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Analysis of the conditions for the development of grain legumes in the Midi-Pyrénées region (France), using the APES-FSSIM-Indicators modeling chain

Par

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Abstract

Grain legumes are generally considered as key crops for sustainable agriculture. They offer many agronomic, environmental and socio-economic benefits when grown in succession with cereals. Although grain legumes have many advantages, their share in European agriculture is still very limited. In the Midi-Pyrénées region (south-west of France), their area varies from 1 to 3% of the total cultivated area, moreover farmers show little interest in growing grain legumes on their farms. In this context, the objectives of the thesis were to; i) identify the main constraints for grain legume production in the Midi-Pyrénées region, ii) identify key technical and socio-economic levers (expressed as scenarios) to promote grain legumes in current cropping systems and iii) assess, by using the APES-FSSIM-Indicators modelling chain, the impacts of these scenarios on the socio-economic and environmental behaviours of three representative arable farm types (FT1, FT2 and FT3) of the Midi-Pyrénées region.

The main constraints have been identified based on bibliography and in consultation with local experts. These constraints are derived from the grain legumes sensitivity to**:** soils and climatic conditions, farmer technical skill and expertise for sowing and harvesting the grain legumes, economic competitiveness in comparison with cereals and their yield and market prices amounts and fluctuations. From the above statement, the alternative scenarios, in comparison to the current situation (reference scenario) have been identified to promote grain legumes. They included, the introduction of new grain legumes rotations in current cropping systems of the region ($S_{tec.innov}$), provision of more premiums to grain legumes ($S_{premium}$**)**, increase in sale price (S_{price}) and yield (S_{yield}) of grain legumes, reduction in price ($S_{price.var}$) and yield ($S_{yield.var}$) variability of grain legumes, and combination of all these components (S_{comb}). All scenarios have been assessed with quantitative environmental and socio-economic indicators and are calculated with the APES-FSSIM-Indicators modeling chain.

Results show that, contrary to expectation, the introduction of new legumes rotations or the reduction of yield or price variability ($S_{tec.innov}$, $S_{price.var}$ and $S_{yield.var}$) did not increase the grain legumes area. However, an increase in grain legumes area was observed for $S_{premium}$, S_{price}, S_{yield} and S_{comb}. The combined scenario (S_{comb}) was found to be most efficient, showing an important increase in grain legumes area by 34 ha, 32 ha and 7 ha respectively for FT2, FT3 and FT1 with a significant change in socio-economic and environmental indicators for all three farm types. The increase in grain legumes area and modification in economic and environmental indicators depend on the farm characteristics and can be explained by the differences in irrigable area between irrigated crops (i.e. maize, peas and soybean), cropping pattern, soil types and climatic conditions (rainfed and irrigation) on the three farms types.

The results obtained from this study show that the modification of policies or the inclusion of new technologies, may lead to several economic and environmental changes, which reveal the adaptation strategies adopted by farmers in order to optimize their farm income. These strategies are mainly implemented by modifying the areas allocated to different crops on different soil types and by changes of management practices. The grain legumes area can be increased on Midi-Pyrénées farming system by the combination of slightly increase in premium, sale price and crop yield of the grain legumes. This methodology can easily be adapted to other regions of France and also EU for identifying the main developmental conditions for grain legumes production provided the skilled experts are properly selected and sufficient data are available for parameterization of the modeling chain.

Key words: cropping system, evaluation of crop model, scenarios, indicators, technological innovation, policy changes

Résumé

Les légumineuses sont souvent considérées comme des cultures clés pour une agriculture durable. Dans ce cadre, elles sont souvent cultivées en association avec les céréales et présentent de nombreux avanatges d'ordres agronomique, environnemental et socio-économique. Cependant, malgré ces nombreux avantages, leur part dans l'agriculture européenne est encore très limitée. Dans la région Midi-Pyrénées (sud-ouest de la France), la superficie occupée par les légumineuses ne représente que 1 à 3% de la superficie totale cultivée, traduisant la réticence des agriculteurs à cultiver ce type de culture. Dans ce contexte, l'objectif de la thèse étaient de: i) identifier les principales contraintes pour la production de légumineuses dans la région Midi-Pyrénées, ii) identifier les principaux leviers techniques et socio-économiques (exprimés sous forme de scénarios) afin de promouvoir les légumineuses dans les systèmes de cultures actuels et iii) évaluer, en utilisant la chaîne de modélisation APES-FSSIM-indicateurs, les impacts de ces scénarios en caculant des indicateurs socio-économiques et environnementaux au niveau de trois exploitations représentatives (FT1, FT2 et FT3) de la diversité observée au niveau de la zone d'étude.

L'identification des principales contraintes a été basée sur la bibliographie et les dires d'experts locaux. Ces contraintes traduisent la sensibilité des légumineuses aux types de sols et de climat, les compétences techniques demandées pour cultiver convenablement des légumineuses, la compétitivité économique des légumineuse par rapport aux autres cultures et à l'actuel prix et rendement des légumineuses et surtout leurs variabilité inter-annuelle. Pour promouvoir les légumineuses, des scénarios alternatifs ont été définis et comparés à la situation actuelle (scénario de référence). Les scénarios alternatifs, se différencie par rapport au scénario de référence par les paramètres suivantes: l'introduction de nouvelles rotations à base de légumineuses dans les systèmes de culture actuels ($S_{tec.innov}$), l'octroie d'une prime spécifique aux légumineuses ($S_{premium}$), l'augmentation du prix de vente (S_{price}) et du rendement (S_{yield}) des légumineuses, la réduction de la variabilité du prix ($S_{price.var}$) et du rendement ($S_{yield.var}$) des légumineuses et enfin, la combinaison de tous ces paramètres dans un seul scénario (S_{comb}). Tous les scénarios ont été simulés et comparés en utilisant la chaîne de modèles APES-FSSIM-indicateurs. Cette chaine de modèles a permis de calculer des indicateurs environnementaux et socio-économiques.

Les résultats ont montré que, contrairement aux attentes, l'introduction de nouvelles rotations et la réduction de la variabilité des rendements ou des prix ($S_{tec.innov}$, $S_{price.var}$ et $S_{yield.var}$)

n'entrainement pas l'augmentation de la superficie des légumineuses. Toutefois, une augmentation de la superficie des légumineuses a été observée pour les scénarios $S_{premium}$, S_{price}, S_{yield} et S_{comb}. Le scénario combiné (S_{comb}) a été jugé comme le plus efficace, montrant une augmentation importante de la superficie des légumineuses, soit 34 ha, 32 ha et 7 ha respectivement pour FT2, FT3 et FT1. Ce changement a entrainé également une modification significative au niveau des valeurs des indicateurs socio-économiques et environnementaux. L'augmentation de la superficie des légumineuses et la variation des indicateurs économiques et environnementaux dépendent des caractéristiques structurelles des exploitations, de la part de la surface irriguable, des systèmes de culture présents et des types de sol au niveau de chaque exploitation.

Les résultats de cette étude montrent que l'application d'une nouvelle politique pour promouvoir les légumineuses, peut conduire, selon les stratégies de production adoptées par les agriculteurs afin de maximer leurs revenus, à plusieurs changements économiques et environnementaux. Ces stratégies se traduisent principalement par la modification des superficies allouées aux différentes cultures sur les différents types de sols et par le changement des itinéraires techniques. Cette méthodologie peut être facilement appliquée à d'autres régions au niveau de la France et de l'Europe afin d'identifier les principales conditions permettant d'augmenter les surfaces allouées à des rotations à base de légumineuse.

Mots clés: système de culture, evaluation modèle de culture, scénarios, indicateurs, innovation technologique, changement de politiques.

General introduction

Depletion of fossil energy resources, climate change and increasing environmental pollution have become a serious threat over the last few decades. This situation is even more critical in the context of increasing energy prices and world population (Nemecek et al., 2008; Schneider, 2008). Crops that could save non-renewable energy resources with less environmental pollution have attracted considerable attention. In this context, the cultivation of grain legumes (pulses) in the European Union (EU) could be one of the best alternative choices, instead of importing soyabean and practicing intensive cereal cultivation, for fulfilling human food requirements and reducing the negative environmental effect of intensive agriculture (Jezierny et al., 2010; Nemecek et al., 2008). Synthetic N fertilizers are considered as one of the most expensive input in modern agriculture, which account for 40 to 65 % of on farm commercial energy use, respectively for developed and less developed countries (Mudahar and Hignett, 1987). Cereals are considered as the major N fertilizer user crops and it is estimated that during 2007 and 2008 approximately 50% of the world N fertilizers have been used only by cereal crops (IFA, 2009). Smil (2001) reported that worldwide about 1.3% of all energy produced is used by the various types of fertilizers and the cost of fertilizers is expected to increase due to increasing use of non-renewable energy resources for other purposes. Between 2003 and 2007, Schneider (2008) noted that N fertilizer prices have been increased by 50%.

Grain legumes due to their ability to fix atmospheric nitrogen (Sprent and Thomas, 1984; Zahran, 1999) unlike other crops not only need less or no N fertilizer (depending on the biophysical conditions) for their optimal growth but also reduce the need of N fertilizer in subsequent crops (Rochester et al., 1998) that can save non-renewable energy resources for synthesis of N fertilizers (Nemecek and Erzinger, 2005). Despite, all these advantages, in France, and indeed in the whole Europe, there is a substantial deficiency of protein-rich material, such as grain legumes, and every year this deficiency is compensated by importing about 75% of the soyabean meal used, mostly from the USA (UNIP, 2009; Nemecek et al., 2008). In the Midi-Pyrénées (MP) region of France, where our study has been conducted, the area allocated to grain legumes is very low (1 to 3% of the total cultivated area) (UNIP, 2009). The increasing proportion of grain legumes in intensive cereal rotations would have a major impact on energy saving, reducing environmental pollution and deficiency of protein-rich raw material (Jezierny et al., 2010; Nemecek et al., 2008). But farmers show little interest in growing grain legumes. Political, agronomic, technical, climatic, and economic reasons are advanced for this lack of interest (Von Richthofen et al., 2006). It is therefore important to identify the main constraints for grain legume production and also the conditions which would enable the promotion of grain legumes in the MP region, which is selected as a test case in this study.

