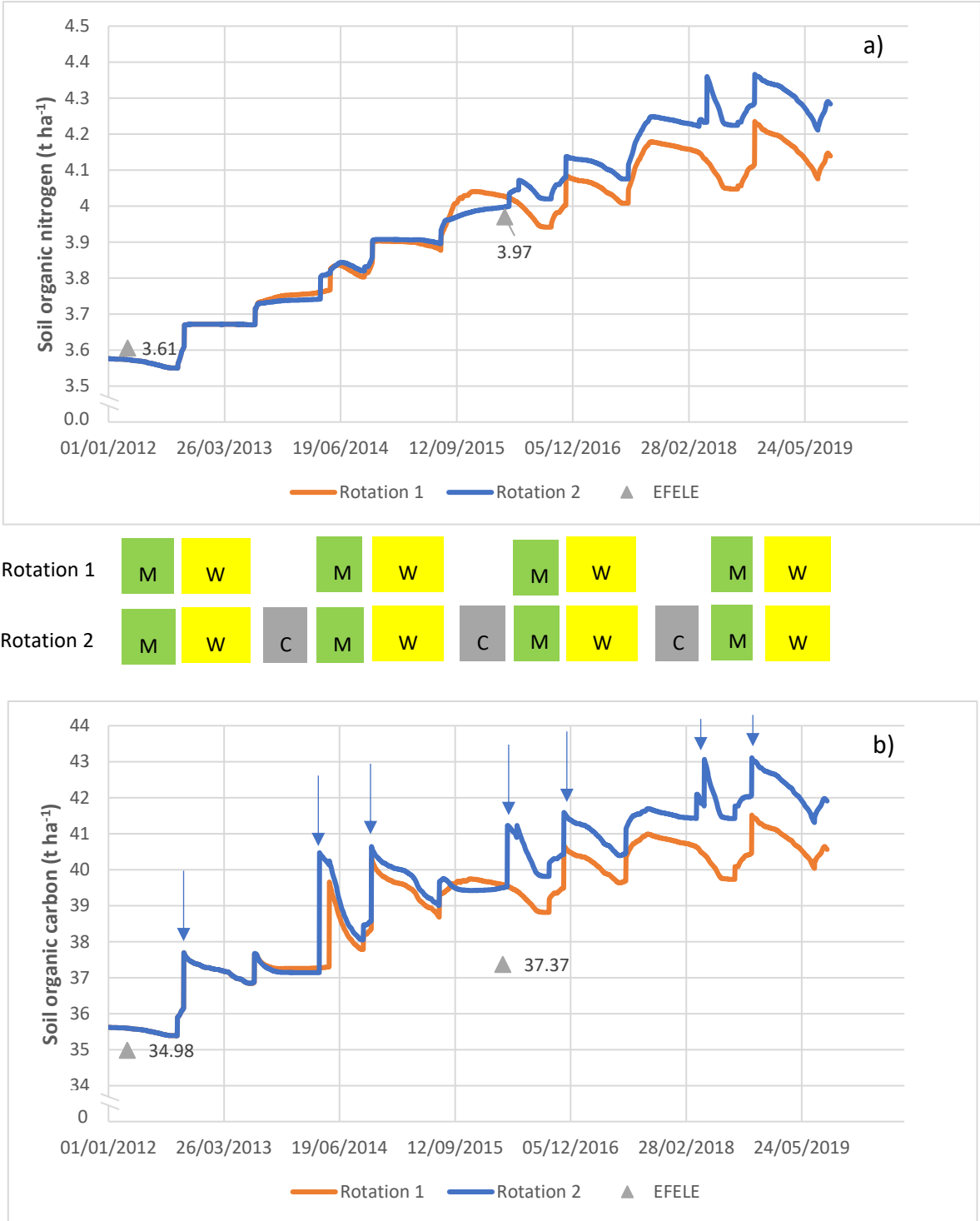


Figure 7: Evolution over 8 years (2012-2019) of simulation of (a) soil organic nitrogen stocks, and (b) soil organic carbon stocks between 0-25 cm for rotation 1 "Maize (M) / Wheat (W) / Fallow" and rotation 2 "Maize (M) / Wheat (W) / Cover crop (C)". The two points of measurements made on EFELE are indicated in grey and the arrows represent the incorporation of crop residues into the pool of fresh organic matter by tillage.

Simulation over time of output related to ecosystem services

This part concerns variables simulated by APSIM, not monitored on the EFELE experiment (“TS/MO” trial; “conventional tillage/mineral fertilizer” treatment) i.e. variables that represent effects of rotation 1 and rotation 2 on ecosystem services identified in the conceptual model. These variables are nitrous oxide and dioxide carbon emission from soil, nitrate leaching and soil erosion, the evolution of extractable soil water and soil phosphorus (Figures 8, 9, and 10).

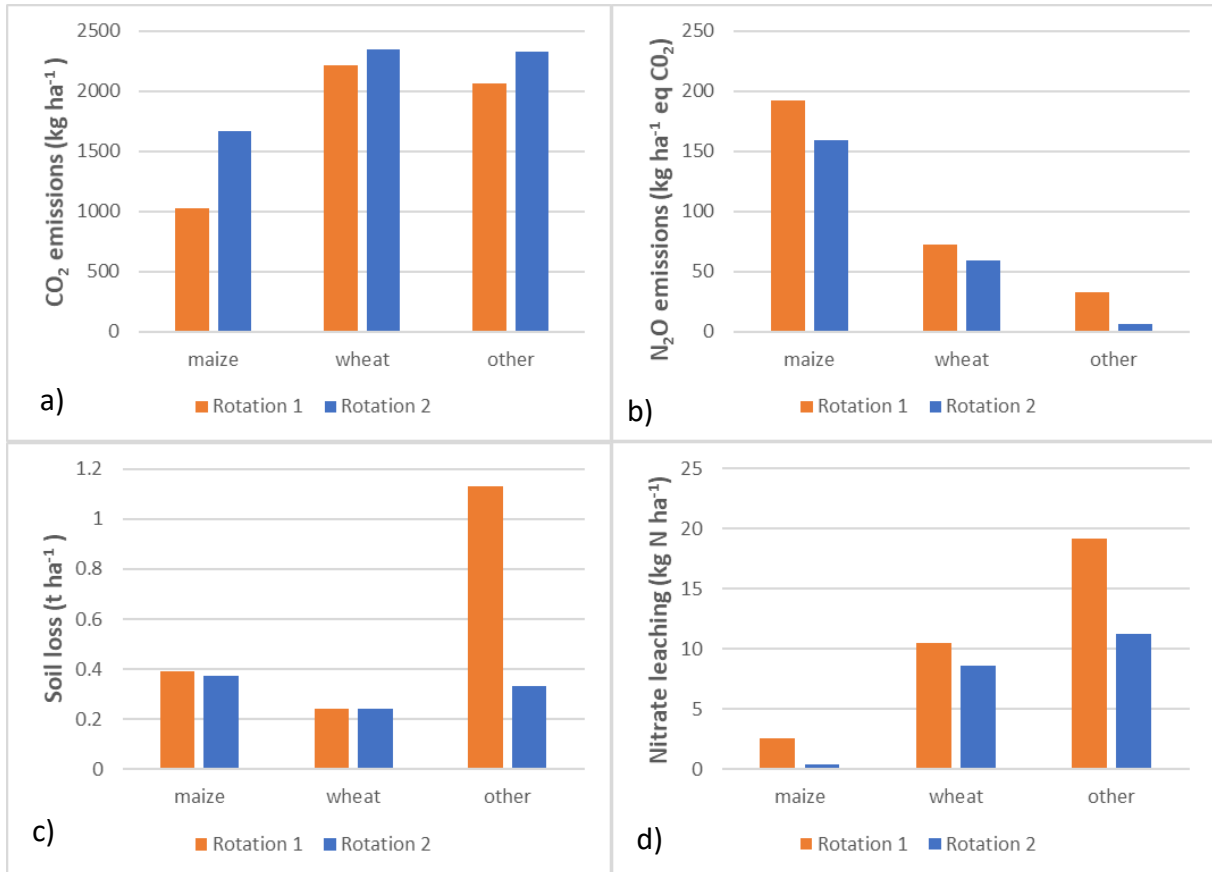


Figure 8: Comparison for maize period, wheat period and fallow/cover crop periods (“other”) of (a) average dioxide carbon (CO₂) emissions, (b) average nitrous oxide emissions (N₂O), (c) average cumulative soil losses, and (d) average nitrate leaching between rotation 1 and rotation 2 simulations (2012-2019). The amount of nitrous oxide emissions has been converted into carbon dioxide equivalent using the global warming power at 100 years of nitrous oxide stated in the fifth report of the GIEC (2013).

During the 2012-2019 period, on the one hand, rotation 1 simulation – without cover crop – had the least carbon dioxide emissions from maize and wheat production (Figure 8a). On the other hand, although simulated quantities were low, rotation 1 simulation had the most nitrous oxide emissions (Figure 8b): for this variable, maize production emitted more nitrous oxide. As the field slope on the EFELE experiment is only 2%, the simulated amount of average cumulative soil loss is very low and does not exceed 0.4 t ha⁻¹, except during the fallow/cover crop period and only for rotation 1, where an average of 1.1 t ha⁻¹ of soil loss is reached over this period (Figure 8c). Simulations for rotation 1 and rotation 2 also differed in nitrate leaching (Figure 8d): for rotation 2 simulation, on average, 41 % less nitrate left the soil profile during the in-between two main crop period. Notice that there was also a delayed effect of the cover crop as it reduced leaching during maize and wheat production.

As far as the evolution of labile phosphorus was concerned (Figure 9), I noticed that its stock decreased over time, before stabilizing at around 520 kg P ha⁻¹ from 2015 to 2019. The annual input of 50 kg P₂O₅ ha⁻¹ explained the large increase in labile phosphorus each year. For the

representation of the available water, the differences between the two simulated systems were mainly visible in periods of low extractable soil water in 2013, 2015 and 2017 (Figure 10).

Finally, as far as ecosystem services were concerned, rotation 2 simulation was better than rotation 1 simulation for almost all variables, except for carbon dioxide emissions.

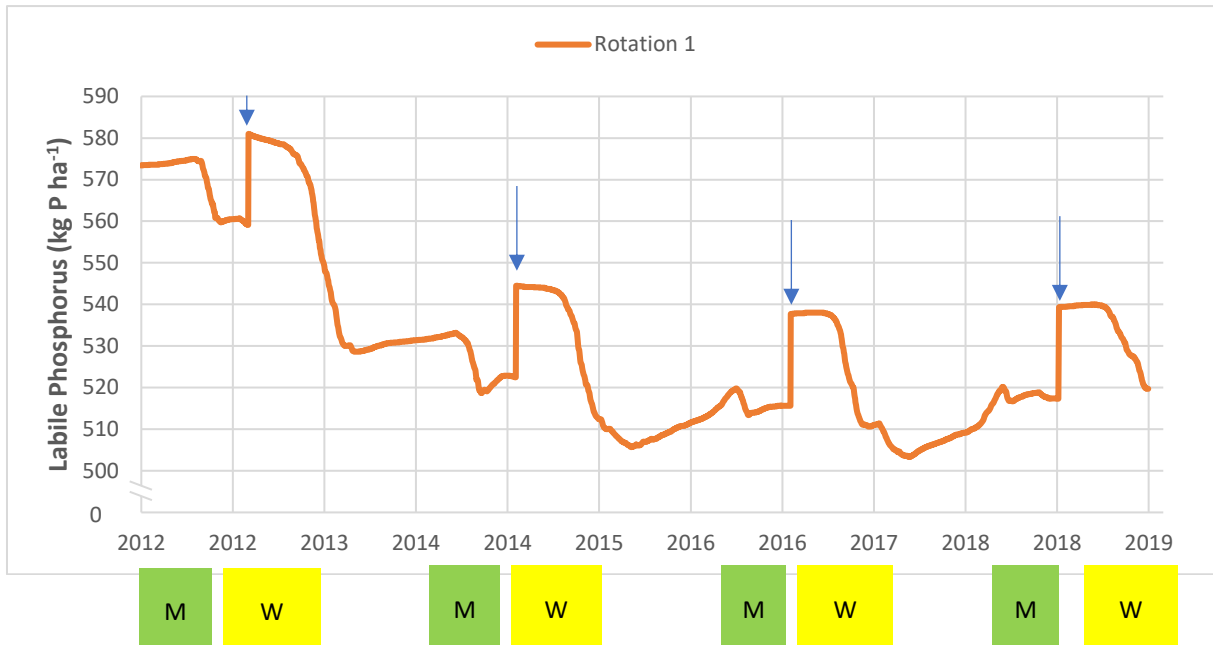


Figure 9: Evolution over time of labile phosphorus in soil for rotation 1 simulation (M, Maize; W, Wheat). Arrows represent the annual P_2O_5 fertilization.