The main agronomic, climatic, and socio-economic constraints for grain legume production in MP region have been identified with the help of local experts. The alternative situations for grain legume promotion have been tested by simulating the different alternative scenarios of technological innovation and policy changes. Previous studies showed that crop models are widely used for simulating such alternative scenarios and in this study we used the modeling chain APES-FSSIM-Indicators (Belhouchette et al., 2010) for this purpose. This thesis as a part of EU project SEAMLESS (System for Environmental and Agricultural Modeling; Linking European Science) (Van Ittersum et al., 2008) was conducted in UMR SYSTEM (Fonctionnement et conduite des systèmes de culture tropicaux et méditerranéens) with INRA and Montpellier SupAgro (France). For the completion of the thesis, we also had collaboration with IAMM (Institut Agronomique Méditerranéen de Montpellier), UMR AGIR (Agrosystèmes et agriculture, Gestion de resources, Innovations & Ruralités) in INRA Toulouse and PPS (Plant Production Systems Group) in Wageningen University (The Netherlands).

CHAPTER 1

GRAIN LEGUMES IN CROPPING SYSTEMS

Outlines of the chapter

The aim of this chapter is to explain the context and objectives of the thesis and then the methodological approach for fulfilling the objectives. This chapter can be declined into three main parts. Part 1 describes the importance of grain legumes in terms of nutritional value and biological N fixation. It also analyse the comparative advantages and disadvantages of growing grain legumes within cereal rotation. This part also describes the current production and development of grain legume production and area over the past few decades in the EU, France and in MP region. At the end of this part main questions (objectives) of thesis are listed, which were constructed from the above portrayal. The second part describes in detail the methodological approach and justification of its choice for this study. The last part describes the main constraints which prevent the development of grain legumes in the Midi-Pyrénéss region.

1.1. Importance of grain legumes in agriculture

The reconciliation of economy and environment is a key factor in achieving sustainability. The EU wishes to achieve the sustainability of its agriculture in order to produce high quality food materials and to manage energy crisis and the risks related to climate and market fluctuations. These risks can be reduced by enforcing a reduction in the possible negative impacts of agricultural activities on the environment (water quality, biodiversity, green-house gas emissions and public health) (MP3-Grain Legumes, 2010). Grain legumes are generally considered as key crops for sustainable agriculture (AEP, 2004; Wani et al., 2003). They belong to the Fabaceae (also called Leguminosae) family of flowering plants. They are commonly known as “poor man’s meat” because of their protein content, and thus are widely consumed by poor population groups. Chickpea, common bean, cowpea, fababean, pea, lupins, groundnut, lentil, pigeonpea and soyabean are the major grain legumes that contribute to human foodstuffs and animal feed (MP3-Grain Legumes, 2010).

1.1.1. Nutritional value

Primarily, grain legumes are grown for their grains, which are used either for human consumption (food legumes) or for animal feed (feed legumes or “proteagineux” in french) (Singh et al., 2007). They are the cheapest sources of supplementary proteins for human compared to meat. For example, the cost of a unit of legume protein is 50% lower than a unit of meat protein in Brazil, 70% in Egypt, 75% in Rwanda and 60% in India (Graham and Vance, 2003; Joshi et al., 2002; Byerlee and White, 2000). They occupy an important place in human nutrition, especially in low-income groups of people in developing countries, which is why they are often called poor man's meat. They are generally good sources of slow-release carbohydrates and are rich in proteins ~18-25% by weight, which is twice the protein contents of wheat and three times that of rice. Soyabean is unique in this family, containing about 35-43% protein in addition to oil (Tharanathan and Mahadevamma, 2003). They also contain high levels of macro- and micro-nutrients (Ca, P, K, Fe, and Zn), vitamins, fiber and complex carbohydrates that all contribute to balanced nutrition. Moreover they complement the consumption of cereals since they provide an amino acid balance and better protein utilization. An optimum nutritional balance diet is composed of cereals and legumes in an approximate ratio of 2 to 1 (MP3-Grain Legumes, 2010). Legume consumption has also been shown to lower cholesterol levels and to reduce the risk of diabetes, breast, colon cancer and heart attacks. Kabagambe et al. (2005) reported that legumes may protect against myocardial infraction by 38% with the use of one third cup of cooked beans on a daily basis.

1.1.2. Biological N fixation

The key strength of grain legumes is their specific characteristic as nitrogen-fixing plants, which fulfil their N requirement from the fixation process (Graham and Vance, 2003). The reduction of N is carried out by a symbiotic association with the *Rhizobium* or *Bradyrhizobium* bacteria within the root nodules of legumes. This process is made possible by an enzyme complex, the nitrogenase, which supports the organic N production process from gaseous N_2 (Crew and Peoples, 2004; Salisbury and Ross, 1978). It is estimated that during the growing season, legumes fix N at the rate of 1 to 2 kg N $ha^{-1}day^{-1}$ (Giller, 2001; Unkovich and Pate, 2000; Van Kessel and Hartley, 2000). Mil (1999) reported that legumes annually fix about 40 to 60 million metric tons in agricultural contexts and 3 to 5 million metric tons in natural ecosystems. It is estimated that "legumes grown for grain, hay, pasture and other agricultural purpose account almost half of the annual quantity of N fixed by biological system (Anonymous, 1984)". Burris and Roberts (1993) reported that biological processes contribute to 65% of the N used in agriculture.

In combination with plant photosynthesis and potential growth (Wery, 1987; Adams et al., submitted), the availability of Phosphorus (P) is considered as a major driving force behind N_2 fixation for signal transduction and membrane biosynthesis and also for ATP requirements for nodule development and function (Ribet and Drevon, 1996). About 33% of the world's arable land is deficient in P (Sanchez and Euhara, 1980), while maximum benefits from N_2 fixation depend on the availability of P in the soil (Kennedy and Cocking, 1997). The other limitations to N_2 fixation are drought, salinity, N fertilisation, and nutrient limitations (Graham and Vance, 2003) through their direct effects on nodules or indirect effect on potential growth and N requirements (Wery, 1987). There is also a genetic variability in N_2 fixation (Sinclair et al., 1987).

1.2. Advantages of growing grain legumes within cereal-based rotations

Grain legumes can offer many agronomic, environmental and socio-economic benefits when grown in succession with cereals. Most of the work on grain legumes is done at field scale by comparing their strengths and weaknesses with those of other crops (mainly cereals) (Wery and Ahlawat, 2007). But to quantify the benefits of grain legumes and to improve their production and their contribution to sustainable farming systems, the entire crop rotation must be considered. Only the analysis of whole rotation allows a correct and adequate evaluation of grain legume cropping systems (Von Richthofen et al., 2006). As compared to cereals, grain legumes are considered as substitute of N fertilizers and enhancers of soil organic matter content due to the N_2 fixation process. Due to this unique characteristic of grain legumes, crop rotation with grain legumes improves soil health, diversifies cropping systems and maintain soil fertility, resulting in many economic, agronomic and environmental advantages (MP3-Grain legumes, 2010). These advantages can be classified into specific (of an N fixing plant) and non-specific advantages. The production of grains without any fertilization within a rotation is a specific advantage of grain legumes provided by the symbiotic fixation process. The other advantages are non-specific because they are shared with some non legume crops: reduction in amount of N fertilizer for the following crop in the rotation, increase in soil organic matter and hence soil fertility, suppression of weeds, insects and diseases due to break cycle, which results in decreasing the negative environmental impacts of insecticides and pesticides applications. Some of these specific and non-specific agronomic, environmental and socio-economic benefits are discussed in the following paragraphs.

1.2.1. Agronomic benefits

Grain legumes are known to increase the yields for the following crops in the rotation (Rochester et al., 1998). Legumes often increase the yield of the subsequent cereals in the rotations as compared to cereals grown after a non-legume crop **(**Rao et al. 1996; Peoples & Crasswell, 1992)**.** Yield increase of 25 to 40% has been observed in maize cultivated after soyabeans and common beans in the eastern region of Central Africa (MP3-Grain Legumes, 2010). Dakora et al. (1987) reported that in African savanna, the rotations cowpea-maize and groundnut-maize have increased the maize yields by 95% and 89% respectively. Salez et al. (1992) stated that the introduction of cowpea as previous crop in sorghum rotations has increased the sorghum yield by 65%. A survey showed that in Europe when farmers were asked about the impact of grain legumes in crop rotations, they referred to them as good crops for improving soil fertility and leading to high additional grain yields for the following crops (Von Richthofen et al. (2006). On average they found that wheat after grain legumes produces 0.6 to 0.9 t ha^{-1} more yield as compared to wheat after cereals.

Haque et al. (1995) explained this yield increase by the positive effect of legume on soil's chemical, physical and biological properties. Application of plant nutrient (Paustian et al., 1997c; Glendining & Powlson 1995) organic amendments and inclusion of legume in continuous cereals rotations help in improving the soil quality and building up the soil carbon pool that consequently increased the crop yields and amount of crop residues returned to the soil (Wani et al., 2003; Paustian et al. 1997b; Wani et al. 1994a). Mvondo et al. (2007) and Peoples et al. (1995) stated that legumes rotations with other crops also increase the biological activity of soil by enhancing the presence of fine roots, millipedes, earthworms and ants and may result in improving the soil fertility and hence the crop yield of the following crops in the rotations.

It is difficult to evaluate the role of grain legumes in changing the total soil N_2 pool, because total soil N_2 pool is very large and annual changes are small (Van Kessel and Hartley, 2000). Therefore long term rotational studies are necessary to quantify such changes. Although such studies are limited, Campbell et al. (2000) evaluated the impact of legume-based cropping systems on total soil N, C and net mineralization over a period of 14 years. They showed an increase of total soil N from 3.26 to 3.58 t ha^{-1} for wheat-lentil rotation as compared to wheat monocrop. Similarly, total soil C was increased from 34.6 to 36.6 t ha^{-1} for the same rotations but with fertilized wheat. They also observed that net mineralization was higher for wheat-lentil rotation as compared to wheat monocrop. Despite a reduction of 13 kg N ha^{-1} per year in wheat-lentil compared to wheat monocrop, the total soil N_2 pool increased at a higher rate (23 kg N ha^{-1} per year compared to 8 kg N /ha per year for fertilized wheat). Another study with cowpea, pigeonpea and chickpea rotated with sorghum and sunflower showed that total soil N_2 contents were increased after 10 years (Rego and Seeling, 1996; Wani et al., 1996). Belowground plant residues are also very crucial for total soil N_2 pool and grain legumes are also very important for that belowground total N pool (Rego and Seeling, 1996; Wani et al., 1996) which depends on N2 fixation by grain legumes (Van Kessel and Hartley, 2000). From the above discussion, it can be concluded that grain legumes can increase the total soil N_2 pool. However, this effect is more obvious on poor soils due to increased N_2 fixation (Van Kessel and Hartley, 2000).

1.2.2. Socio-economic benefits

The maximum economic benefits from grain legumes are obtained with long-term rotations because their beneficial effects become apparent only over long periods (Chalk, 1998). The reasoning of the rotation is too often based on "the most profitable crops" without considering the entire rotation of which they form a part**.** The profitability of a crop is considered independently of the succession of different crops that make up the rotation. The isolated comparison of crop gross margin does not reveal the monetary value of grain legumes for the following crop (Von Richthofen et al., 2006). The calculation of rotation gross margin demonstrates that inclusion of grain legumes in intensive cereal rotations does not cause a drop in farmers' income. On the contrary in most cases grain legumes rotations offers slightly higher gross margins than intensive rotations with 75% or more cereals, as shown in Figure 1.1 for different rotations in Europe (Von Richthofen et al., 2006).

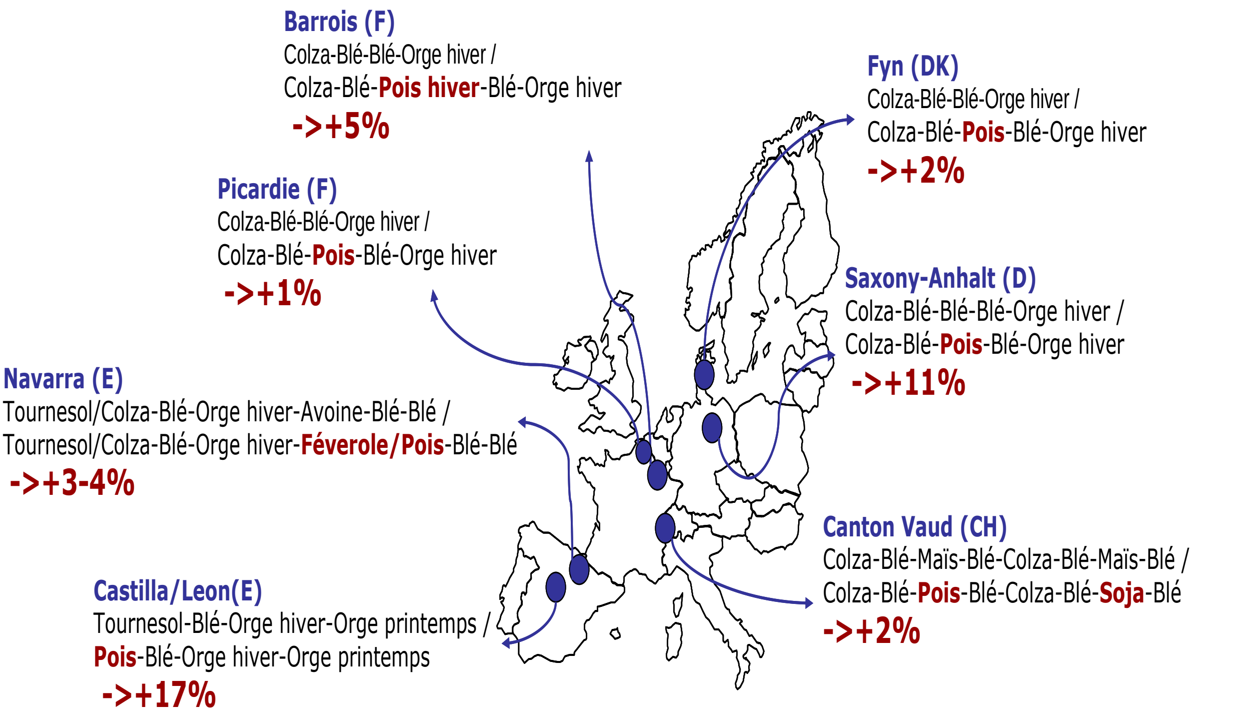

Figure 1.1: Increase in gross margin of rotations after introduction of grain legumes in different regions of EU (Von Richthofen et al., 2006).

In Saxony-Anhalt (Germany), inclusion of peas in five-year rotations with 80% cereals increased the gross margin by 29 €/ha (11%). Similarly for four-year rotations this advantage was still 11 €/ha (4%) higher (Von Richthofen et al., 2006). Rao et al. (1999) and Von Richthofen et al. (2006) also found that crop rotations including grain legumes (cowpeas and pigeon pea) have gross margins equal to/or greater than cereals rotations without grain legumes. Carrouée et al. (2002) compiled different available sources, and discussed the benefits and impacts of introducing grain legumes into crop rotations. They came to a generally positive assessment. Rao et al. (1999) found that cropping systems based on annual grain legumes were 32-49% more profitable than continuous maize cropping. Von Richthofen and GL-Pro partners (2006) found that pesticide and soil tillage costs can be reduced by 20-30% and 25-30% respectively by including the legumes as preceding crop in cereals rotations. They also found that total cost can be reduced by 50 €/ha for pea-cereal rotations as compared to five year cereals rotations. Another study conducted by UNIP (2008) in Eure et Loir region of France showed that overall peas-wheat rotation can save 60-150 €/ha as compared to continuous cereal rotation.

1.2.3. Environmental benefits

Legumes can play a critical role in natural ecosystems, agriculture, and agro-forestry due to their ability to fix atmospheric N_2 which makes them economical and environmentally-friendly crops (Graham and Vance, 2003). The ability of grain legumes to fix atmospheric nitrogen saves non-renewable energy resources used for synthesis of N fertilizers, as manufacturing nitrogen fertilizer is a high energy-consuming process (Nemecek and Erzinger, 2005). Nemecek et al. (2008) stated that introducing grain legumes into European crop rotations offers interesting options for reducing environmental burdens, especially in a context of depleted fossil energy resources and climate change. They found that the introduction of peas in cereal-based rotations induced a significant reduction in; i) consumption of fossil fuels (14%) as compared to continuous cereal-based crop rotations and ii) nitrogenous emissions by decreasing the losses of ammonia (-26%), nitrous oxide (-10%) and nitrogen oxides (-11%). The reasons are the lower quantity of N-fertilizers and also the reduced use of machinery. Bouwman (1996) found on 87 plots, N_2O emissions fluxes ranging between 0 and 30 kg N-N_2O ha^{-1} per year for fertilized plots, in comparison with 0 to 4 kg N ha^{-1} per year in unfertilized plots. It is estimated that fields planted with legumes can maintain N_2O fluxes as low as 0-0.07 kg N ha^{-1} per year (Conrad et al., 1983). A study in Germany, France, Switzerland and Spain concluded that the introduction of grain legumes in intensive cereal rotations is likely to reduce energy use, global warming potential, ozone formation and acidification as well as eco- and human toxicity per unit of cultivated area (Nemecek et al., 2008). Considering that it takes about 1.5 litres of fuel oil equivalent to produce one kilogram of mineral nitrogen, and that cereal crops receive 180 kg nitrogen per hectare, thus growing legumes can save 270 litres/ha of oil equivalent (UNIP, 2008).

Ncube et al. (2008) found that when cowpea, pigeonpea or groundnuts were introduced before sorghum, nitrogen fertilization was reduced on average by 130 kg of N ha^{-1} in the following season for the production of sorghum. Nemecek et al. (2008) noted that for the same yield, the amount of nitrogen applied on the wheat crop after pea was 14% lower than the single wheat rotation. He also found that the amount of nitrogen applied to wheat following pea was reduced from 180 kg N ha^{-1} to 157 kg N ha^{-1}. This is confirmed in a study by UNIP (2008) which showed that pea rotated with wheat can save between 20-50 Kg N ha^{-1} as compared to wheat-wheat rotation. Wery and Ahlawat (2007) stated that grain legumes can save 20-60 kg/ha of N for the following cereal with a supplemental yield of 1 t ha^{-1}. Jensen (1997) also found an average N benefit of about 20 kg N ha^{-1} from peas in a crop rotation. He also found that after a pea harvest, greater quantities of mineral N are found in the soil than after a cereal harvest, which can be used by the following crop. Food legumes such as cowpea, mung bean, mothbean, pigeonpea, groundnut and fodder legumes such as berseem were found to increase yields of subsequent cereal crops in semi-arid India by an equivalent effect of 30–40 kgN ha^{-1} (Lal et al., 1978; Rao et al., 1983).

It is assumed that in intensive cropping systems the introduction of grain legumes could help in reducing the weeds, insects and diseases, due to breaks in the cycle of these agents **(**Mwanamwenge et al., 1998; Peoples et al., 1995; Robson, 1990). Bulson et al. (1997) and Liebman and Dyck (1993) also stated that crop rotations with legumes could provide successful strategies for weed, insects and diseases suppression due to disruption of conditions suitable for their development and may lead to reduce the applications of pesticides and fungicides as compared to continuous cereal rotations **(**MP3-Grain legumes, 2010). Nemecek et al. (2008) showed that inclusion of peas in cereal-based rotations (wheat-canola-wheat-wheat-winter barley) in Saxony-Anhalt (Germany) has reduced the use of pesticides by 10%. This reduced use of pesticides resulted in significant environmental benefits because it reduced terrestrial eco-toxicity by 7%.