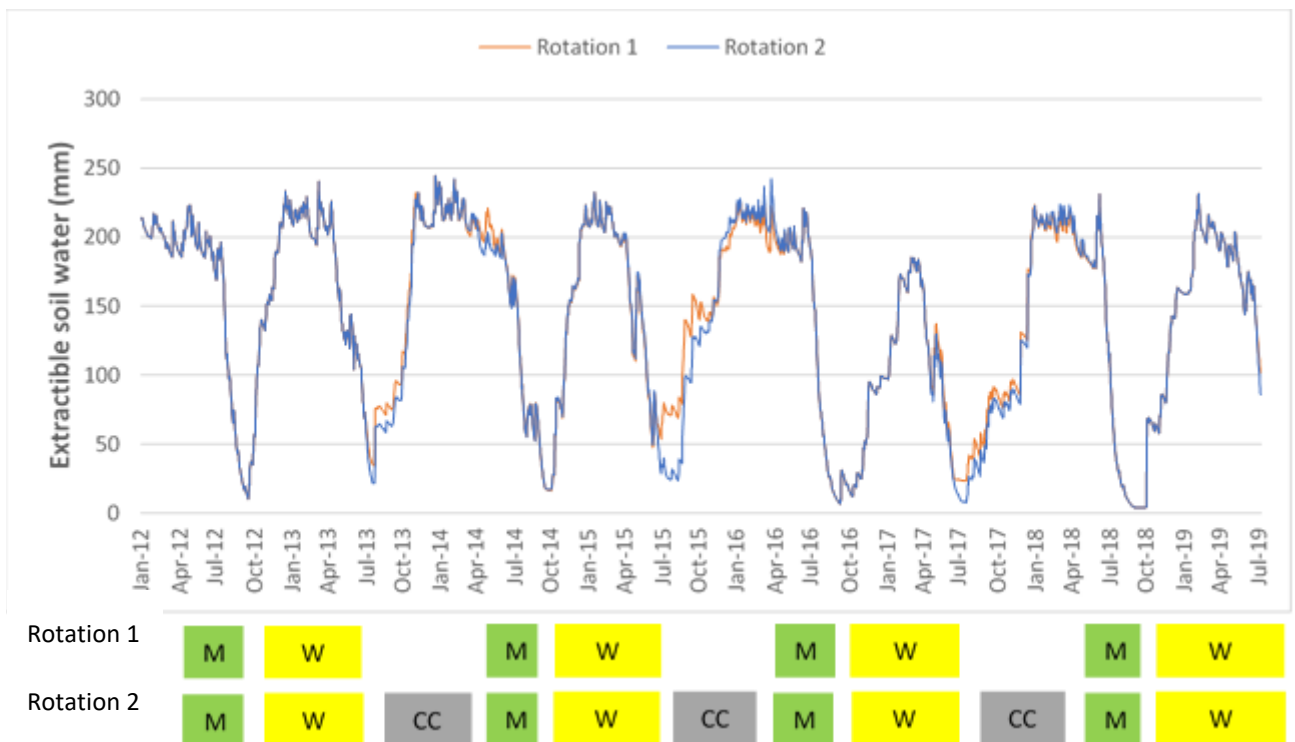


Figure 10: Evolution of extractable soil water for rotation 1 and rotation 2 simulations (M, Maize; W, Wheat; CC, Cover Crop).

Definition of the level of information required to describe soil in APSIM

Crop yield, soil organic carbon (SOC) and nitrogen (SON) content are the only variables, that can be compared between the EFELE experiment and the rotation 1 and rotation 2, those for which I tested soil profiles described by (1) four layers, (2) two layers and (3) one single layer. Details of the results are showed in Appendix 3.

There are very few differences between simulations. The differences in RMSE values between simulations did not exceed 0.1 t ha^{-1} and for CCC these differences did not exceed 0.03 (Table 8).

For SOC and SON the soil 3 does not describe a layer between 0-25 cm it will therefore not be considered. The simulation results show very few differences between soil 1 and soil 2, the variations between these two soils are of the order of 0.48 t ha^{-1} for SOC and non-existent for SON (Table 8). Thus, it would seem that the degree of soil description has little influence on the simulations for yield, soil organic carbon and nitrogen contents.

Table 8: Comparison of soil organic carbon and soil organic nitrogen data in March 16, 2016 between EFELE experiment and rotation 2 with soil 1 and soil 2.

	Depth (cm)	Organic carbon (t ha^{-1})	Organic nitrogen (t ha^{-1})
EFELE	0-25	37.37	3.97
Soil 1	0-25	39.50	4.00
Soil 2	0-25	39.98	4.00

6. Discussion

a. Interest and limits of the conceptualization method

In this work, the agroecosystem conceptualization approach described by Lamanda et al. (2012) has the main advantage of synthesizing a large amount of knowledge on a specific topic. By conceptualizing a model *de novo* rather than starting directly from an existing numerical model whose underlying conceptualization is not necessarily accessible, we explicitly point out the processes, interactions and elements of a system in relation to the problem posed and which we consider essential to represent in our system. As my work is a step to take into account, in the *de novo* design of systems, the long-term effects of crop diversification on the provisioning of different ecosystem services, conceptual modelling is an interesting upstream of mathematical modelling because it allows:

- identification of indicators that can inform the provision of ecosystem services and elements of the system involved in the processes related to this ecosystem services.
- Simplified representation of a complete causal chain between the elements of the diversification-based agroecosystem and an ecosystem services indicator.
- The assembly of knowledge that allows new hypotheses to be formulated within the system and that evolve over time.

Then by confronting the conceptual model created with the mathematical models, we make sure to choose a mathematical model that meets the objectives of the design.

A questionable point in our conceptual model is the position of pH variable in the active environment. However, it is recognized that this variable are subject to change over time because of climate and crops, for example (Jones et al., 2004; Wang et al., 2015) and APSIM have a module which can provides a representation of the acidification of soil (Keating et al.,

2003). So, it might have been appropriate to place it within the system with BAPs to represent the influence of diversification on the chemical properties of the soil. Furthermore, although an effort has been made to find references with pedoclimatic conditions close to those of the EFELE experiment, many references reported studies located in regions (China, India, Argentina, etc.) with different pedoclimatic conditions from the ones of the Brittany region (while others did not inform the soil type!). Another limit is the lack of references about some aspect; for example, it was not possible to represent the influence of crop diversification on the biological diversity of the soil fauna.

b. Advantages and limits of APSIM

Practical aspect

From a practical point of view, the APSIM has the advantage of having an internet platform that contains a lot of information about modules and supports (videos, training manuals) allowing a new user to quickly understand the model. Another advantage is that APSIM has a help structure (<https://github.com/APSIMInitiative/ApsimX/issues>) that can be used in case of questions about APSIM, or if there is a defect with the crop model.

The necessary adaptation of APSIM to the context of this study

In order to design systems whose objective is to optimise the provisioning of ecosystem services rendered by crop diversification, it is necessary to use a mathematical model capable of simulating the physical, biological and chemical functioning of a soil-plant-atmosphere system influenced by a technical system (crop management system, crop rotation). Among the crop simulation models, it was found – thanks to the conceptual approach – that APSIM was the one that made it possible to simulate a high number of variables related to ecosystem services.

APSIM is a crop model widely used in the southern hemisphere. Indeed, evaluation of APSIM is well-established and well-documented in Australia and Africa (Gaydon et al., 2017). For simulations in regions with a pedoclimate very different from the ones in the previously mentioned areas, there is a significant effort to adapt the model.

In particular, in our case, cultivars sown on the EFELE experiment were not available in the model. For maize, I created a cultivar based on EFELE's cultivar characteristics and multiple references (Keith & Richard, 2012; Morel et al., 2018; Teixeira et al., 2015).. Hereafter are some examples of parameters used for the phenology recalibration of APSIM forage maize cultivar: thermal time from emergence to end juvenile phase; thermal time from flag leaf appearance to flowering; thermal time from flowering to start grainfill; thermal time between flowering to maturity. For wheat, an APSIM cultivar, available in the EU Plant variety database (EU Plant variety database (v.3.2.1), 2020) has been used. For the cover crop, there is no mustard module yet, so it was chosen to use a crop from the same family available, a winter rapeseed cultivar. This is a big limitation of our work because Rotation 2 is supposed to be the simulation closest to the one of the EFELE experiment.

All these differences between the simulations and the rotation of the EFELE experiment may explain the low accuracy for predicting crop yield compared to other crop modelling studies (Ojeda et al., 2018; Teixeira et al., 2015). In addition, using maize as an example, the yield observed on the EFELE experiment appears to be much less variable than the values predicted by APSIM. This can be explained by a higher sensitivity of the cultivar I created to water deficit. APSIM maize module can reproduce the effect of water deficits on plant processes like photosynthesis, phenology, and leaf-expansion (Crop Module Documentation, 2020).

However, the years 2016 and 2018 are the two years of simulations where the soil water level between flowering and harvest is the lowest (Figure 10) and rainfall is lower compared to the previous two years, 2012 and 2014 (Figure 2). Another explanation for these differences is that APSIM does not make it possible to verify that the forage maize harvest has taken place when the dry matter rate of the whole plant is about 32%. Thus, considering information about phenological parameters, it was estimated that the maturity stage of the cultivar I created corresponded to the 32% dry matter stage.

Concerning the rotation 1 simulation, the insertion of the SoilP module (which represents the availability of phosphorus in soil) penalized the simulated yield compared to observed yield. Indeed this module is well adapted for maize (Soil modules documentation-SoilP, 2020), however there is no validated parameterization for wheat in APSIM yet. Thus, thanks to file sent by a farming system modeller at the University of Queensland containing parameters suitable for others crops that are phosphorus sensitive, phosphorus parameters were implemented in APSIM to simulate phosphorus flows in rotation 1. This phosphorus module could not be introduced in rotation 2 because conversely to wheat module, the canola module is not currently take into account by APSIM phosphorus module.

Parameterisation of soil condition and calibration

In order to make the simulations work properly, APSIM offers the possibility to inform and complete a large number of variables related to soils, crops and crop management systems. APSIM requires daily values of precipitation, maximum and minimum temperatures and solar radiation but also measurable soil physical parameters for different soil layers and parameters related to phenology or crop biomass partitioning. However, during the test of the model in our case and contrary to studies carried out in other regions of the world (Chen et al., 2008; Dalgliesh et al., 2016; Yang et al., 2018a), not all of these parameters could be measured or evaluated based on field data. Soil data such as soil water content near saturation, field capacity and permanent wilting point could not be accurately reported for all soil layers (25-60 cm and 60-90 cm). As well as the crop rooting parameters (kl and xf in APSIM), the crop lower limits (crop lower limit in APSIM) and the values of the APSIM parameters Fbiom and Finert (Probert et al., 1998) were estimated according to the literature (Dalgliesh et al., 2016) and do not accurately reflect the actual conditions observed on the EFELE experiment, which may explain the poor fit of the simulation results concerning yields and the difference with EFELE experiment about soil organic carbon and soil nitrogen carbon. Indeed, these parameters influence the way in which the crop interacts with soil resources, especially with water resource. For the parameters Fbiom and Finert they are important because they are used in the calculation of the soil organic matter. Moreover, when comparing the simulations of sole crops with the simulations of crop rotations, it can be seen that the quality of representation is not improved; it remains similar or even decreases for wheat. The same phenomenon is observed for the analysis of the volumetric water content at 15–cm depth. For some years, the model slightly overestimated volumetric water content for Rotation 2 compared to Rotation 1 (Figure 6). These results should be related to the remarks made by Teixeira et al. (2015) who reported the importance to choose representative initialization values for soil water. Moreover Kollas et al. (2015) mentioned that the superiority of the adjustment of rotation simulations compared to single year simulations may be very small due to (i) insufficiently parameterized crops, which affect the performance of the following crop, and (ii) lack of water and/or nitrogen limiting growth in crop rotations. The same authors point out the limited capacity of the models to fully capture the positive effect of the introduction of an intermediate crop on the yield of the following main crops and explain that further research on carry over effects from the previous crop to the next crop is needed to improve the representation of crop rotations.

c. A dataset with insufficient observed data

First, the EFELE dataset is very interesting as it provides a lot of information necessary for APSIM to establish the characteristics (i) of each soil layer and (ii) of the climate. But a weakness is that it has not been created to test a model and therefore, the number of observation data is a bit low to be able to calculate relevant statistical parameters. Furthermore, some important variables are missing (e.g. nitrogen stress in plants, water stress, biomass monitoring). So, the small number of data compared for the variables monitored on EFELE makes it difficult to interpret the results and analyse the quality of the crop simulation by APSIM.

A comparison with variables measured several times on the plants themselves such as Leaf Area Index would have been more adequate. However, no such variable was evaluated on the EFELE experiment. This remark can be reiterated regarding the evaluation of the simulation quality of APSIM for soil organic carbon and soil organic nitrogen. Indeed, although the simulated and observed data for the date of March 16, 2016 diverge little, the comparison of these values provides only a first indication and does not allow a precise decision on the performance of APSIM in the representation of the dynamics of soil organic matter. Similarly, for the variables that are not monitored in the “TS/MO” trial of the EFELE experiment, even if the diversification effect thanks to cover crop is visible for some variables such as erosion or leaching, it is difficult to go beyond this simple observation as it is not possible to relate the values obtained to field references. These comparisons could have made it possible to verify whether there is a delayed effect of intermediate cropping on nitrate leaching on the EFELE experiment (Figure 8d), or whether it is rather a difference due to the precision of the model. Similarly for the comparison of different degrees of soil description, more measured data from EFELE for the monitored variables is needed to complete and improve the comparisons and why not extend to other variables that are not currently monitored to confirm whether a less stratified soil description may be sufficient to simulate processes involved in outputs such as phosphorus dynamics or soil emission of carbon dioxide and nitrous oxide.

d. Perspectives

First of all, it is necessary to complement the work done here with new simulations based on more and better described observed data, especially to accurately initialize soil conditions. In parallel, work with researchers and modellers would make it possible to optimize the simulation of the growth and development of certain crops already available on APSIM by creating and/or modifying cultivars. This approach would make it possible to determine whether APSIM in its current state is a truly effective tool for simulating the growth of crops in rotation and for representing variables that can be linked to ecosystem services, all in Brittany pedoclimatic context. Then, based on what has already been done, particularly with regard to assessing the impact of a crop management system on a system over long periods of time (Bahri et al., 2019; Kisaka et al., 2016), APSIM could also be used in the long-term representation and analysis of several crop diversification scenarios. However, it can be stated from this first work that APSIM is a tool capable of being taken in hand by a person who does not have a strong knowledge in modelling, with the possibility of appropriating the software fairly quickly and to make several modifications to the model in connection with the study of crop diversification and to observe the consequences. Subsequently, if the model calibration step proves to be conclusive and with the objective of designing a powerful tool within the framework of system design, APSIM could be improved in order to integrate new processes, such as the modelling of processes that condition the carry-over effects involved in the simulation of crop rotations or the modification

of the physical properties of the soil by the technical itinerary and biological activities that is represented in a summary manner in crop models including APSIM (Malézieux et al., 2009). In this approach, model coupling could be interesting and more appropriate than *de novo* modelling (Malezieux et al., 2009). Struc-C, a mechanistic model inspired by RothC-26, seeks to describe how the SOC influences the dynamics of soil structure and consequently its physical behaviour (Malamoud et al., 2009). Similarly, the introduction of weed competition and disease incidence into the crop model would make it possible to transcribe disease reduction through crop diversification (Appendix 2). However, thought must also be given to the need to include too many formalisms, at the risk of having to calibrate the model too much or not being able to inform it, or even not being able to explicitly describe the processes and thus reduce the power of the model (Stockmann et al., 2013)

7. Conclusion

In this work, I searched a crop model able to simulate a diversified agroecosystem in various pedoclimatic contexts and to represents several variables related to the provision of ecosystem services over time. For this, the conceptualization approach described by Lamanda et al. (2012) help us to identify, thanks to the construction of an “*ideal*” system, the essential elements that the crop model should have to meet the objective. Among the three crop models evaluated APSIM was the best suited to implement the ideal system. Then the ability of APSIM to simulate outputs related to ecosystem services for some crops in a particular pedoclimate context was evaluated. Even though APSIM showed weaknesses to predict crop yield, principally because of a lack of cultivar crop adapted to Brittany climate, it provide encouraging results for other variables (soil water content, soil organic carbon and soil organic nitrogen) even with low soil description and it showed his potential to study ecosystem services over time. Nevertheless, the lack of observed data and detailed information to complete all the initial soil description parameters prevent us to clearly validated the crop model. So an adaptation work with researchers and modellers combine with an information-gathering campaign about soil could optimize crop model's simulations and determine whether APSIM in its current state is a truly effective tool for simulating a diversification-based agroecosystems and for representing the evolution over time of variables that can be linked to ecosystem services in the Brittany region.