The introduction of legumes in continuous cereal-based cropping systems can also improve biodiversity, although, as stated by Munier-Jolain and Collard (2006) this effect is not specific to grain legumes. In regions where crop rotations are fairly diverse, as in Switzerland, no additional break-crop effect can be found after the introduction of grain legumes. But in regions where crop rotations are not very diverse, legumes can help in introducing biological diversity. Nemecek et al. (2008) stated that legumes can contribute to the conservation of biological diversity by promoting diversity of crops. The biodiversity points given by the SALCA assessment method (Jeanneret et al., 2006) were higher (7.3) for rotations with grain legumes as compared to rotation without grain legumes (7.1).

1.3. Disadvantages of grain legumes

1.3.1. Nitrate Leaching

Although legumes have many advantages, they also have some disadvantages. It is generally considered that the reduction in number of N fertilizer applications and total amount of N fertilizer over the legume-based rotation reduces the risk of nitrate leaching. But this is not always true. N leaching occurs on both legume and cereal-based cropping systems (Dinnes et al., 2002; Fillery, 2001; Poss and Saragoni, 1992; White, 1988). However, this can differ with soil type, climate (more rainfall) and growing season (winter or spring). Crew and Peoples (2004) found that N leaching was higher for soils with high hydraulic conductivity, drained soil exposed to flood irrigation or high rainfall. Fillery (2001) stated that there is a higher chance of N leaching during summer or winter fallow in legume-based systems. Nemecek et al. (2008) showed that crop rotations with peas cause a 4% higher nitrate leaching. They gave several reasons for this behaviour: longer period of bare soil, higher amount of mineral nitrogen in soil after the pea crop, shallow root system of pea crop, more N content of pea straw than wheat straw that leads to higher N mineralization. Von Richthofen et al. (2006) also found that the risk of nitrate leaching is often increased by the inclusion of a grain legume crop in cereal rotations. However, where possible it can be reduced by efficient catch-crop management, intercropping or sowing of winter grain legumes. Drinkwater et al. (1998) found the reverse results, with cereal-based systems giving an average N leached 7% higher that of legume-based systems.

The situation is different with perennial forage legumes which are growing for a longer period during the year and therefore extract nitrate from soil. For example Owens et al. (1994) showed a 48-76% reduction of nitrate leaching by including alfalfa in the rotation of cereal crops. One should not draw definite conclusions from such studies because of the use of the best management practices in most such studies and the use of different rates of N fertilizer (Sinclair and Cassman, 1999). Some researchers argue that N derived from legumes has the same negative effects as N derived from chemical fertilizers, and the increased production obtained from N fixed by legumes seems to be insufficient to match the requirement of increasing population (Cassman et al., 2002; Smil, 2001; Sinclair and Cassman, 1999). However, Crew and Peoples (2004) compared the sustainability of both sources of N in terms of ecological integrity, energy balance and food security and found that N derived from legumes is potentially more sustainable than chemical sources of N.

1.3.2. Labour requirements

Rao et al. (1999) reported that maize rotated with cowpea required similar labour as a maize monocrop rotation. He also found that maize rotated with different legumes as intercrop resulted in change in labour use. For example, maize crops rotated with cowpea and pigeonpea required respectively 15% and 32% less labour as compared to continuous maize rotation. Wery and Ahlawat (2007), on the other hand, arrived at the opposite conclusion, that labour requirements are higher for legume-based systems than cereal-based systems due to the fact that legumes are less mechanized and more labour is needed for weeding, as no effective post-emergence herbicide is available. They also show that sowing date has a strong effect on the efficiency of labour, for example spring-sown peas and chickpea may improve the efficiency of labour, by reducing the period of high requirement of labour as compared to cereals which are mostly winter sown. This statement is supported by Nemecek and GL-Pro partners (2006), who found that in Saxony-Anhalt region (Germany), the cultivation of only winter rapeseed and winter cereals required a high number of labour in autumn for all agricultural operations i.e. tillage, seedbed preparation and sowing, which requires powerful and expensive mechanisation. However they found that it can be managed by integrating grain legumes into the rotation. For example, when a 500-ha farm (average plot size 20 ha) introduces spring peas into a five-year rotation of rapeseed–wheat–wheat–wheat–barley (resulting in rapeseed–wheat–pea–wheat–barley) more than 300 tractor hours/ha were saved between August and October. On the other hand, they found that only about 80 additional hours were required in spring. This indicates that machines and manpower were used more efficiently and the grain legume rotation allowed a larger cropped area to be managed.

1.3.3. Susceptibility to pests and diseases

The cost of protecting legumes against pest increases with the number of legumes in the system, as it is considered that legumes are more susceptible to pests and diseases than cereals, especially in the tropics and sub- tropics (Beaver et al., 2003; Coyne et al., 2003).

1.4. Problem definition

The above discussion on the importance of grain legumes and their agro-environmental and socio-economic advantages show that introduction of grain legumes into cereal crop rotations offers interesting options for reducing environmental problem, especially in a context of depleting fossil energy resources and climate change (Schneider, 2008). Despite the many advantages of grain legumes for sustainable development, their place in European agriculture and agricultural policies is still limited. Globally, grain legumes are grown on about 196 million hectares (production of 268 Mt/year) with 37% of this area in Asia, 18% in Africa and 24% in South America (FAO STAT). The area dedicated to grain legumes in the EU (2.2 million hectares with a production of 5.9 Mt/year) representing between 1% and 7% of the arable crop area, that is sown with grain legumes in European countries (Von Richthofen and

GL-Pro partners, 2006). This is very low compared to Brazil (44%), USA (32%), India (18%), Canada (13%) and Australia (9%), (Schneider, 2008). With 1,652,000 ha of grain legumes, France contributes about 33% of the total grain legumes production of EU. The main types of grain legumes grown in France are peas and fababeans. Peas contribute 60% of the total production of grain legumes, with 475,000 tonnes, while fababeans contribute 39%, with 316,000 tonnes. Lupins contribute only a small volume of 9600 tonnes as given in Table 1.1 (UNIP, 2009). Figure 1.2 shows the evolution of area grown with peas, fababeans, and lupins in France between 2002 and 2009 (UNIP, 2009).

Table 1.1: Distribution of surface area and production of the main grain legumes in France.

Grain legume	Surface (1000 ha)	Production (1000 tonnes)
Peas	101000	475000
Fababean	61000	316000
Lupins	3200	9600

Source: UNIP, 2009

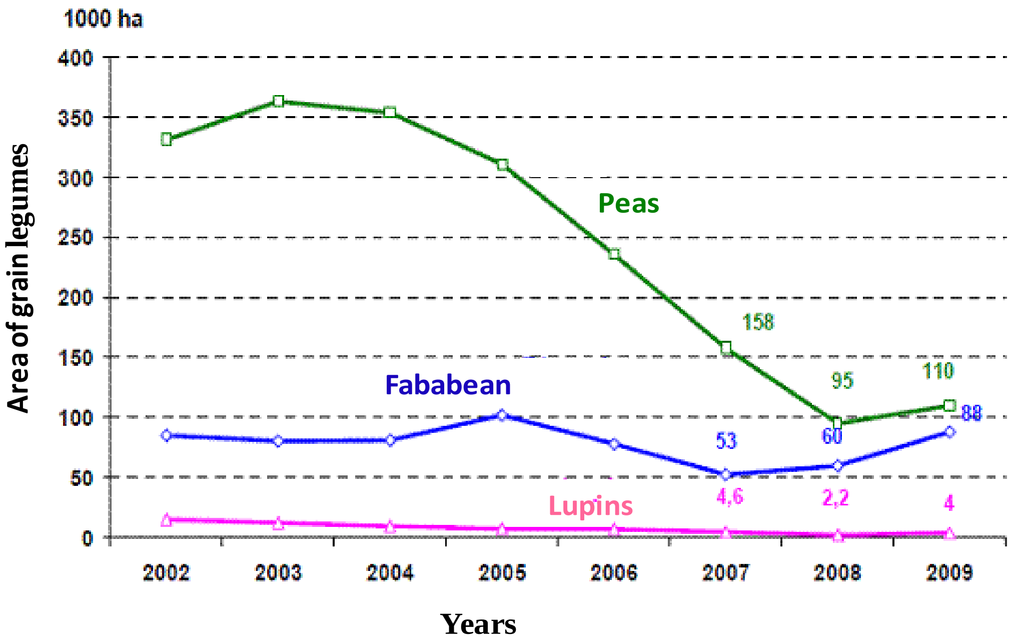

Figure 1.2: Evolution of area grown with the main grain legumes in France (Source: UNIP, 2009).

In the MP region, the grain legumes area varies between 1 to 3 % of the total cultivated area (Agreste, 2009) whereas the potential of these crops is estimated to be 15 to 25% (GL-Pro partners, 2007). Moreover, there is a considerable deficiency in Europe of protein-rich raw material, used for animal feed. Over 75% of Europe's requirements are imported every year to cope with this deficiency (Nemecek et al., 2008) which is equivalent to 35 million tonnes of soyabean meal (UNIP, 2009). It is therefore, important to assess the factors influencing the cultivation of grain legumes and to assess strategies to improve and develop this sector. For this purpose, we considered the MP region as a test case region. This region was selected on the basis of many distinctive features, e.g. i) First French region in terms of both number of farms (47,451) and agricultural area (2,540,000 ha); ii) Most of the EU arable crops are cultivated in a wide range of biophysical conditions: cereals (durum wheat, soft wheat, maize, and barley), legumes (soyabeans, peas, fababeans) and oilseeds (sunflower and rape); iii) Small grain-legume area of total cultivated area (1-3 %) compared to cereals (29%), iv) experimental and farm survey data are available.

Hence, **the general objective of this thesis** is to identify the main conditions enabling the introduction of legumes in the current MP cropping systems, while covering the socio-economic, environmental and technical issues. From this general objective we have identified some **specific questions (objectives)** for this thesis:

1. What are the main technical, agronomic, climatic, and socio-economic constraints to the introduction of grain legumes into cereal-based cropping systems?
2. What are the new strategies (technological innovation and economic incentives) to increase the proportion of grain legumes in current cropping systems?
3. What are the economic and environmental impacts of those strategies in comparison with current cropping systems?