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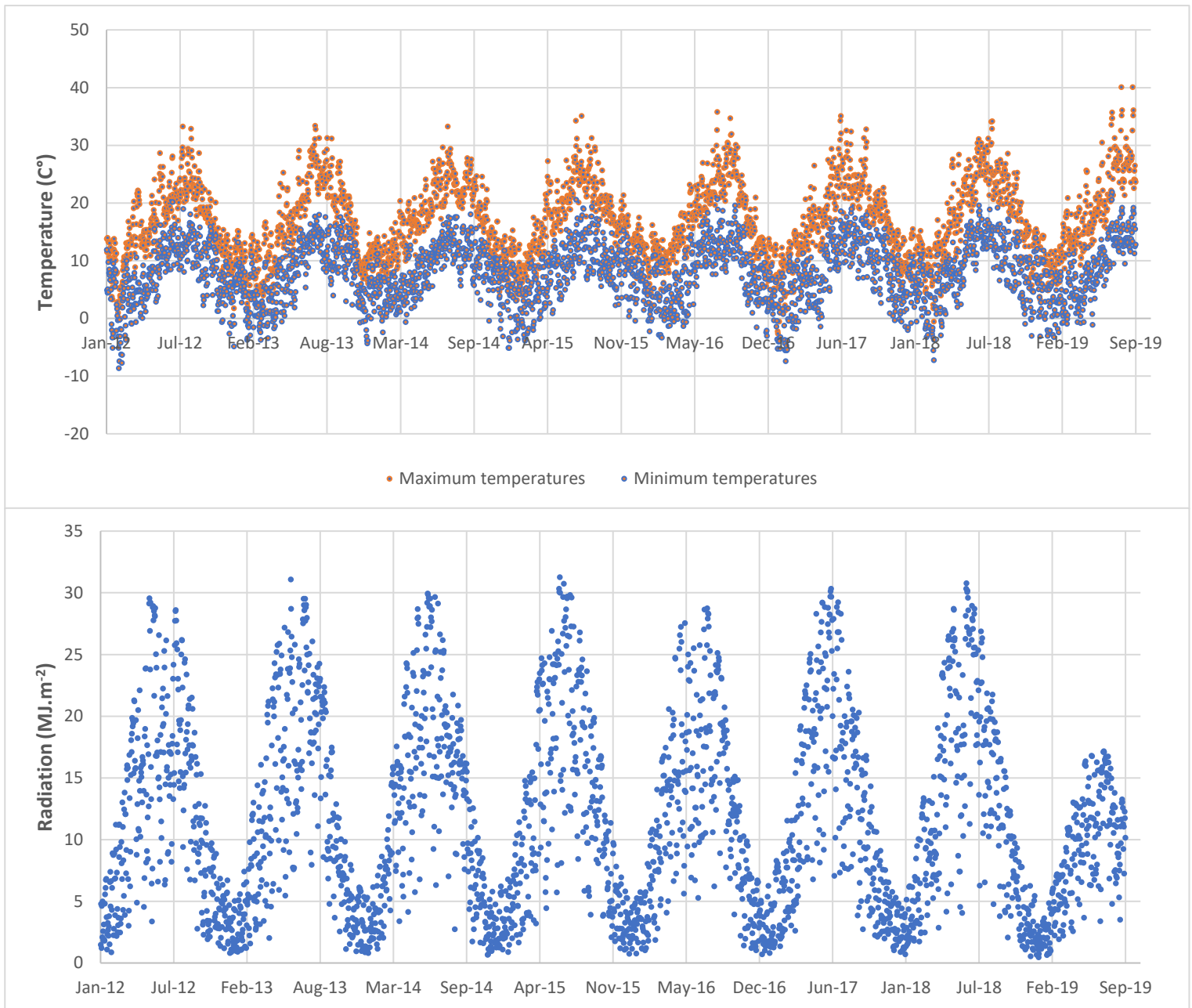
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Appendix 1



Daily maximum and minimum temperatures and solar radiation at EFELE experiment between January 2012 to August 2019

Appendix 2

Elements necessary to the conceptual modelling of an agro-ecosystem based on diversification, according to the decision tree (Figure 1). The numbers refer to the dynamic analysis scheme of the conceptual system (Appendix 2).

ES	Subject	Time and place of the study	Cropping system	Soil type	Figures	Reference	N°.
Production	Enhancing yield stability with crop diversity	Meta-analysis about 37 articles around the world	Intercropping	-	Cereal-grain legume intercropping (CV%=22.1) significantly increased yield stability compared with the respective legume sole crops (CV%= 31.7) (n=54). Higher yield stability in cereal-grain legume intercropping (CV%=16%) compared with sole cropping of cereals (CV%=27%) (n=15).	Raseduzzaman, Md., et Erik Steen Jensen. 2017	[1]
	Rising yield thanks to crop diversity	2 years China	Intercropping (tobacco/maize ; potatoe/maize ; sugarcane/maize ; wheat/broad bean)	-	During the first growing year, LER between 1.31 and 1.84 following the intercropping combination and between 1.33 and 1.83 for the second growing year.	Li, Chengyun et al. 2009	[2]
	Impact of tillage and diversification on productivity	7 years India	Rotation (maize-wheat-mungbean ; maize-chickpea-Sesbania ; maize-mustard-mungbean ; maize-maize-Sesbania) and three tillage practices (Zero Tillage, Permanent Bed, Conventional Tillage)	Sandy loam	Significant interaction effect on stover yield between tillage practices and crop rotations : PB-MWMb and ZT-MCS plots registered 55.8-59.6% higher stover yield compared to CT-MMS. Maximum N, P and K content (0.563, 0.226 and 1.198%, respectively) in maize stover were recorded with ZT.	Yadav, M. R. et al. 2017	[3]
		24 years USA	Two tillage treatments (No-Till and Plow-Till) assessed with 24 or 12 years corn monoculture with or without interseeded cover crops	Clay loam, Loamy sand, Silt loam	Total yield was significantly higher (3.2%) in NT compared to PT on loamy sand. Total yield was significantly higher (9.5%) for NT than PT on silt loam. Corn yields under NT-CC was 13.4% higher, than those under PT-NC.	Nunes MR, et al. 2018	[4]
		12 years USA	2 years (corn-soybean) and 4 years rotations (corn-field peas-winter wheat-soybean) with no-till	Sandy clay loam	The yield of Soybean yields was 22% higher in in the 4 years rotation than soybean within the 2 years rotation.	Lehman RM, et al. 2017	[5]
		2 years France	Intercropping (pea/cereal)	-	Reduction of disease score on pods by 19–50% in the intercrop when ascochyta blight was moderate to severe. Reductions of disease severity by 32% and 49% were observed in the moderate and severe epidemics about stems.	Schoeny, Alexandra et al. 2010	[6]
	Crop diversity influences pest control	10 years USA	Crop rotation + Cover crop (winter rye)	Sandy loam	Canola and rapeseed rotations consistently reduced the severity of Rhizoctonia canker, black scurf, and common scab (18 to 38% reduction), and canola rotations resulted in higher tuber yields than continuous potato or barley/clover (6.8 to 8.2% higher). The combined effect of a canola or rapeseed rotation and winter rye cover crop reduced disease severity by 35 to 41% for black scurf and 20 to 33% for common scab relative to continuous potato with no cover crop.	Larkin, Robert P., et al. 2010.	[7]
		2 years China	Intercropping (tobacco/maize ; potatoe/maize ; sugarcane/maize ; wheat/broad bean)	-	Northern maize leaf blight in intercropped plots was decreased by 17.0 until 55.9% following the year.	Li, Chengyun et al. 2009	[8]
		2 years China	Cultivar mixtures in rice	-	Disease-susceptible rice varieties planted in mixtures with resistant varieties had 89% greater yield and blast was 94% less severe than when they were grown in monoculture.	Zhu, Y. et al. 2000	[9]
	Effect of crop rotation and intercropping on weeds	6 years Iran	Continuous winter wheat, maize-winter wheat, sugar beet-winter wheat and different cropping systems (high-input, medium-input, low-input, integrated and organic systems)	Silt loam	Weed seed density in continuous winter wheat of approximately 6300 seeds/m2 was higher than other rotations with about 5000 seeds/m2. Weed seed densities in organic and integrated cropping systems, (about 5000–6000 seeds/m2) were higher than conventional and high-input cropping systems (about 2000 seeds/m2).	Koocheki Alireza et al. 2009	[10]
		Meta-analysis about 34 articles around the world	Legume companion plant	-	Lower weed biomass and a higher yield than non-weeded or weeded control treatments, in 52% and 36%, respectively. Greatest benefits for maize, with yields 37% higher than those for non-weeded control treatments.	Verret V, et al. 2017	[11]

Greenhouse gases regulation	Effect of intercropping and fertilization on N ₂ O emissions	1 year China	Intercropping (maize/soybean)	Silt loam	The cumulative N ₂ O emission from the monocultured maize treatment was 16.9 kg ha ⁻¹ over the entire growing season, which was significantly higher of the two intercropped treatments by 36.6% and 32.2%. Short-term N ₂ O emissions after the two nitrogen applications accounted for 74.4%–83.3% of the total emissions.	Huang, Jianxiang, et al. 2019	[12]
	Impact of long-term application of organic manure and mineral fertilizer	17 years China	Rotation (maize-wheat) and different fertilization treatments with fertilizer and manure	Ferralic Cambisol	With manure more annual N ₂ O (3.01±0.11 kg N ₂ O-N ha ⁻¹) and CO ₂ (28 663±1147 kg C ha ⁻¹) emissions in comparison with inorganic fertilizer (NPK : 1.29±0.061 kg N ₂ O-N ha ⁻¹ and 16125±209 kg C ha ⁻¹) and with no fertilizer treatment (0.58±0.029 kg N ₂ O-N ha ⁻¹ and 10 565±288 kg C ha ⁻¹).	Zhai, Li-mei et al. 2011	[13]
Erosion control	Reduction of GHG emissions with intercropping	2 years Argentina	Intercropping (maize-soybean)	Medium loam	Lower emission with intercrop systems : CO ₂ emission rates were (354±14) and (357±13) µg C m ⁻² h ⁻¹ in the soybean and maize sole crops respectively, whereas that in the 2 intercrop systems was (284±10) and (290±17) µg C m ⁻² h ⁻¹ . N ₂ O emission rates were (13.5±0.8) and (14.0±0.7) µg N m ⁻² h ⁻¹ in the soybean and maize sole crops, respectively, whereas that in the intercrops was (11.5±0.8) and (12.0±0.8) µg N m ⁻² h ⁻¹ .	Dyer, Lisa, et al. 2012.	[14]
	Tillage impacts the CO ₂ emissions from soil	12 years USA	2 years (com-soybean) and 4 years rotations (com-field peas-winter wheat-soybean) with no-till	Sandy clay loam	Average daily N ₂ O fluxes were 24% lower for the 4 years rotation (2.34 ± 0.56 g N ₂ O-N ha ⁻¹ d ⁻¹) compared with the 2 years rotation (3.06 ± 0.59 g N ₂ O-N ha ⁻¹ d ⁻¹)	Lehman RM, et al. 2017	[15]
Erosion control	Effect of cover crop on runoff and erosion in a maize cropping system	4 years Lithuania	Maize	Silt loam	Total CO ₂ emissions from soil in DP, SP, DC, SC and NT technologies were respectively 6.05, 4.25, 4.97, 4.42, 3.94 µmol m ⁻² s ⁻¹ before autumn soil tillage and 29.88, 22.50, 16.73, 13.72, 10.00 µmol m ⁻² s ⁻¹ after autumn tillage.	Buragiėnė, Sidona et al. 2019	[16]
	Stabilization of aggregates by MO	3 years Belgium	Winter cover crop of rye and Italian ryegrass	Sandy loam & Silt loam	Reduction of runoff and erosion by more than 94% thanks to cover crops compared with untilled post-maize harvest plots. During two seasons, plots that had been covered during the previous intercropping period lost 40 to 90% less soil compared with maize plots that had been left bare between October to April.	Laloy, Eric, et C. L. Bielders. 2010	[17]
Impact of the association on bulk density	Intercropping red clover with silage corn provide soil erosion control	10 years France	Maize, wheat, tomatoc, legumes	Silt loam Silty clay loam	MWD = 0.35 -0.03x (sequestered SOC) -0.009x (C input). R ² =0.77	Kong et al. 2005	[18]
	Impact of tillage on the bulk density of the horizon 5-10 cm	6 years Canada	Intercropping (silage maize/red clover)	Orthic Grey Brown Luvisol	Runoff reduction with the maize-clover system ranged from 45 to 87%. Reduction of soil loss from the maize-clover system as compared to the corn system ranged from 46 to 78%.	Wall, G. J., et al. 1991	[19]
Impact of the association on bulk density	Impact of tillage on the bulk density of the horizon 5-10 cm	11 years Canada	Zero or conventional tillage	Aquic Hapludalfs, Psammentic Hapludalfs, Typic Hapludalfs	$\rho = 1.573 - 0.0640T - 0.367P - 0.06886TxP - 0.0725SOM - 0.0311Cl - 0.0012SOMxCl$ T: tillage or not; P: rank or inter-rank; SOM: soil organic matter (%); Cl: clay (%).	Kay et VandenBygaert 2002.	[20]
	Impact of the association on bulk density	3 years Canada	Intercropping (maize/legumes)	clay Silty clay	Reduced bulk density compared to maize monoculture. Da of 1.28 for monoculture maize versus 1.20 for association monoculture. Reduced bulk density compared to maize monoculture. Da of 1.36 for maize monoculture versus 1.28 for association monoculture.	Latif et al. 1992	[21]