1.5. Methodological approach for conducting this study

Agriculture facilitates a link between socio-economic and natural environment and faces several problems to manage its multiple functions in a sustainable way (Ewert et al., 2009). Policy is considered as an important pillar to balance these multiple functions of agriculture and sustainable development. The efficacy of policy designs and their functioning can be improved by understating their possible impacts on agriculture and via agriculture on sustainable development. The complex issues of sustainability and sustainable development and impacts of policy changes can be addressed through Integrated Assessment and Modeling (IAM) (Harris, 2002). Over the last few decades much progress has been made in IAM for agriculture application. However, most of them are applicable only within the small range of its model components for answering some specific answers, such as IMAGE (Integrated Modeling of Global Environmental Change) (Bouwman et al., 2006), DICE and RICE (Regional Integrated model of Climate and the Economy (Nordhaus and Yang, 1996; Nordhaus, 1993), RAINS (Regional Air Pollution Information and Simulation model) (Amann et al., 1999). Moreover they have limited flexibility to extend the range of possible applications. Recently, in the SEAMLEES project (Van Ittersum et al., 2008) a framework (SEAMLESS-IF) was developed, in which it was tried to overcome some of the limitations of earlier IAM models. This framework integrates relationship and processes across disciplines and scales and support policy and technology design in combining the quantitative analysis with qualitative judgements and experiences (Therond et al., 2009; Ewert et al., 2009). The SEAMLESS-IF framework was built on the concept of systems analysis and enables flexible coupling of models and tools, as well as the extension of its models components through modularity (Adam, 2010; Donatelli et al., 2008). For example, the flexibility, modularity and possibility of further extension in the current list of components make the APES component of the framework, a special model that can be used for large number of crops and crop rotations in wide range of biophysical conditions. These particular features of APES make us possible to develop a new pea module, which was not already present in this model. Scenarios based approaches and their assessments through a set of indicators are increasingly applied in IAM (Belhouchette et al., 2010; Sharma and Norton, 2005; Van Ittersum et al., 2008). In this study we used the scenarios and indicators based approach of SEAMLESS at regional level, using the APES-FSSIM-Indicators modeling chain (Van Ittersum et al., 2008). This modeling chain allows *ex-ante* assessment of policies and innovations on the economic, social and environmental performance of farming systems in an EU region (Belhouchette et al., 2010). The limitations on time and data availability restricted us to consider only three representative arable farms types (Andersen et al., 2007) in a single region (Midi-Pyrénées) of France SEAMLESS-IF also includes a set of methods and approaches to support the different steps of integrated assessment of scenarios development, assessment and their analysis through sustainable indicators (Ewert et al., 2009; Therond et al., 2009). It comprises three main phases (Figure 1.3) which have been followed in this study.

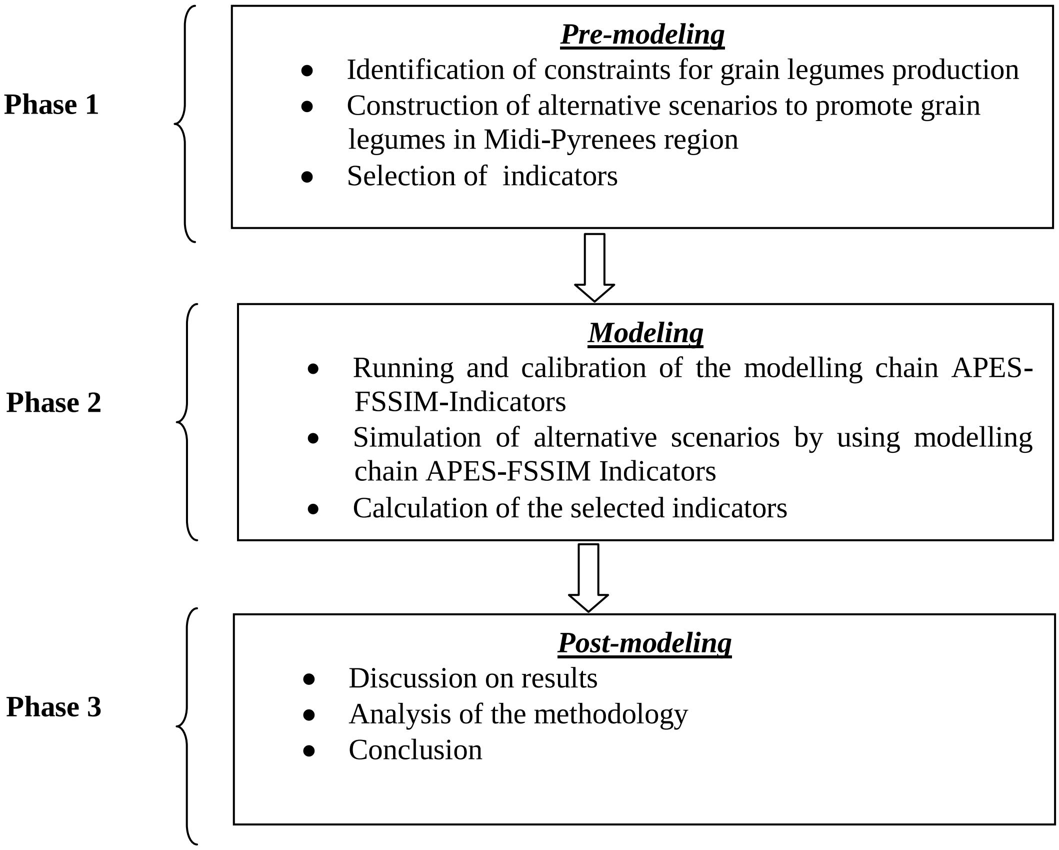

Figure 1.3 : An overview of the three phase's procedure for conducting this study.

1.5.1. Phase 1: Pre-modeling phase

This phase allowed us to:

i) Identify the main soil, climatic, technical, agronomic, and socio-economic constraints explaining the low area and farmers' lack of interest in growing grain legumes in the MP region. In this study, we drew on the knowledge of local experts to identify these constraints (For more detail see section 1.6)

ii) Propose a set of solutions, which can help in identifying the main conditions (alternative scenarios) for increasing the area of grain legumes in the region. For this purpose, different scenarios of technological innovation and policy changes, and their combination, are considered. These scenarios were identified through workshops and consultation with local experts (For more detail see chapter 3, section 3.2.2.4).

iii) Identify the list of environmental and economic indicators likely to reflect the impact of the above defined alternative scenarios at field and farm scale, i.e. whether these alternative scenarios, when compared to the reference scenario (current situation), would change the area of grain legumes as well as the economic and environmental indicators or not. In this study these indicators are selected to cover the range of advantages and disadvantages of cereal rotations with and without grain legumes (For more details see chapter 3, section 3.2.2.5)

1.5.2. Phase 2: Modeling phase

This phase deals with the simulation of reference (or baseline or current) as well as alternative scenarios and calculation of the selected indicators.

i) As described above the scenarios and their economic and environmental impacts have been assessed with the APES-FSSIM-Indicators modeling chain (Figure 1.4). The aim of using the first model (APES, at field scale) is to simulate the input and output variables of the main crops cultivated under a wide range of biophysical conditions **(**For more details see chapter 2, section 2.4). The goal of this step is to get for each activity (crop by rotation, technique and soil type) the input/output coefficient (yields and externalities) and to use them as input in the FSSIM model at farm level. The aim of using the FSSIM model is then to run the model for selected arable farm types in the region and to calculate the economic and environmental indicators at farm scale (For more details see chapter 3, section 3.3.1.4).

ii) All indicators were calculated and expressed at farm scale. The agronomic and environmental indicators were first calculated at field scale and then aggregated at farm scale (For more detail see chapter 3). The only exception concerns the total energy consumption, which has been calculated outside this modeling chain by using the INDIGO method of energy calculation as described by Pervanchon et al. (2002).

1.5.3. Phase 3: Post-modeling phase

This phase is made of:

- The analysis and discussion of the results of the scenarios simulation, in term of change in legumes area, cropping pattern and selected indicators. Secondly we analyse which alternative scenarios have an important impact and why some alternative scenarios did not have significant impact for change in legumes area as well as in the economic and environmental indicators (For more detail see chapter 3, section 3.3).
- The critical analysis of the methodology used to achieve the objectives of the study; whether all questions raised in the pre-modeling phase have been answered or not. In this part we also identified the stronger and weaker points of this methodology and how to improve them (For more details see chapter 4.2) and perspectives of this approach.