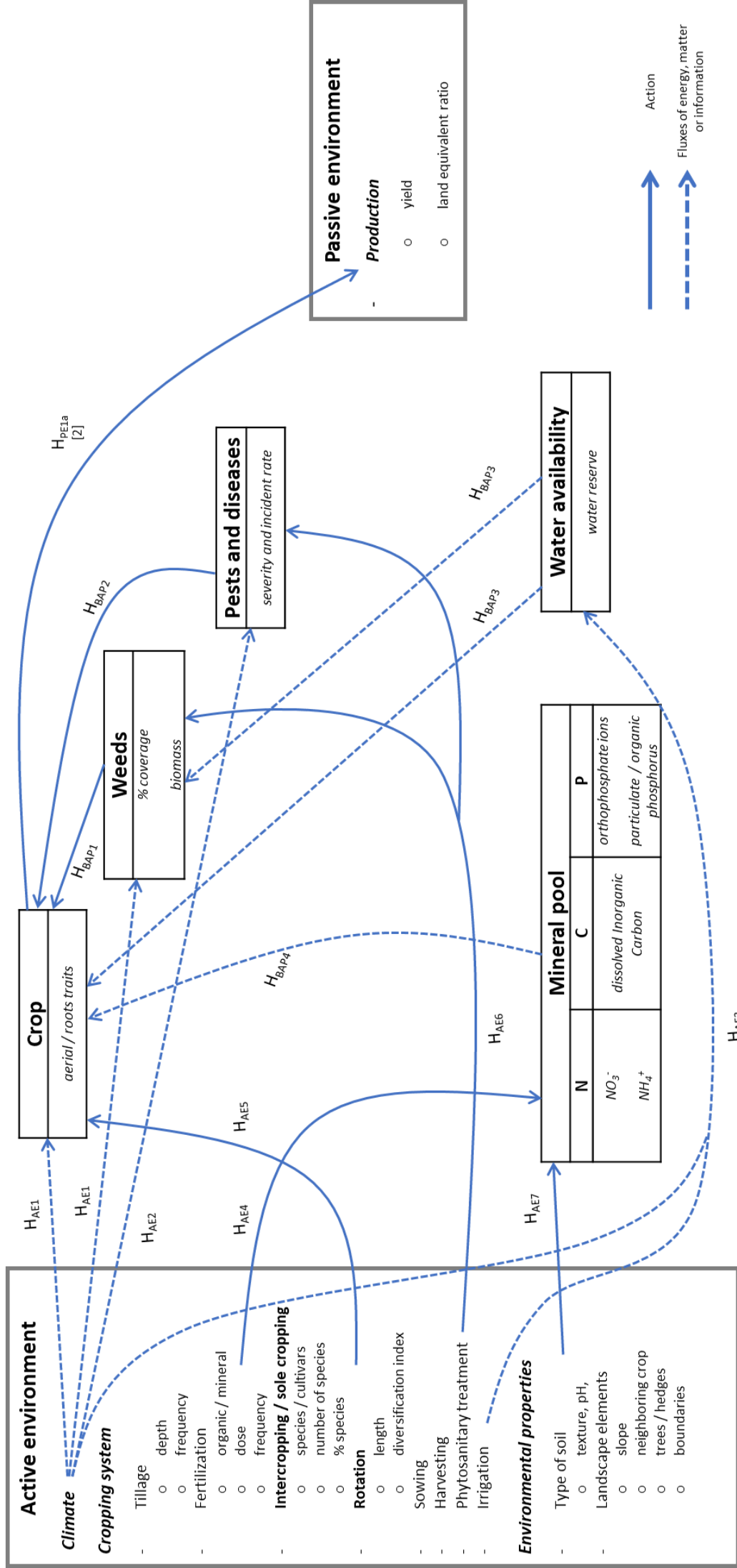
	Increasing the stability of the aggregates by roots	< 1 year New Zealand	Barley, wheat, white clover, lupin, Italian ray grass, prairie grass	Silty loam	Legumes have a greater impact than non-legumes thanks to their more N-rich exudates that promote the growth of fungi. Increased MWD by 50% for barley and wheat compared to the cropland control (0.42mm - 0.6mm). 100% increase for lupin compared to no-culture control (0.42mm - 0.82mm).	Haynes et Beare 1997	[22]
	Tillage management impacts the soil loss	7 years Croatia	Conventional tillage, no-tillage and deep tillage treatments	clay loam Stagnosols	Average annual soil loss under NT (0.53 t ha ⁻¹ year ⁻¹) and DT (3.11 t ha ⁻¹ year ⁻¹) were significantly lower than that under CT (13.11 t ha ⁻¹ year ⁻¹).	Bogunovic et al. 2018	[23]
Water quality	Simulation impacts of catch crops on N leaching	13-17 years France	Catch crops (white mustard ; italian ryegrass radish or winter cereal)	Haplic luvisol, Dystric cambisol, Rendzina	Catch crops decrease N leaching from 36 to 62% following the condition and remained efficient on the long term.	Constantin, J. et al. 2010.	[24]
	Intercropping maize-red fescue to reduce nitrogen leaching	3 years Denmark	Intercropping (maize/red fescue)	Sandy loam Coarse loam	Intercropped maize had 15–37 % lower N leaching than monocrop maize.	Manevski, Kiril, et al. 2015	[25]
	Intercropping to reduce N leaching in fields with N fertilizer over-dose	2 years China	Intercropping (maize/soybean ; maize/groundnut ; maize/ryegrass ; maize/alfalfa) and total amounts of N fertilization of 375 kg pure N ha ⁻¹	Calcareous alluvial soil	Compared to the sole maize treatment, nitrate leaching losses during the maize growing period were reduced by 20.9-174.8 (maize-groundnut), 35.2-130.8 (maize-ryegrass), 60.4-122.0 (maize- alfalfa), and 30.6-82.4 kg ha ⁻¹ (maize-soybean) following the year.	Nie, Sheng-wei et al. 2012	[26]
	Influence of cropping system about N leaching	Meta-analysis about 44 articles	Water and fertilizer management and use of cover crops	-	Adjusting water application to crop needs reduced nitrate leaching by 80%. Improved fertilizer management reduced nitrate leaching by a mean of 40%. Replacing a fallow with a non-legume cover crop reduced nitrate leaching by 50%.	Quemada, M. et al. 2013.	[27]
Water supply	Strip-intercropping enhanced temporal soil water distribution	3 years China	Strip intercropping (maize/pea)	Aridisol	During the co-growth period, the accumulated ΔSWS value in the M/P system was averaged 28 mm, significantly greater than ΔSWS value of 5.6 mm in the PM/P system. After pea harvest, the M/P system had a narrow range of ΔSWS value, whereas the PMP system had significantly greater negative ΔSWS value averaging -33.1 mm.	Chen, Guodong et al. 2018.	[28]
	Tillage influences soil water content	5-11 years Argentina	Conventional tillage and conservation tillage	Silty loam Sandy loam	Soil water contents at the end of fallow after different crops were 11 to 15% greater with conservation tillage than with conventional tillage.	Buschazzo et al. 1998	[29]
	Crop rotation and tillage effects on soil water	6 years USA	Crop rotation (continuous cotton ; cotton-wheat-fallow rotation), two tillage treatments (conventional ; no-till)	Olton Loam soil	Under irrigated condition, regarding average seasonal water content the rotation treatment shows an increasing of 13% and 7.7%, for no till and conventional tillage respectively, compared to continuous cotton with conventional tillage. Same observations for dryland condition.	Bordovsky et al. 1994	[30]
Carbon storage	C immobilisation	1 years France	intercropping (chicpea/durum wheat ; durum wheat/lentil)	Calcareous cambisol	MBC and MBP of the rhizosphere x2 compared to sole crops and bulk soil.	Tang et al. 2014	[31]
	Rising SOM mineralisation	7 years China	Intercropping (maize/wheat ; wheat/faba bean)	Sandy loam	Soil organic C decomposed (%) was 1.7 time in soil samples from maize/wheat and maize/faba bean intercrop plots than from maize plots after 112 days of incubation.	Cong, Wen-Feng et al. 2015a	[32]
	increasing SOC in first 20 cm in crop diversification condition	7 years China	Intercropping (maize/faba bean ; wheat/faba bean)	Sandy soil	Intercrop systems showed increases in soil organic carbon by 9.5%, compared to initial state. SOC content was 4% greater in intercrops than in sole crops. Difference of about 184 kgC/ha/year.	Cong, Wen-Feng et al. 2015b	[33]

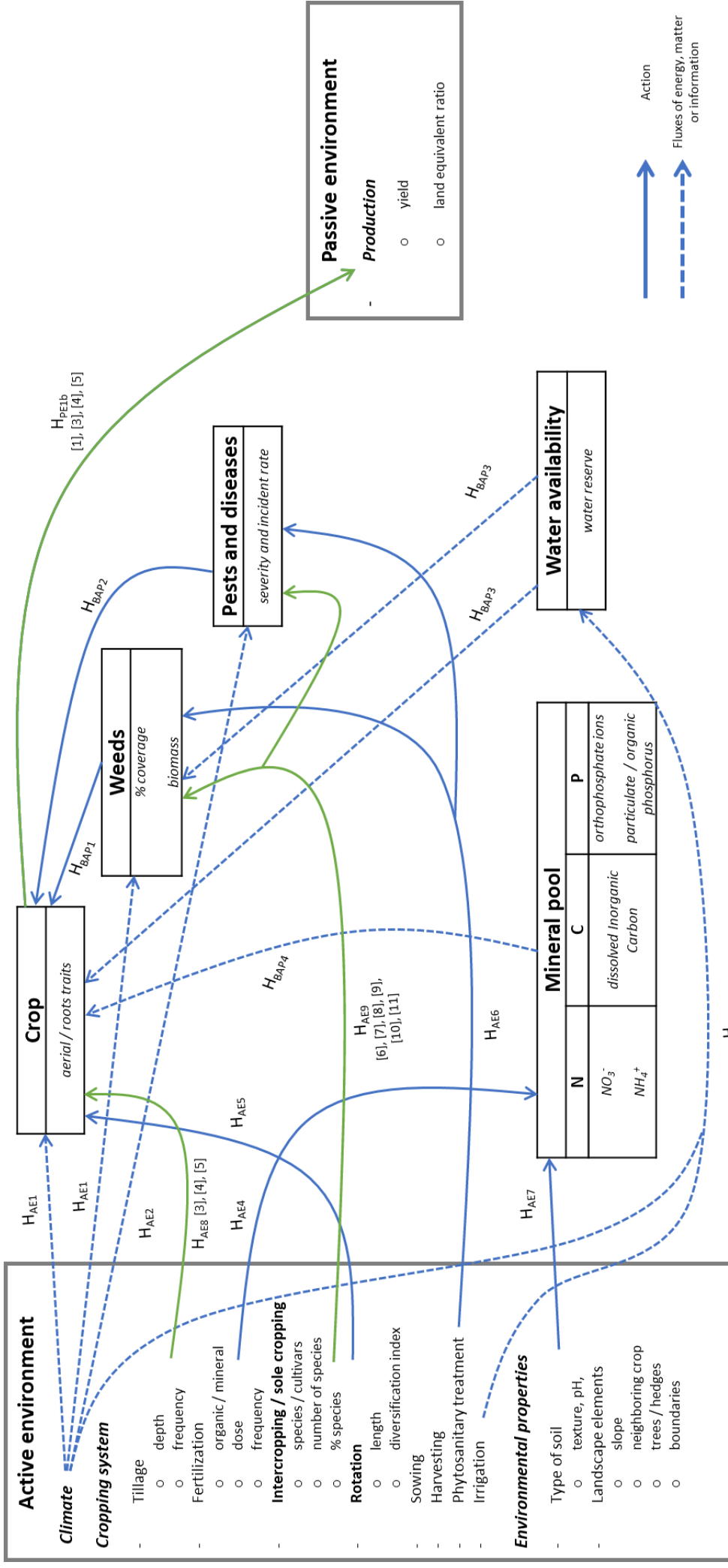
Long term effect of tillage in maize rotations on SOC for the soil depths 0–15 and 15–30 cm	7 years India	Maize-based crop rotations and three tillage practices (Zero Tillage, Permanent Bed, Conventional Tillage)	Sandy loam	SOC content in PB and ZT plots were higher (23.6 to 35.3%) than the CT. Maximum SOC contents was recorded in maize-chickpea-sesbania sequence, which were 18.9 and 20.4% higher compared to maize-mustard-mungbean and maize-maize-sesbania crop rotations, respectively. The highest SOC content was found in ZT/PB-maize-wheat-mungbean treatment (6.88/7.19 g.kg ⁻¹ of soil) and ZT/PB-maize-chickpea-sesbania treatment (7.15/7.15 g.kg ⁻¹ of soil).	Parthar et al. 2016 [34]
Additional C storage per practices	France	Arable farms	-	Extension of cover crop : + 2.019 MtC/year ; Agroforestry : + 1.102 MtC/year ; No till : + 0.677 MtC/year ; insertion and elongation of grassland : + 0.756 MtC/year. Storage potential mainly in arable farms with 86% of total potential.	Sylvain Pellerin et al. 2019 [35]
Composition root residues.	Germany	Pea Oats	Clayey silt	4.1% of total C 7.9% of total C	Wichern 2007 [36]
Composition aerial residues.	Germany	Pea Oats	Clayey silt	40% of total C 35.3% of total C	Wichern 2007 [37]
Rhizodeposition	Germany	Pea Oats	Clayey silt	29.6% of total C 30.8% of total C	Wichern 2007 Wichern 2007 [38]
Nitrogen and phosphorus regulation	7 years China	Intercropping (wheat-maize ; wheat-faba bean ; maize-faba bean)	Sandy loam	Soil organic N content in the top 20 cm was 11% greater in intercrops than in sole crops. Difference of about 45 kgN/ha/year.	Cong, Wen-Feng et al. 2015 [39]
Increased absorption of P.	3 years	Maize intercropping with oilseed, turnip, faba bean, chickpea and soybean	Aridisol	Average shoot P contents of maize/turnip, maize/faba bean, maize/chickpea and maize/soybean intercropping increased by 44.6%, 30.7%, 39.1%, and 28.6%, respectively, compared with the weighted means of the corresponding monocultures, and were highest at 40 kg P ha ⁻¹ .	Xia H-Y, et al (2013) [40]
N facilitation is influenced by crop combinations and patterns of strip intercropping.	10-11 years China	Intercropping, either continuous or rotational	Sandy loam	20% increase compared to pure crops. Absorption of 32-44 kg P/ha/year so be it 3.4-7.1 kg P/ha/year more than monocultures.	Z. Wang et al. 2015 [41]
Improving soil phosphorus availability by intercropping.	5 years China	Intercropping and rotational intercropping	Orthic Anthrosol	N uptake by maize increased at two years under continuous (278-265 kg/ha) or rotational (235-267 kg/ha) intercropping with faba bean compared to monocropping (162-203 kg/ha).	Li, Chun-Jie et al. 2011 [42]
Intercropping increases the rhizosphere P availability in a low P soil.	1 year Algeria	Intercropping (maize/cowpea)	Ferralsol	For cowpea compared with fallow, the increase in P Olsen in the rhizosphere was higher in the intercropping (62 % higher) than in sole cropping (23 % higher). For maize compared with fallow, the increase in Olsen P in the rhizosphere was also higher in intercropping (24 % higher) than in sole cropping (8 % higher).	Latati, M. et al. 2014 [43]
Intercropping increases the rhizosphere P availability in a low P soil.	40 years France	Intercropping (wheat/chickpea)	Luvisol	Phosphorus availability was increased in the rhizosphere of both species, especially when intercropped in a low P soil. Durum wheat increased its rhizosphere Olsen-P concentration by +60% when grown as sole crop, and by +90% when intercropped. For chickpea this increase amounted to +96% and +186%, respectively.	Betencourt, Elodie et al. 2012 [44]