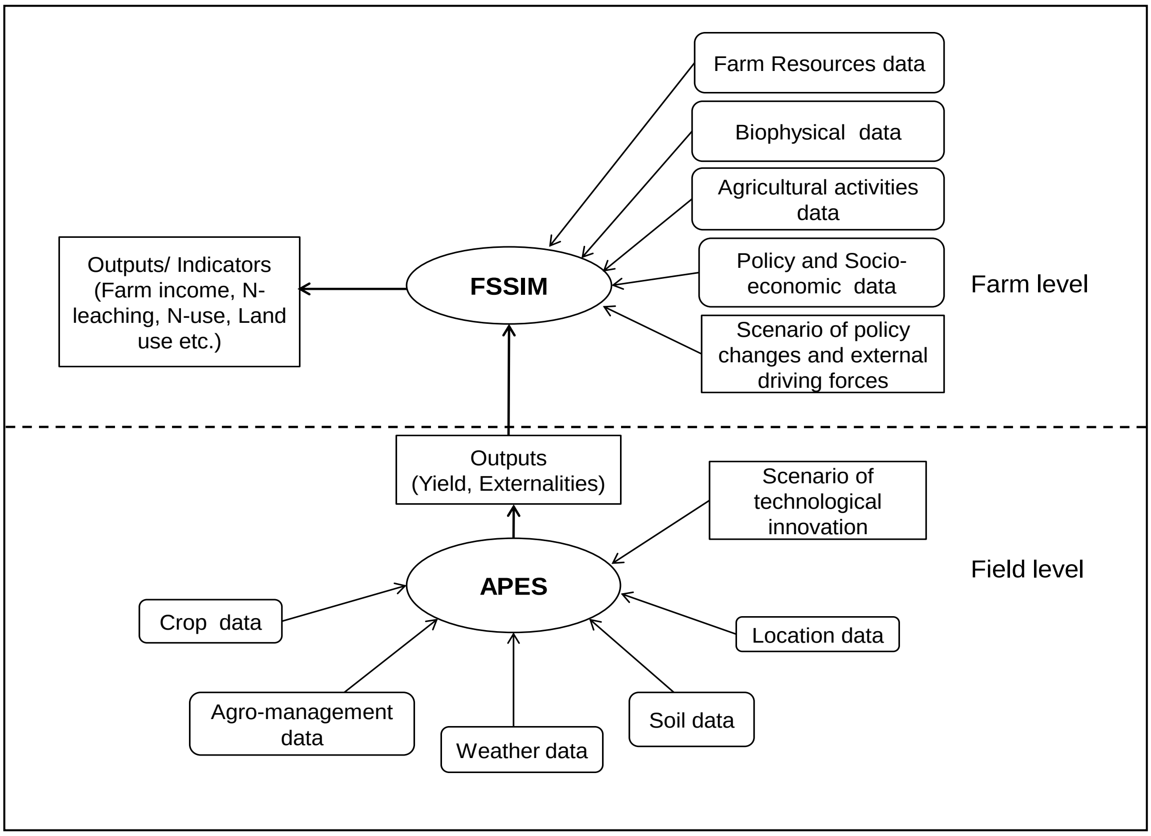

Figure 1.4 : Modelling chain APES-FSSIM-Indicators. *The principle of working with this modeling chain is to use the field experimental data in APES to generates the yield and externalities and use them in addition to farm and survey into FSSIM model to calculate the economic and environmental indicators at farm level. With this modeling chain, the scenarios of technological innovations and policy changes can also be simulated at field and farm scale respectively.*

1.6. Constraints concerning the production of grain legumes

1.6.1. Types of grain legumes considered in this study

This study considered only peas (*Pisum sativum*), fababeans (*Vicia faba*) and lupins (*Lupinus spp*), which are the major grain legumes cultivated in EU (Jezierny et al., 2010) and France (UNIP, 2009). Although, other grain legumes (soyabean, bean, lentil, chickpea) are also cultivated in France, their area is marginal (GL, Pro, 2005) and it was difficult to collect enough information on them with the regional experts. Generally, the experts confirmed that key constraints for fababean and soybean are almost the same.

1.6.2. Procedure for the identification of constraints for grain legumes production in the Midi Pyrénées region

Local expert knowledge has been used for the identification of constraints and limitations for grain legume production in the MP region. For this purpose four experts were identified from the study area (Table 1.2). The main agronomic, climatic, technical and socio-economic constraints for grain legume production were identified with the help of these experts.

Table 1.2 : Skills, expertise and functions of the identified experts.

Experts n°	Skills/Expertise	Function
1	Adviser for technical and inputs control	Agricultural adviser for the Ariège Agricultural department
2	- Implementation of the strategy work "Livestock and Environment" - Design of actions and individual services to help farmers to anticipate the regulatory requirements for the orientation of their farms	Head of Agronomy and Environment of Haute-Garonne Agricultural department
3	- Implementation and monitoring of experiments - Participation in the regional program for the development of cultivation techniques	Technical advice for the Gers Agricultural department
4	Expertise in growing conditions of pea, fababean and lupins	Researcher in the institute of plants (ARVALIS)

The identification of constraints with local experts was completed in two steps. In the first step we prepared a questionnaire (For more detail see Annex 1), which was sent to experts who were asked to complete it. The questionnaire contained questions such as:

- What are the main grain legumes crops suitable for the biophysical conditions of the region and on which soil types are those grain legumes cultivated?
- In which types of cereal rotations do farmers prefer to introduce grain legumes?
- What are the differences between rotations with grain legumes and rotations without grain legumes in terms of yield, input cost (fertilizer, pesticide), labour etc?
- What are the main biophysical, agro-environmental (soils, sensitivity to frost, pest and diseases, sensitivity to excess and deficit of water etc.) and technical (sowing, harvesting…) problems faced by farmers during both sowing seasons (spring and winter) of the main grain legumes?
- What are the main agro-environmental impacts (N leaching and soil erosion, soil fertility, organic matter, pesticide application, energy consumption) of grain legume cultivation in irrigated and rainfed climatic conditions with different soil types?
- What are the differences in cost of winter- and spring-sown legumes in terms of socio-economic indicators such as labour, irrigation, fertilisation and pesticide application etc.?

In this phase, we could not get the answers to all the questions in complete form, as most of the questions concerned the complex integrated impacts of soil types, legume type, growing season, etc. Therefore, the experts tried their best to answer the question in a simplified way as far as they could. They answered the questions by fully or partially completing the questionnaire, supplemented by e-mails with general information on grain legume cultivation and the technical, climatic, and socio-economic issues faced by farmers for growing grain legumes and their possible agro-environmental and socio-economic impacts in comparison with cereals. In the second step, we held specific telephone meetings with all the experts. The purpose of these meetings was to complete the remaining questions, clarify the responses of the questions in cases of any difficulty for us or for the experts. The answers of all these questions are compiled in following section in the form of climatic, soil types, technical and agronomic and economic constraints for grain legume production in the MP region.

1.6.3. Key constraints

1.6.3.1. Climate issues

Pea is the main grain legume cultivated in the EU (GL-Pro partners, 2007), in France (section 1.4) and in the MP region. One can find two types of peas according to their plantation timing (winter pea sown in October-November and spring pea sown in January-February). According to experts, peas are good cool-season alternative for regions not suited for growing soyabeans, because they are comparatively less frost sensitive and may tolerate low temperatures during germination and growth. This is also confirmed by Miller et al. (2002). Experts further reported that in MP the most suitable planting period for peas is December and January (early spring). This is because of the chances of heavy frost in October and November, but also because it helps to reduce disease pressure and lodging problem (compared to October sowing) and risk of yield loss due to high temperatures and drought during the grain formation stage (compared to February sowing).

Based on the plantation timing, fababean can also be classified into two types (spring fababean and winter fababean). According to experts, winter and spring fababean cannot tolerate the severe cold and frequent heat and drought conditions respectively. Thus the most suitable sowing period is December or January. This finding was also confirmed by Carrouée et al. (2003) and GL-Pro partners, (2007), who suggested planting of fababean in mid-December. For lupins we could not get information's from experts' concerning their climate issues.

1.6.3.2. Soil issues

The experts reported that pea and fababean are tolerant to calcareous soils with $CaCO_3$> 2%, while lupin is not suitable for such soils. They should not be grown on clay and limestone plateaux of the MP region with more than 2.5% limestone in the topsoil. In shallow soils, pea and lupin are more sensitive to drought as compared to fababean. Fababean is also more tolerant to waterlogged soils in winter, compared to pea and lupin.

1.6.3.3. Technical and agronomic issues

The experts reported that the lack of competitiveness with cereals and alternative break crops (e.g. rapeseed) are the major obstacles for grain legume production. According to the experts more technical skill and expertise are required for sowing and harvesting legumes, compared to cereals. For example, pea is characterized by a high tendency to lodging, so for sowing, it requires perfectly levelled soil with special equipment, which makes it more costly than other crops. Similarly, fababean seeds are very large (500-700 g per 1000 grains, which is 2-3 times the size of peas), which causes problems during drilling and harvesting, implying to adapt drills and combines. Carrouée et al. (2003) also reported the same technical problem (drill and combine adjustment) faced by farmers during the drilling and harvesting of fababean due to the large seed size. They also reported diseases as one of the major reasons, for the farmers lack of interest in growing grain legumes in the region e.g. Anthracnose (lupin), Botrytis fabae and Ascochyta (winter fababean), rust (spring fababean) and root disease of Aphanomyces (pea) (Gueguen et al, 2008).

1.6.3.4. Economic issues

The experts stated that the changes in agricultural policies (CAP reforms) are one of the major factors for farmers' lack of interest in cultivating grain legumes. According to a report of UNIP (2009), in France, the impact of CAP reforms on the evolution of grain legume area and production can be analyses in two main phases of agricultural policy changes (UNIP, 2009).

Developmental phase between 1981 and 1993: During this phase, the area under legumes grew very rapidly (Figure 1.5). The main driving force behind this growth was the establishment of an aid plan for the production of proteins intended to limit Europe's dependence on the major producers of soyabeans. The area of grain legumes peaked during this period at around 754,000 ha in 1993 (Figure 1.5) (UNIP, 2009). The main measures of this aid plan included the pro-active EU policy for protein and market standardization, i.e.

i) Provision of minimum price to farmers for growing peas, fababeans and lupins, and a subsidy for first users of these crops products in the animal feed supply chain.

ii) Provision of compensatory aid to adjust farmer's income, in case of fluctuating price of protein in the market.

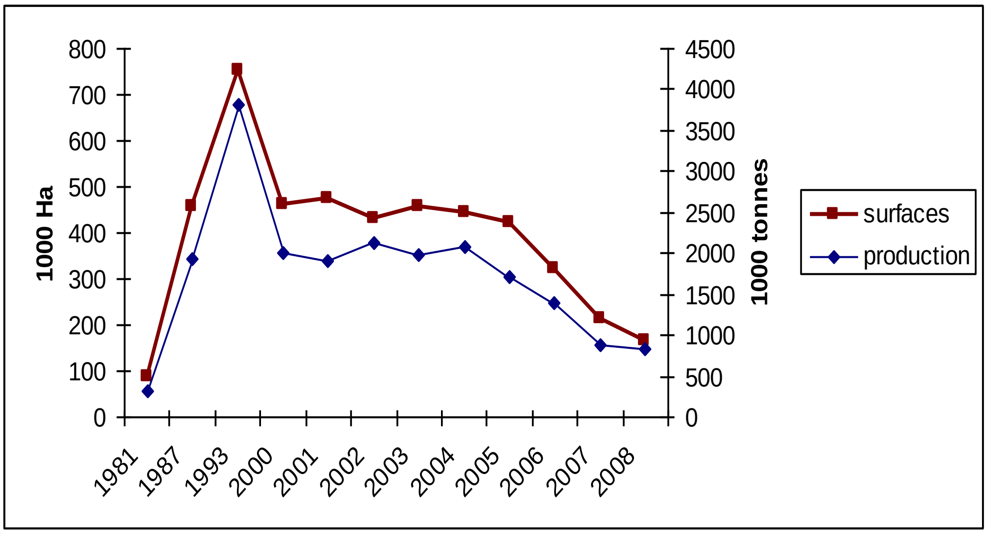

Figure 1.5 : Evolution of area and production of grain legumes in France between 1981 and 2008 (Source: UNIP, 2009).