Changing soil P stock without P fertilization.	4 years	Intercropping (maize/faba bean)	Orthic Antrosol	20.2% decrease from initial status: 20.3 mg P/kg → 16.2 mg P/kg. 32.5% decrease compared to monoculture. 30.1% decrease from initial status: 20.3 mg P/kg → 14.2 mg P/kg. 46.8% decrease compared to monoculture.	Z. Wang et al. 2014 [45]
N2 fixation in intercrops	2-3 years Denmark	Intercropping (pea/bartley)	Sandy loam	Higher proportion of N in legumes is derived from atmospheric N2 fixation in intercrops than in monocrops, 62–82% on average in sandy soil.	Jensen, Erik Steen. 1996 [46]
Long term pH-modification by intercropping	China 9 years	Intercropping (maize/faba bean ; maize/wheat)	Sandy loam	Soil pH in maize/wheat and maize/faba bean intercropping was significantly reduced by 3.2 % and 1.9 %, respectively.	Wang et al. 2014 [47]

Appendix 3

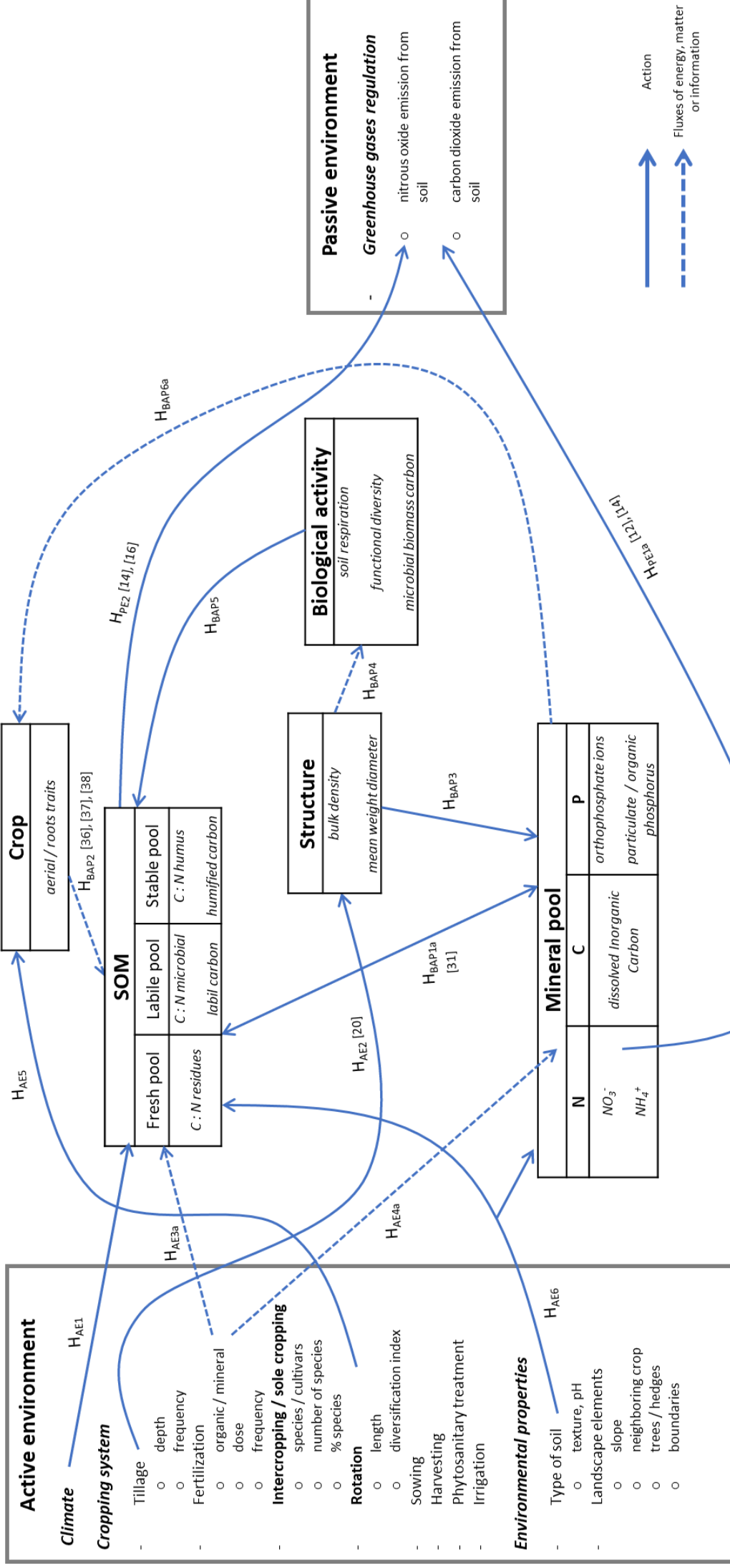
Dynamic schemes of the conceptual system. The numbers [x] are referenced in the table Appendix 2.

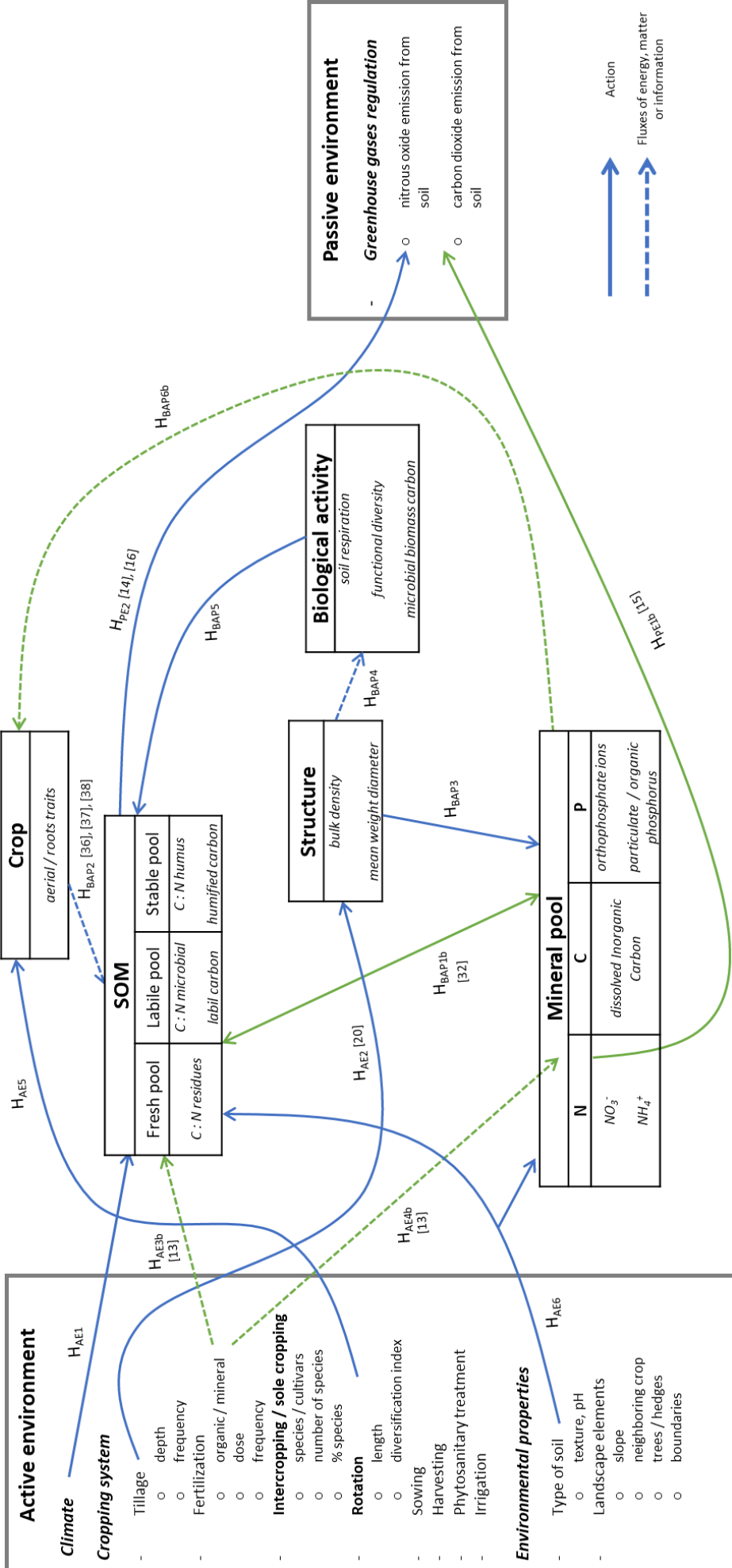




Dynamic analysis of conceptual model of an agro-ecosystem regarding the effect of crop diversification on production. The scheme shows the main hypotheses and the state variables (in *italics*) linking the elements of the system. In green are represented the processes which appears over the time :

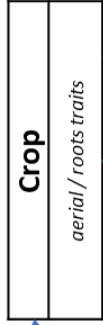
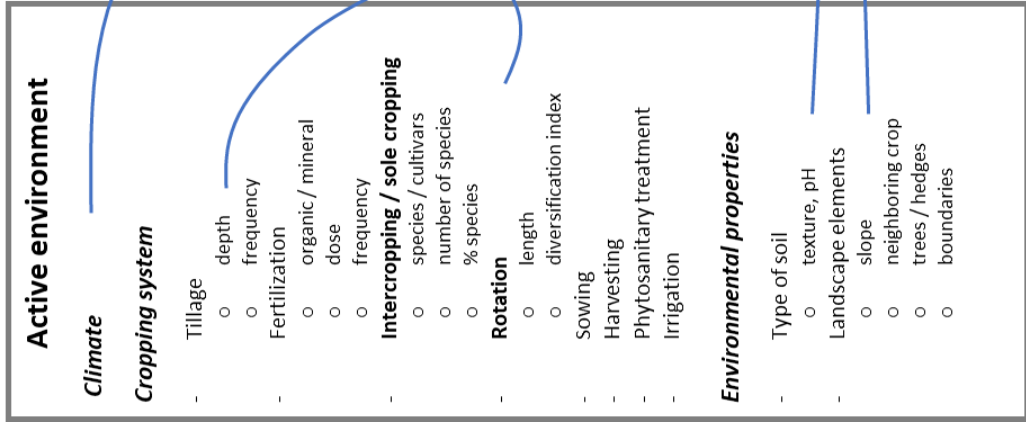
- H_{AE1} : Quantity of light and temperature shared between the crop and weeds and which influences the growth and development of plants.
- H_{AE2} : The light and temperature affects the intensity of attacks by pests and diseases.
- H_{AE3} : The amount of water from rainfall and irrigation, which fill the water reserve.
- H_{AE4} : A given quantity of inorganic fertiliser spread on field and supply the mineral pool.
- H_{AE5} : The choices related to diversification strategies (crops rotation/continuous crop, intercropping/sole cropping, etc.) which influence the structure of crop in time and space and his relations with the other BAPs.
- H_{AE6} : The phytosanitary treatments controls the population of weeds, pests and the diseases which may reduce the crop yield.
- H_{AE7} : The soil characteristics (temperature, pH, moisture, texture, etc) influence the physico-chemical reactions in soil and so the elements of mineral pool.
- H_{AE8} : The intensity of tillage management affects the crop and may reduce the quantity of the product harvested.
- H_{AE9} : The diversification strategies affects also the population of weeds, pests and the threat of diseases.
- H_{AE10} : The weeds competition with the crop for the nutrients affects the production.
- H_{AE11} : The damages causes by pests and diseases reduce the crop yield.
- H_{AE12} : The amount of water uptakes by crop and weeds from water reserve.
- H_{AE13} : The absorption of NH₄⁺, NO₃⁻, HPO₄²⁻, H₂PO₄⁻ by crop from mineral pool.
- H_{PE1a} : Crop diversity enhance the yield compared to sole crop.
- H_{PE1b} : Improvement of the productivity and the stability of yield over years in response to crop diversification and tillage management.