Declining phase between 1993 and 2008: During this phase legume area began to decline slowly due to a price ratio[1], especially for compensatory payments. Although in 1998, a Maximum Guaranteed Quantity (MGQ) was fixed at 3.5 Mt for grain legumes, the CAP reform applied from 1st January 1993 (CAP reform 1992 called "Mac Sharry") changed the context: the guaranteed prices were reduced to bring them closer to market prices, especially for arable crops, and direct subsidies were applied with mandatory set-aside. Despite the aid, farmers' interest in growing grain legumes and income related to grain legumes decreased strongly in this context. After the 2003 CAP reform, aid to protein crops was aligned with grain production rather than area, changing from 72.5 €/ha in 2000 to 63 €/t in 2004. In addition, grain legumes also got a standard decoupled aid of 55.57 €/ha (Table 1.3). For this reason, a slight recovery in legume cropping area was observed in 2001, but this recovery was short-lived and cultivated area reached, in 2008, its lowest level since the 1980s (165,000 ha), with a 63% decrease between 2004 and 2008 (Table 1.3) (UNIP, 2009). The same trend of decrease in legumes area was also observed in the MP region (Figure 1.6).

[1] The Price Ratio serves a similar purpose to price comparison - it compares the performance of one stock relative to another (or to an index). Some traders use the Price Ratio as a general tool to select outperforming stocks.

Table 1.3 : Impact of evolution of CAP reforms on surface area of grain legumes in France (Source: UNIP, 2009).

Evolution of CAP reforms	Year	Evolution of grain legumes area (1000 ha)
Granted prices + aide for produers	1978	101
Direct aid for farmers (78.45 €/T)	1993	754
Direct aid for farmers (72.5 €/T)	2000	461
Direct aid (63 €/T) + Specific aid (55.57 €/T)	2004	445
Direct aid (63 €/T) + Specific aid (205.57 €/T)	2010	165

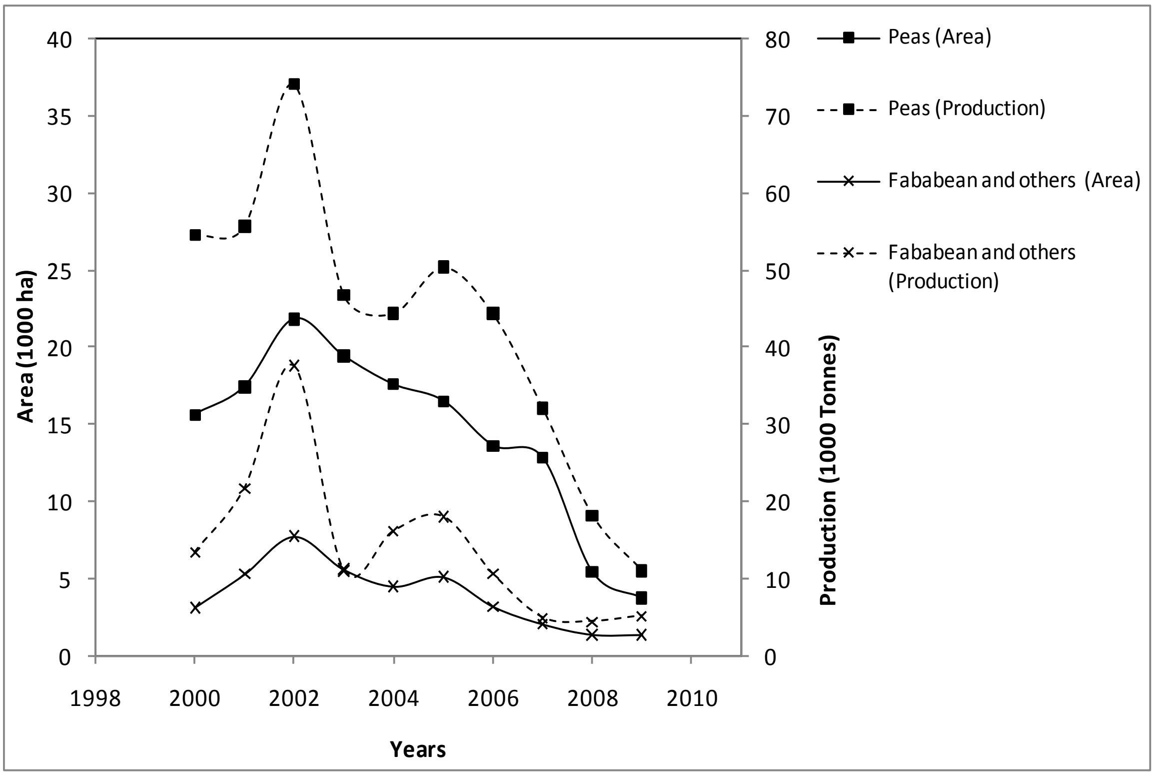

Figure 1.6 : Evolution of surface area and production of grain legumes in the Midi-Pyrenees region between 2000 and 2009 (Data from INRA Toulouse).

In addition to policy changes (lower aid after CAP reforms), the experts identified lower yield and sale price, risk of fluctuating yield and prices and higher cost of seeds as main constraints for grain legumes production, especially in the presence of other more profitable crops such as wheat. Von Richthofen et al. (2006) after a survey of 533 farmers in Europe and France, reported that lower market price, grain yield and the risk of yield fluctuations is also one of the major obstacle of legume cultivation. According to Jeuffroy and Ney (1997), wheat (*Triticum aestivum*) yields increased by 120 kg ha^{-1} per year from 1981 to 1996, while for peas it increased by only 75 kg ha^{-1} per year over the same period. Schneider (2008) also reported the same trend of increasing yield gaps for wheat and pea crops in France for the same period (Figure 1.7). This fact can also be explained by an example of a farmer in the Ariege department of MP region **(**Chambre d'Agriculture de l'Ariege, 2009). In 2009 that farmer received 300 €/ha of aid (CAP reforms 2003) for growing rainfed wheat and 356 €/ha for rainfed grain legumes (Chambre d'Agriculture de l'Ariege, 2009). At harvest, he obtained yields of both crops as 5 and 2.5 t/ha for wheat and peas respectively. He sold the product (grains) at market price of 180 €/t for wheat and 140 €/t for peas. For growing both crops he spent 459 and 481 €/ha for wheat and peas respectively (Table 1.4). At the end he observed that wheat is more profitable than peas, with a difference in income of 516 €/ha (= 741-225). To make pea competitive with wheat, this 516 €/ha can be compensated by increasing the premium, sale price or crop yield of peas crop. It is estimated that peas can be competitive only if it receives a premium of 872 €/ha instead of 356 €/ha, or market sale price must be increased from 140 to 346.5 €/t, or peas yield should be 6.19 t ha^{-1} instead of 2.5t ha^{-1}. Any of them could make the peas competitive with wheat but are not happening in the region.

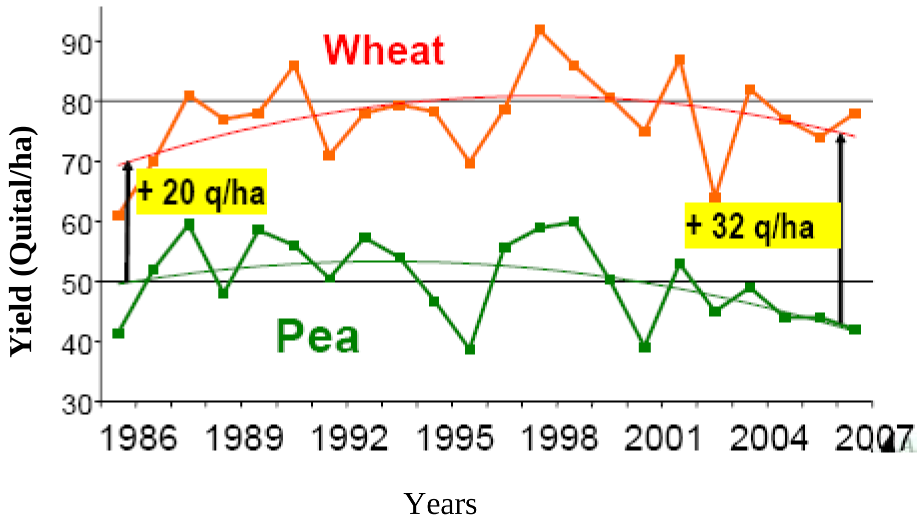

Figure 1.7: Increase in yield gap for wheat and peas crops over recent two decades (Schneider, 2008)

Table 1.4: Comparison of wheat and pea crops for different variables observed at farm (Chambre d'Agriculture de l'Ariege, 2009)

Variables	Crops	
	Wheat	Pea
Premium (€/ha)	300	356
sale price (€/t)	180	140
Yield (t/ha)	5	2.5
Total cost (€/ha)	459	481
Gross Margin (Price * yield) (€/ha)	900	350
Gross product (Premium + gross margin) (€/ha)	1200	706
Total income (Gross product - Cost) (€/ha)	741	225

1.7. Concluding remarks

Overall, this chapter illustrates that grain legumes have many specific and non-specific agronomic, economic, and environmental benefits, when they are gown in succession with non-legumes crops. The chapter also described the disadvantages of legumes-based cereal rotations in term of nitrate leaching, labour requirement and susceptibility to pest and diseases. The description of advantages and lower area of grain legumes in France as well as in MP region directed us in designing and identifying three specific objectives of the thesis. The review of literature helped us in selecting the SEAMLESS-IF modeling chain APES-FSSIM-Indicators, for its ability to conduct ex-ante assessment of policies and technological innovation on the socio-economic and environmental performance of farming systems (Belhouchette et al., 2010). Moreover the flexibility, modularity and possibility of further extension in the current list of crop components in the APES model and its ability for simulating the wide range of MP biophysical conditions lead to develop a new pea's crop module specific to this study (The detail description of this new pea module is given in chapter 2 and section 2.3). To fulfil the first objective of the thesis, this chapter also described the climatic, soil, technical, agronomic and economic constraints that prevent grain legumes promotion, identified with the help of local experts of the study area. It can be concluded that these constraints are the main driving forces behind the lack of farmer's interest in growing grain legumes on their farms and consequently the lower area of grain legumes in MP. These constrains helped us in identifying the alternative scenarios that could cope with these constrains and could help in promoting the grain legumes area in the study area. The type of alternative scenarios based on these constraints and the procedure for identifying these alternative scenarios are explained in chapter 3, section 3.2.2.4).