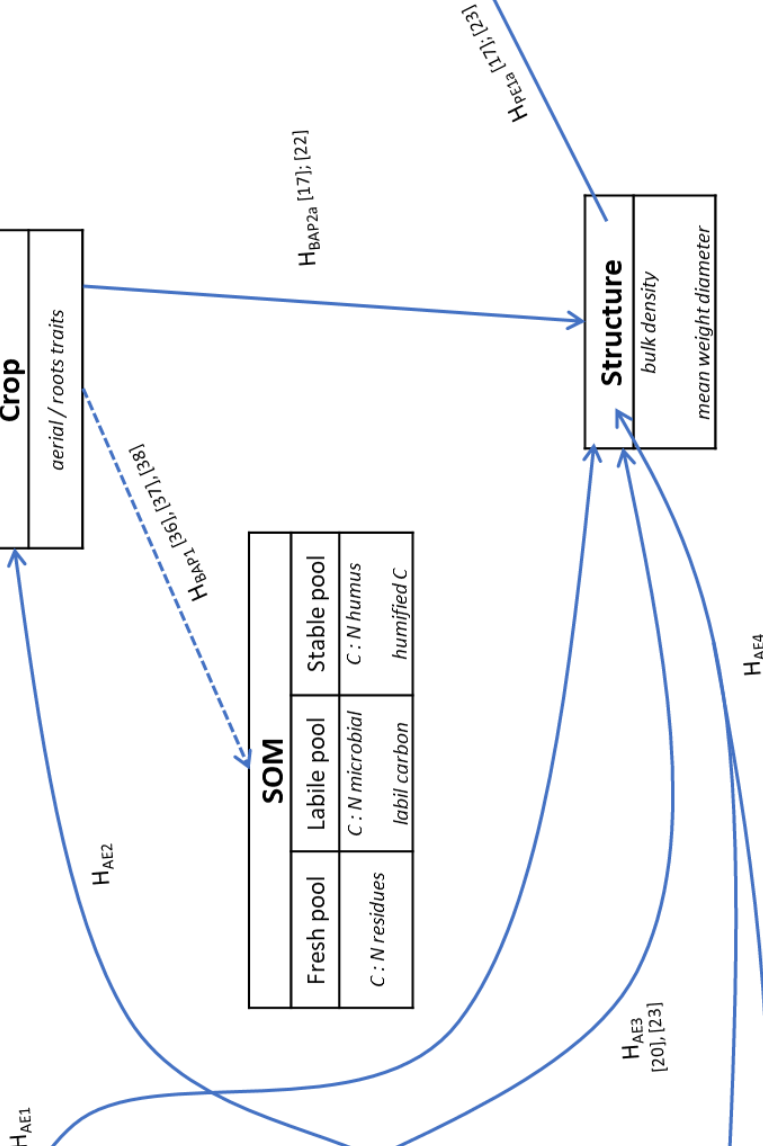


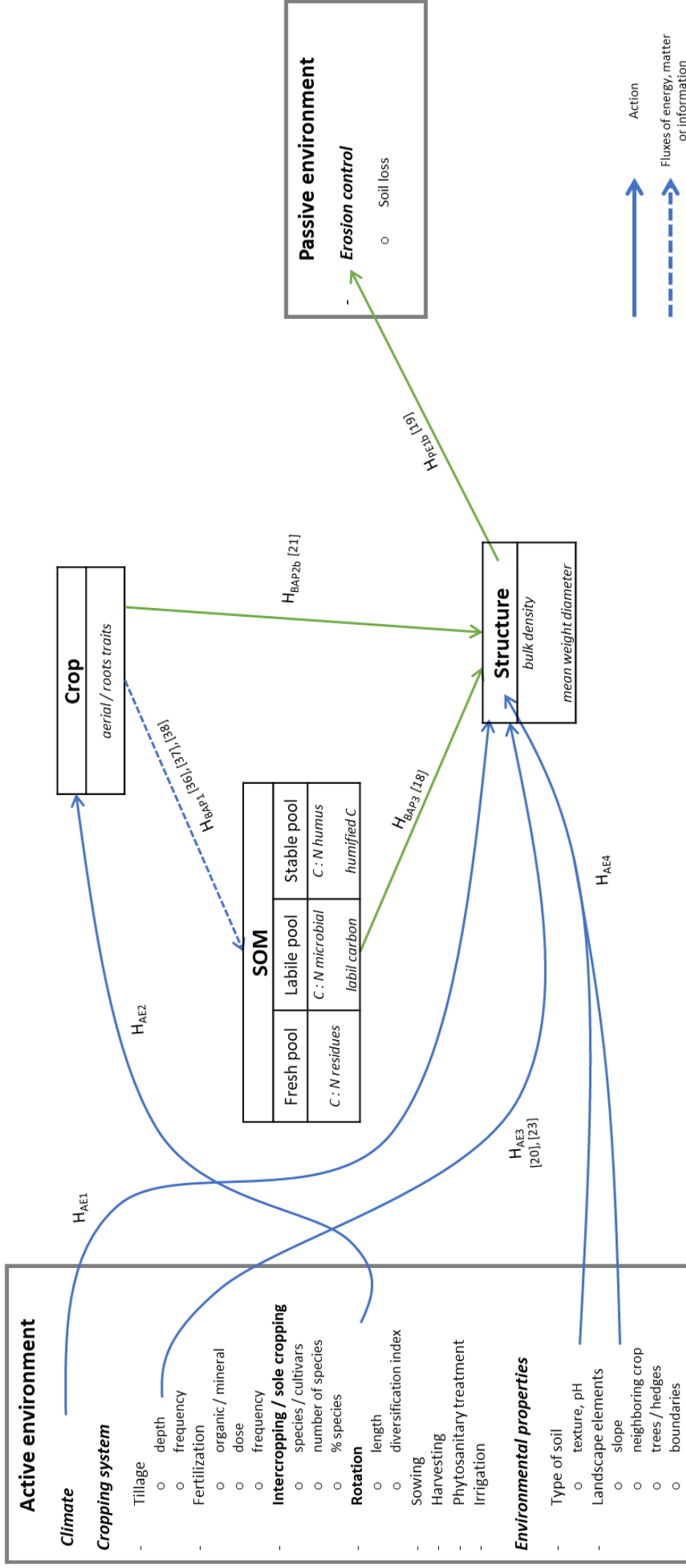
Dynamic analysis of conceptual model of an agro-ecosystem regarding the effect of crop diversification on Greenhouse gases regulationemissions. The scheme shows the main hypotheses and the state variables (in italics) linking the elements of the system. In green are represented the processes which appears over the time :

- H_{AE1} : Conditions of moisture and temperature which affect the rate mineralisation of SOM.
- H_{AE2} : The intensity of tillage changes the structure of soil.
- H_{AE3} : A given quantity of manure which reach and enriches the SOM.
- H_{AE4} : A given quantity of inorganic fertiliser spread on field and supply the mineral pool.
- H_{AE5} : The manure incorporated in SOM has an impact on GHG over the long term
- H_{AE5b} : Inorganic fertilizers which are incorporate in the mineral pool affect long term GHG emissions.
- H_{AE6} : The choices related to diversification strategies (crops rotation /continuous crop, intercropping/sole cropping, etc.) which influence the structure of crop in time and space and his relations with the other BAPs.
- H_{AE6a} : The soil characteristics (temperature, pH, moisture, texture, etc) influence the physico-chemical reactions in mineral pool and in SOM.
- H_{BAP1} : Mineralisation and immobilisation process between SOM and mineral pool. Crop association influences the rate of immobilisation.
- H_{BAP1b} : Crop association increases the SOM mineralisation.
- H_{BAP2} : Crop residues and rhizodeposition enrich the SOM.
- H_{BAP3} : The WFPS impacts the soil mineral N.
- H_{BAP4} : The oxygen diffusion affects the activity of microorganisms.
- H_{BAP5} : The soil micro-organisms influence the transformation of SOM
- H_{BAP6a} : The absorption of NH_4^+ and NO_3^- by crop decrease the concentration of this elements in mineral pool.
- H_{BAP6b} : N facilitation influenced by crop association.
- H_{PE1a} : Crop diversity participates to reduce infra-annual N_2O emissions.
- H_{PE1b} : The length of rotation impacts the N_2O emissions.
- H_{PE2} : Crop diversity and tillage participates to reduce infra-annual CO_2 emissions.



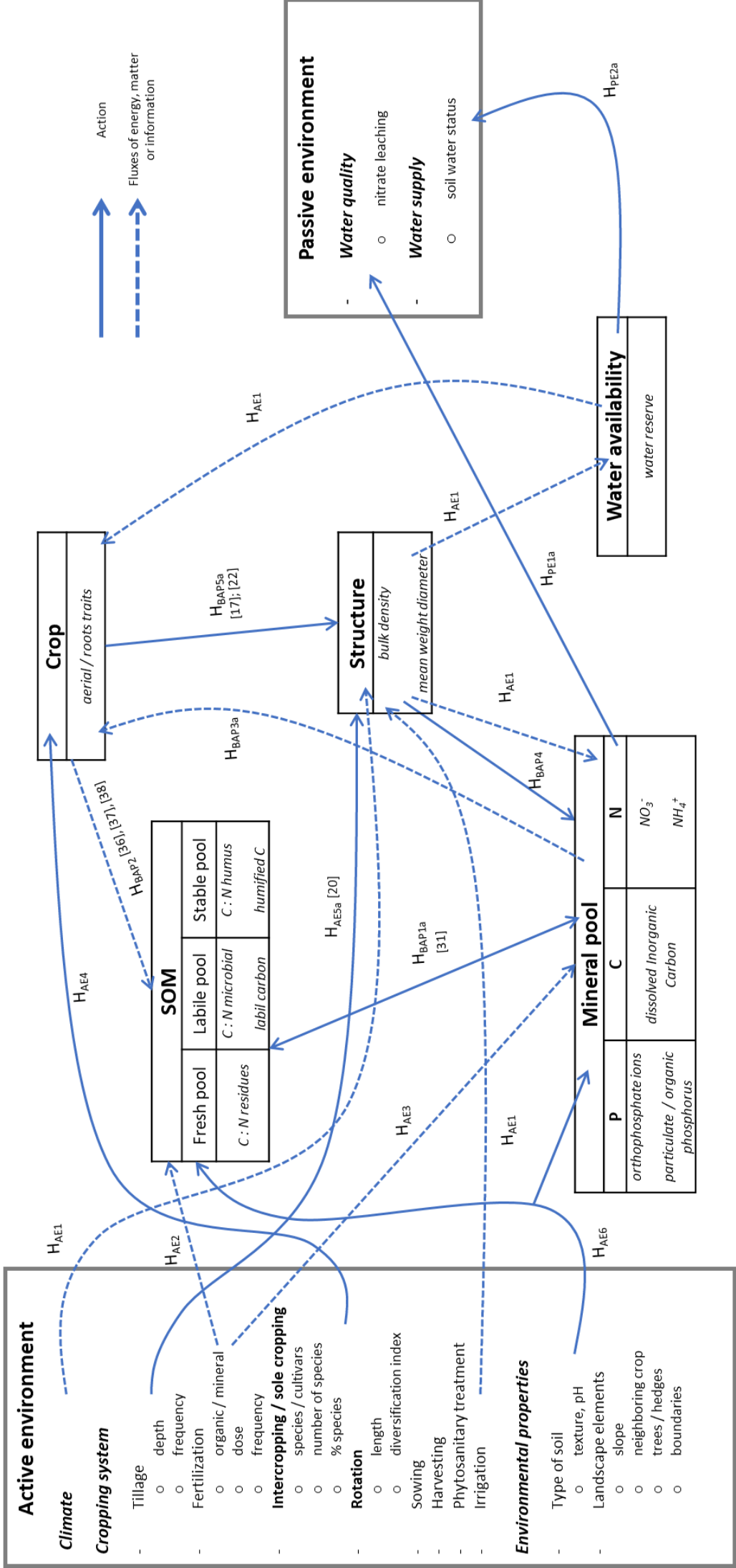
SOM		
Fresh pool	Labile pool	Stable pool
<i>C : N residues</i>	<i>C : N microbial labile carbon</i>	<i>C : N humus humified C</i>

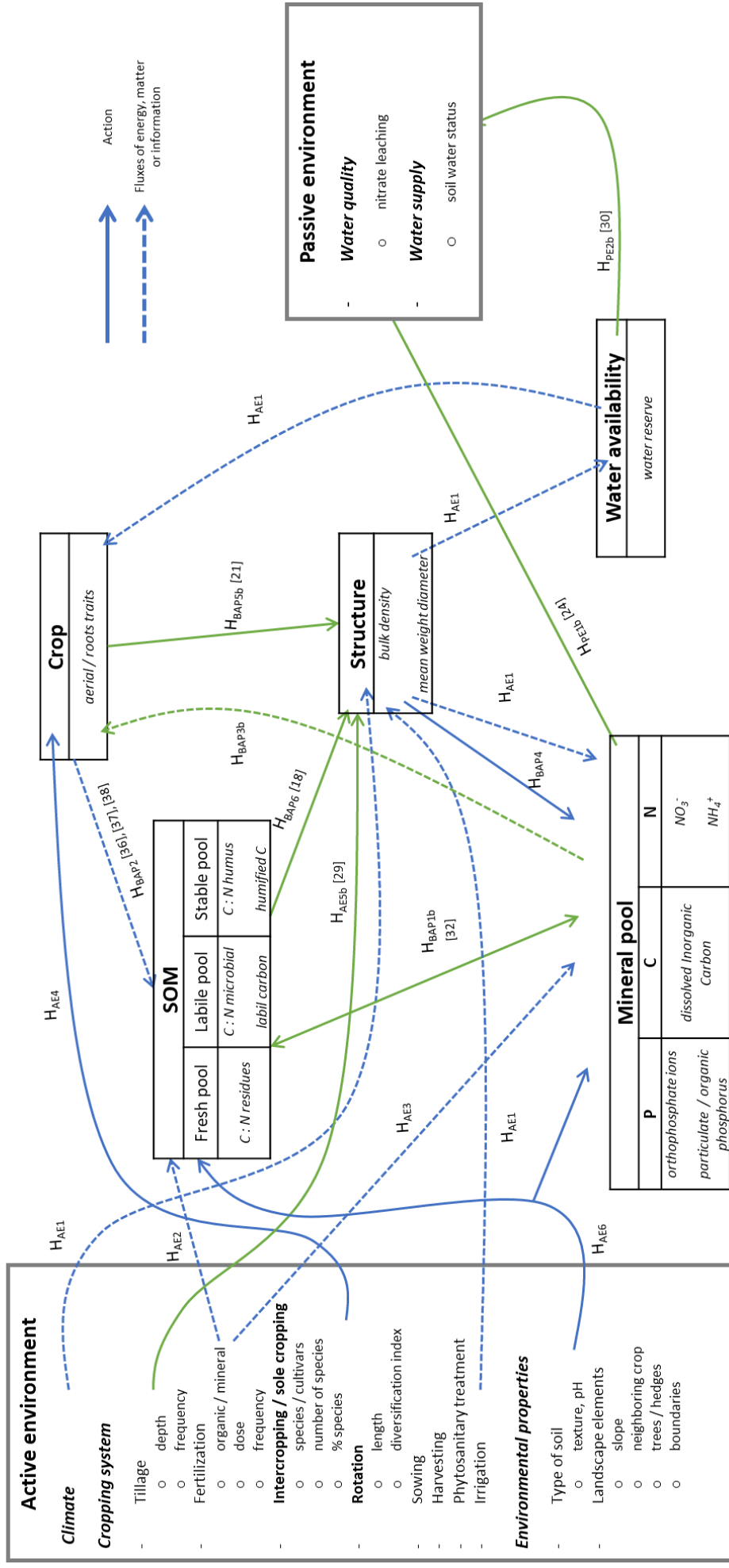




Dynamic analysis of conceptual model of an agro-ecosystem regarding the effect of crop diversification on Erosion control. The scheme shows the main hypotheses and the state variables (in *italics*) linking the elements of the system. In green are represented the processes which appears over the time :

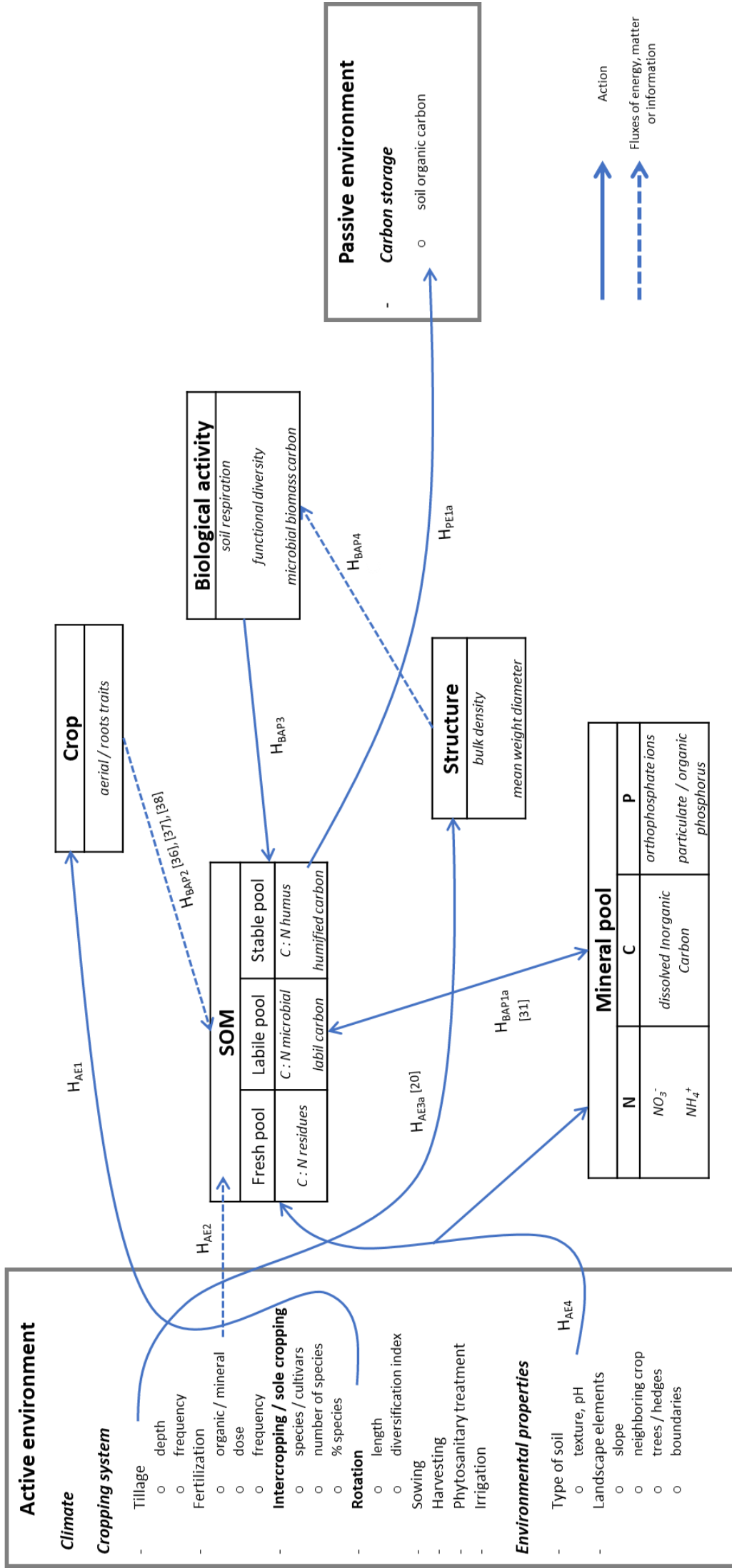
- H_{AE1} : The rainfall intensities impacts the soil surface structure.
- H_{AE2a} : The choices related to diversification strategies (crops rotation /continuous crop, intercropping/sole cropping, etc.) which influence the structure of crop in time and space and his relations with the other BAPs.
- H_{AE3} : The intensity of tillage changes the structure of soil
- H_{AE4} : The properties of plot and soil affect the soil structure.
- H_{BAP1} : Crop residues and rhizodeposition enrich the SOM..
- H_{BAP2a} : The soil coverage and roots of plants modify the soil structure.
- H_{BAP2b} : Crop associations can modify the bulk density.
- H_{BAP3} : The MO participates to stabilize the agregates of soil.
- H_{FE1} : Diversification and tillage management affect the infra-annual runoff and soil Erosion control .
- H_{FE1b} : Intercropping reduce long term runoff and soil loss.

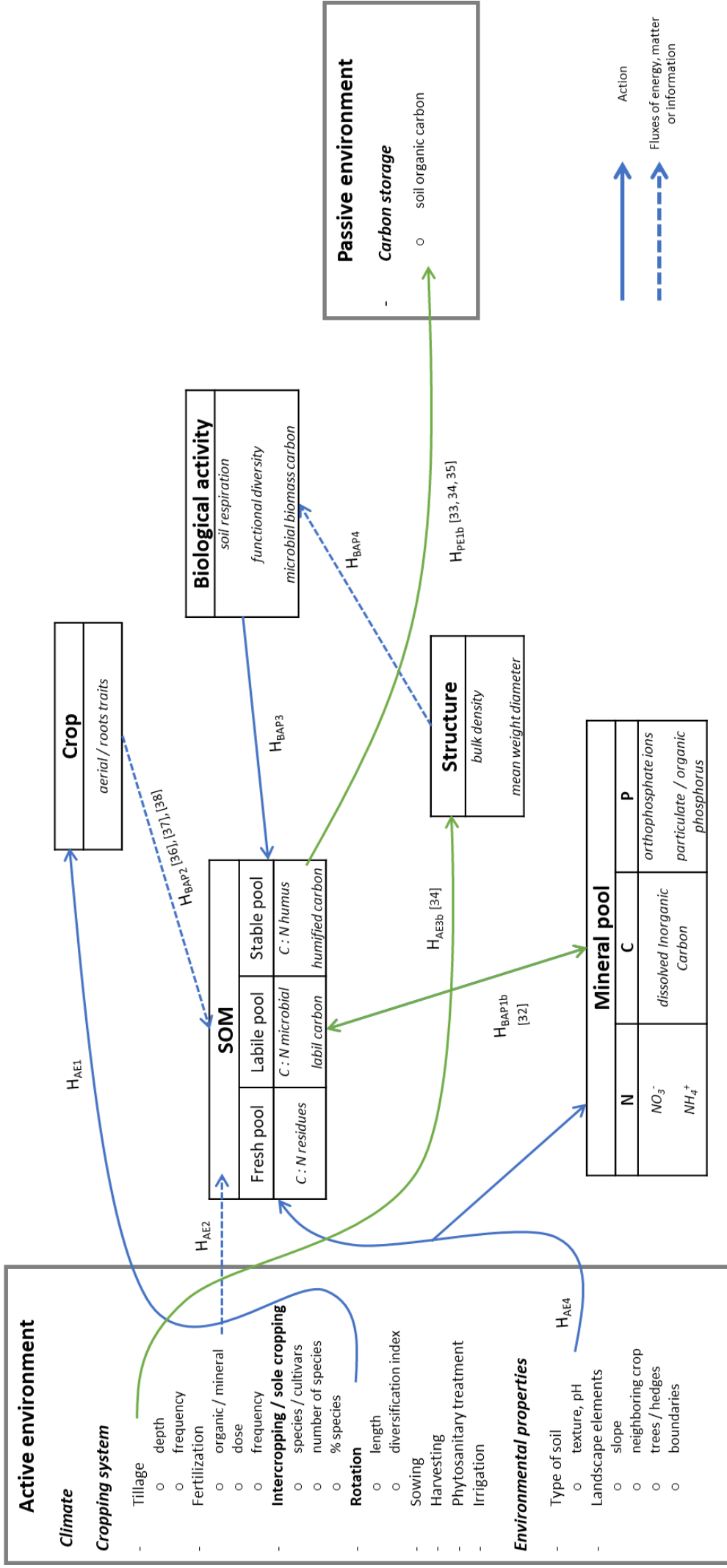




Dynamic analysis of conceptual model of an agro-ecosystem regarding the effect of crop diversification on water quality and supply. The scheme shows the main hypotheses and the state variables (in *italics*) linking the elements of the system. In green are represented the processes which appears over the time :

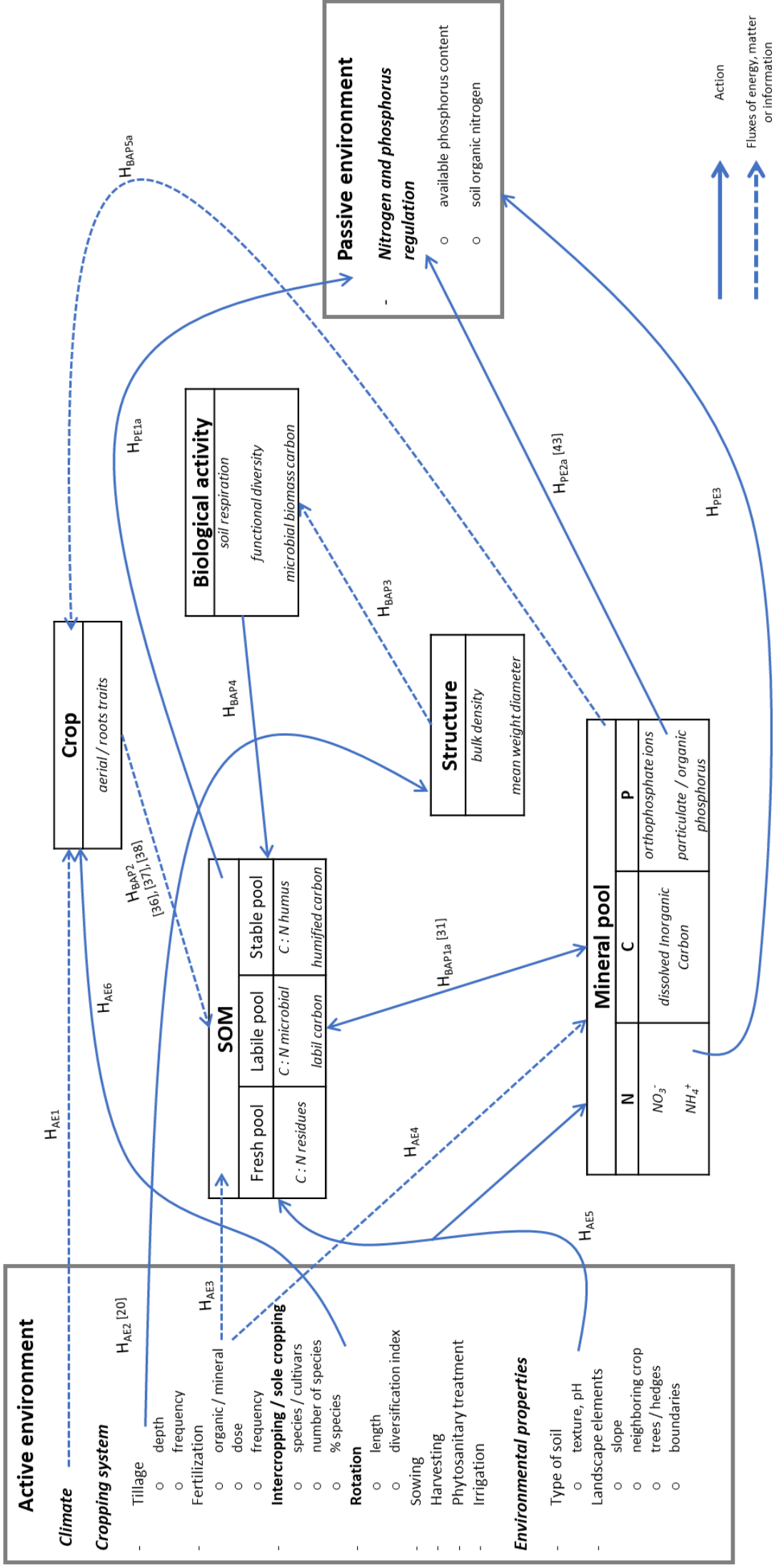
- H_{AE1} : Amount of water from rainfall and irrigation which circulates within the BAP structure, mineral pool, water and crop.
- H_{AE2} : A given quantity of manure which reach and enriches the SOM.
- H_{AE3} : A given quantity of inorganic fertiliser spread on field and supply the mineral pool.
- H_{AE4} : The choices related to diversification strategies (crops rotation / continuous crop, intercropping/sole cropping, etc.) which influence the structure of crop in time and space and his relations with the other BAPs.
- H_{AE5a} : The intensity of tillage changes the structure of soil.
- H_{AE5b} : Tillage influence soil water content.
- H_{AE6} : The soil characteristics (temperature, pH, moisture, texture, etc) influence the physico-chemical reactions in mineral pool and in SOM.
- H_{BAP1a} : Mineralisation and immobilisation process between SOM and mineral pool. Crop association influences the rate of immobilisation.
- H_{BAP1b} : Crop residues and rhizodeposition enrich the SOM.
- H_{BAP2} : Crop association increase the SOM mineralisation.
- H_{BAP3a} : The absorption of NH₄⁺ and NO₃⁻ by crop decrease the concentration of this elements in mineral pool.
- H_{BAP3b} : N facilitation influenced by crop association.
- H_{BAP4} : The WFPS impacts the soil mineral N.
- H_{BAP5} : The soil coverage and roots of plants modify the soil structure.
- H_{BAP7} : The MO participates to stabilize the aggregates of soil.
- H_{BAP8} : The soil coverage and roots of plants modify the soil structure.
- H_{PE1} : Crop diversification limits the N leaching.
- H_{PE2} : Crop diversification remains efficient to reduces the N leaching over the long term.
- H_{PE3} : Crop diversification influences the soil water content.
- H_{PE3b} : Crop diversification and tillage management impacts the soil water over the long term.

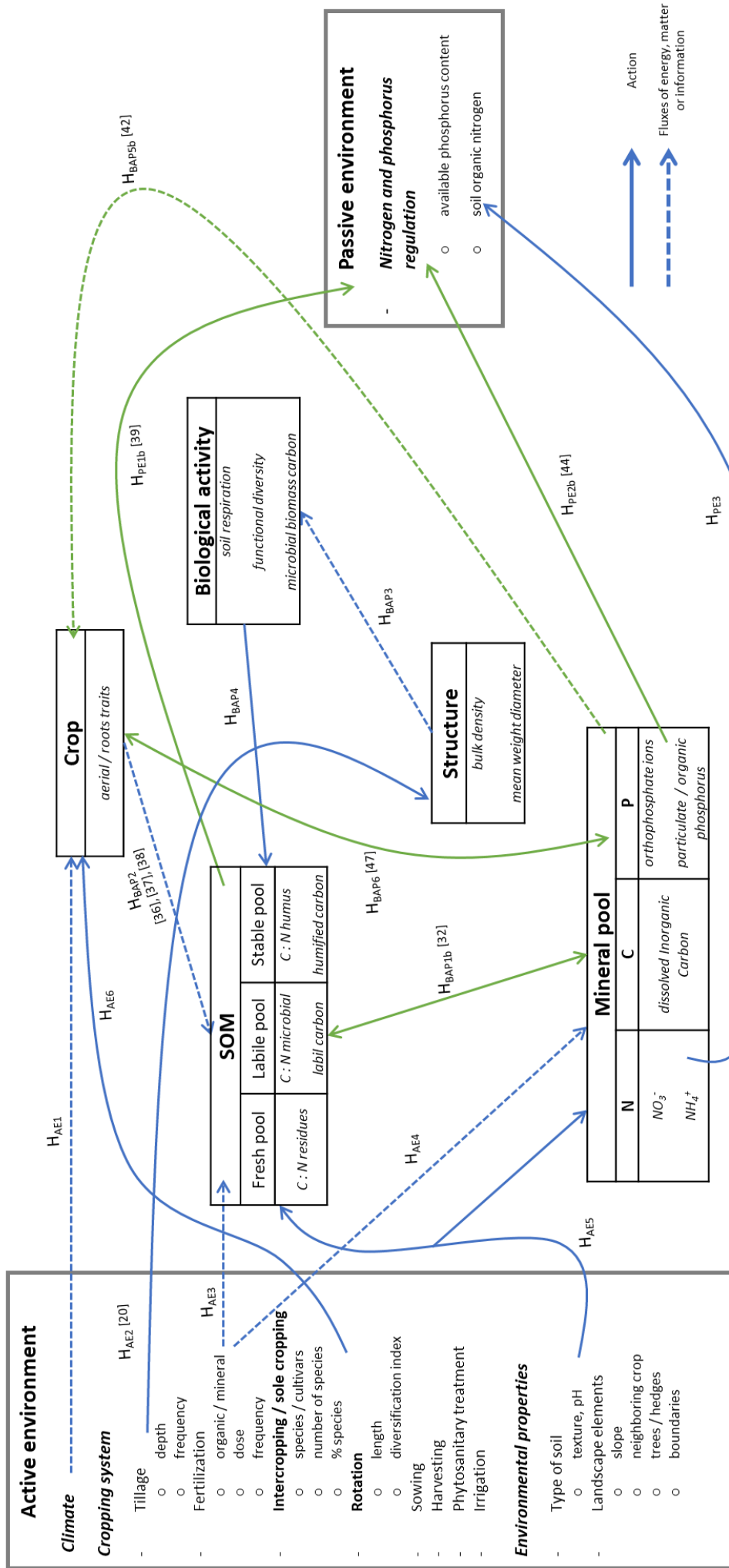




Dynamic analysis of conceptual model of an agro-ecosystem regarding the effect of crop diversification on carbon storage. The scheme shows the main hypotheses and the state variables (in *italics*) linking the elements of the system. In green are represented the processes which appears over the time :

- H_{AE1} : The choices related to diversification strategies (crops rotation/continuous crop, intercropping/sole cropping, etc.) which influence the structure of crop in time and space and his relations with the other BAPs.
- H_{AE2} : A given quantity of manure which reach and enriches the SOM.
- H_{AE3a} : The intensity of tillage changes the structure of soil.
- H_{AE3b} : Tillage management affects the SOC.
- H_{AE4} : The soil characteristics (temperature, pH, moisture, texture, etc) influence the physico-chemical reactions in mineral pool and in SOM.
- H_{BAP1a} : Mineralisation and immobilisation process between SOM and mineral pool. Crop association influences the rate of immobilisation.
- H_{BAP1b} : Crop association increases the SOM mineralisation.
- H_{BAP2} : Crop residues and rhizodeposition enrich the SOM.
- H_{BAP3} : The oxygen diffusion affects the activity of microorganisms.
- H_{PE1a} : The soil micro-organisms influence the transformation of SOM.
- H_{PE1b} : Amount of carbon sequestered in SOM.
- H_{PE1b} : Crop diversification enhances SOC over the long term.

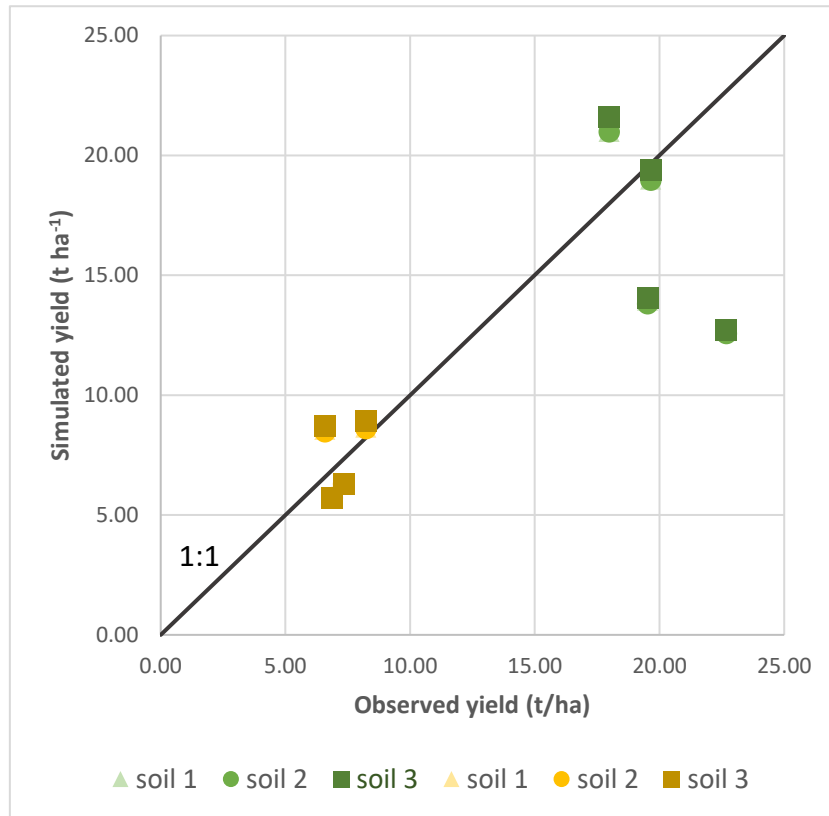




Dynamic analysis of conceptual model of an agro-ecosystem regarding the effect of crop diversification on N and P regulation. The scheme shows the main hypotheses and the state variables (in *italics*) linking the elements of the system. In green are represented the processes which appears over the time :

- H_{AE1} : N_2 fixation by legumes
- H_{AE2} : The intensity of tillage changes the structure of soil.
- H_{AE3} : A given quantity of manure which reach and enriches the SOM.
- H_{AE4} : A given quantity of inorganic fertiliser spread on field and supply the mineral pool.
- H_{AE5} : The soil characteristics (temperature, pH, moisture, texture, etc) influence the physico-chemical reactions in mineral pool and in SOM.
- H_{AE6} : The choices related to diversification strategies (crops rotation/continuous crop, intercropping/sole cropping, etc.) which influence the structure of crop in time and space and his relations with the other BAPs.
- H_{BAP1a} : Mineralisation and immobilisation process between SOM and mineral pool. Crop association influences the rate of immobilisation.
- H_{BAP1b} : Crop association increases the SOM mineralisation.
- H_{BAP2} : Crop residues and rhizodeposition enrich the SOM.
- H_{BAP3} : The oxygen diffusion affects the activity of microorganisms
- H_{BAP4} : The soil micro-organisms influence the transformation of SOM.
- H_{BAP5a} : The absorption of NH_4^+ and NO_3^- by crop decrease the concentration of this elements in mineral pool.
- H_{BAP5b} : N facilitation influenced by crop association.
- H_{BAP6} : N facilitation influenced by crop association.
- H_{PE1} : Amount of carbon sequestered in SOM.
- H_{PE2} : Crop diversification enhances SON over the long term.

Appendix 4



Observed vs. simulated dry matter (DM) yield for maize and wheat in the EFELE experiment (“TS/MO” trial) in 2012-2019. Wheat crop is represented by yellow marks and maize crop by green marks.

Statistical summary on the accuracy of APSIM to simulate crop DM yield for maize and wheat in the EFELE experiment (“TS/MO” trial; “conventional tillage/mineral fertilizer” treatment) in 2012-2019 for rotation 2 simulation with soil 1 and soil 2 and soil 3.

	Soil 1		Soil 2		Soil 3	
	Maize	Wheat	Maize	Wheat	Maize	Wheat
No. Obs	4	4	4	4	4	4
Observed data -mean (t ha ⁻¹)	19.95	7.24	19.95	7.24	19.95	7.24
Simulated data - mean (t ha ⁻¹)	16.67	7.32	16.59	7.27	16.95	7.42
Observed data - SD (t ha ⁻¹)	1.96	0.72	1.96	0.72	1.96	0.72
Simulated data -SD (t ha ⁻¹)	3.98	1.50	4.04	1.48	1.65	1.72
RMSE (t ha ⁻¹)	5.91	1.27	6.00	1.24	5.96	1.37
CCC	-0.37	0.23	-0.36	0.25	-0.40	0.24

No. Obs, number of observations; SD, standard deviation; RMSE, root mean square error; CCC, concordance correlation coefficient.



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Titre anglais : Which crop model to simulate the ecosystem services provided by crop diversification in Brittany ?
Titre français : Quel modèle de culture pour simuler les services écosystémiques fournis par la diversification des cultures en Bretagne ?

Because current farming systems have many issues, particularly related to their negative impacts on the environment, it is necessary to operate a transition toward more sustainable agriculture and redesigning cropping systems. Crop diversification, which acts on planned biodiversity as well as associated biodiversity, is a solution for designing disruptive sustainable farming systems, able to provide several ecosystem services. Designing such farming systems including various levels of crop diversification via crop rotation and intercropping needs crop modelling because it allows assessing ecosystem services provided by a wide range of virtual systems, on different climate-soil contexts, on a long-term basis. Consequently, the objective of this study is to define detailed, by the conceptualisation of an "ideal" system, characteristics that a crop model should have to simulate crop diversification and its consequences on various ecosystem services relevant in Brittany region. For this, among 3 crop models (APSIM, DSSAT, STICS), we select the best crop model according to the detailed characteristics proposed in "ideal" system and we test its relevance in Brittany region. APSIM comes out as the crop model best suited to respond to our objective and to simulate and follows indicators related to the provision of ecosystem services. However, despite encouraging results, APSIM shows some limits to getting use to Brittany pedoclimate context principally because a lack of adapted cultivars and complete information about initial conditions of soil. Thus, given this weakness, it is necessary to set up an adaptation step of the crop model and to complete this work with other simulations whose outputs will be compared with more observed data. In this way, it could be established whether APSIM is a good tool for designing systems based on crop diversification in the Brittany Region.

Étant donné que les systèmes agricoles actuels posent de nombreux problèmes, notamment en ce qui concerne leurs effets négatifs sur l'environnement, il est nécessaire d'opérer une transition vers une agriculture plus durable et de revoir la conception des systèmes de culture. La diversification des cultures, qui agit sur la biodiversité planifiée ainsi que sur la biodiversité associée, est une solution pour concevoir des systèmes agricoles durables, capables de fournir plusieurs services écosystémiques. La conception de tels systèmes agricoles incluant divers niveaux de diversification des cultures (la rotation des cultures ; cultures associées) nécessite une étape de modélisation permettant d'évaluer sur le long terme les services écosystémiques fournis par l'agroécosystème dans différents contextes pédoclimatiques. Par conséquent, l'objectif de cette étude est de définir en détail, par la conceptualisation d'un système "idéal", les caractéristiques que devraient avoir un modèle pour simuler la diversification des cultures et ses conséquences sur les différents services écosystémiques. Pour cela, parmi 3 modèles de culture (APSIM, DSSAT, STICS), nous sélectionnons le meilleur modèle de culture en fonction des caractéristiques détaillées proposées dans le système "idéal" et nous testons sa pertinence en région bretonne. APSIM ressort comme le modèle le mieux adapté pour répondre à notre objectif et pour simuler et suivre les indicateurs liés à la fourniture de services écosystémiques. Cependant, malgré des résultats encourageants, APSIM montre certaines limites à l'utilisation dans le contexte pédoclimatique breton, principalement en raison d'un manque de cultivars adaptés et d'informations complètes sur les conditions initiales du sol. Ainsi, compte tenu de cette faiblesse, il est nécessaire de mettre en place une étape d'adaptation du modèle de culture et de compléter ce travail par d'autres simulations dont les sorties seront comparées à des données observées pertinentes et plus nombreuses. Ainsi on pourrait établir si APSIM est un bon outil pour concevoir des systèmes basés sur la diversification des cultures en Région Bretagne.

Mots-clés : Diversification, Ecosystem services, Conceptualisation, Model validation, APSIM, Brittany

Key Words: Diversification, Services écosystémiques, Conceptualisation, Validation du modèle, APSIM, Bretagne

* Élément qui permet d'enregistrer les notices auteurs dans le catalogue des bibliothèques universitaires