CHAPTER 2

THE APES MODEL AND ITS APPLICATION

Outlines of the chapter

This chapter deals with the first model (APES) in the modeling chain of APES-FSSIM-Indicators, which simulating production and externalities of various crop types and rotation at field level. It is divided into two main parts. Part 1 starts with the usefulness of crop models in simulating crop behaviour and the introduction of modularity in crop models for solving specific problems. This part also describes the APES model in detail, to justify our choice of this model for this study. Part 1 ends with our contribution in developing the pea module for this study and the main assumptions for adapting the wheat module into a pea module under the context of this study. Part II is a publication submitted to European Journal of Agronomy, which the application of the newly developed pea's module as well as the simulation results of other main crops cultivated under wide biophysical conditions of the study area. The aim of this work is to reproduce the input/output coefficients (yield and externalities) for use as input in the FSSIM model. An additional work has also been done for the global and dynamic evaluation of this model by using expert knowledge from local experts of the region. The purpose of this additional work was to see, if when no experimental data is available, is it possible to elicit expert knowledge in a model-compatible format, both for cumulative and dynamic variables, in order to use this "expert dataset" to evaluate a cropping system model at regional scale.

2.1. Crop models

A crop is defined as an "Aggregation of individual plant species grown in a unit area for an economic purpose". A model is a schematic representation of the conception of a system or a set of equations, which represents the behaviour of a system (Murthy, 2003). The progress in models during recent decades highlighted their usefulness for simulating, at field scale, the growth and development of crops under diverse conditions of soil, climate and management (e.g. CropSyst, Stockle et al., 2003; DSSAT, Jones et al., 2003; APSIM, McCown et al., 1996). Most of these models are designed to assess the impact of agricultural management on production activities in specific environments and operate only for a single comprehensive entity of soil, crop and climate (e.g. STICS, Brisson et al., 2003; EPIC, Sharpley and Williams, 1990). Mostly these models have a specific structure and they do not allow for easy plug-in of models for new agricultural production activities. Adam et al. (2010) and Donatelli et al. (2010) reported that it can be difficult to update such tools, especially for research groups and projects which have not developed them.

Models need to be constructed specifically for each research question (Passioura, 1996) and they should be as simple as the nature of their objectives allows, including only the degree of detail needed for those specific objectives and minimum data requirements (Sinclair and Seligman, 1996). It is possible to construct crop growth models for simulating specific problems (Adam et al., 2010), but modular crop modeling frameworks are necessary. Modularity in crop models makes it possible to include different components that can be combined in different ways according to the objective of the simulation, data availability, and type of cropping system, diverse biophysical conditions and management practices. Adam et al. (2010) reported that in a few existing crop models the modularity is achieved by a set of modules with different degrees of complexity for a specific crop or soil process based on the available input data;

2.2. Description of the APES model

The APES model was developed for the SEAMLESS project (Van Ittersum et al., 2008) as a part of the modeling framework to assess the agricultural and environmental policies and technological innovations in different EU regions. It is a dynamic soil-plant-atmosphere modular system and can simulate the behaviour of a large range of land-bound activities (arable crops, vineyards...) with interaction of various soils, climate and agro-technical management options (Adam, 2010; Therond et al., 2010; Donatelli et al., 2008). It is a tool for assessing the impact of management practices on crop production and environmental externalities. APES has the capability to simulate the soil-water budget, soil-plant nitrogen budget, crop phenology, crop canopy and root growth, biomass production and partitioning, crop yield, residue production and decomposition, and soil erosion (Adam, 2010; Therond et al., 2010; Mahmood et al., submitted). Outputs of this model include information on crop growth and development, yield and externalities such as nitrogen leaching, soil erosion and the fate of pesticides (Figure 2.1). It also has the ability to simulate different crop rotations which are generally assumed to be uniform in soil and climate characteristics and management practices (Therond et al., 2010).

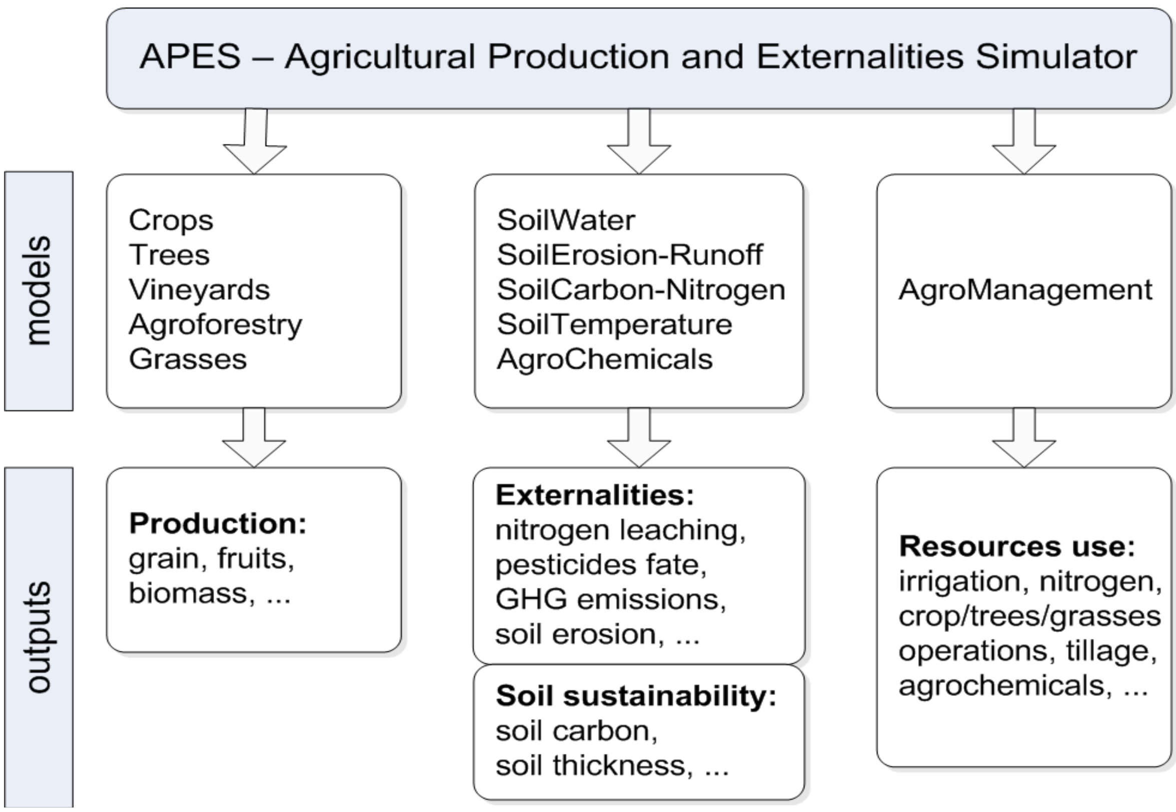

Figure 2.1 : Main typology and outputs of APES model (Donatelli et al., 2010)

The main novelty in this model is the modular programming approach used in the model's implementation (Adam, 2010; Donatelli et al., 2010). This feature renders the model flexible and modular. Moreover, APES has been designed with the possibility of further extending the current list of components, if required (Donatelli et al., 2010). The flexibility and modularity of the APES model makes it possible to develop a large range of modeling solutions (Adam, 2010) covering the various types of crop (e.g. legumes, oilseeds, cereals). For this purpose we had to select the best fit of modeling solution (MS) for specific applications, either already existing in the model or created specifically. There was previously no modeling solution for legume crops in this model. Due to the particular feature of APES modularity, we were able to develop, as a first step, a modeling solution for the pea crop in the context of this study. APES is made of two main groups of software units: the simulation engine which uses the modeling framework MODCOM (Hillyer et al., 2003) and the model components with a cross-component unit to compute mass balance (Donatelli et al. 2010).

2.2.1. Model component

A model component can be defined as a piece of software expressing a crop or soil process which is used to create a cropping system model (e.g. light interception, water uptake, soil water, soil N, soil C-N…). Model components can be further grouped into soil components, production enterprise components, weather components and agricultural management components. A component can contain many modules, which represent the specific conceptualization of a crop or soil process implemented within a component, e.g. Radiation Use Efficiency (RUE) for biomass production within the crop component, crop phenology (determinate vs. indeterminate), crop canopy dynamics (Leaf Area Index or LAI - expansion and senescence), dry matter production and partitioning according to the effects of stress factors, root growth etc. (Adam, 2010; Donatelli et al., 2010). Table 2.1 lists the current components and modules available in APES.

Flexibility in APES can be obtained by easily combining different components and modules which help in creating diverse modeling solutions according to the objective of the simulation and data availability. Each modeling solution (MS) is a combination of components to construct an effective simulation model for a given crop. All model components use the daily time step process for integration and communication across modules. Each component contains one or more alternative existing modules which can simulate a given crop processes (Donatelli et al., 2010) (Figure 2.2). Moreover, APES has been designed with the possibility of further extending the current list of components and modules when necessary (e.g. crop disease component, Salinari et al., 2008).

Table 2.1 : Components and modules available in APES (Adam, 2010).

Components	Modules Available
Light interception	- Homogenous - Pronk (Pronk et al., 2003)
Crop component	Phenology modules - Thermal time - Photothermal time - Photovernal time - Indeterminate phenology
	Leaf area expansion module - Biomass accumulation dependent (Spitters and Schapendonk, 1990)
	Dry matter production module - Radiation use efficiency (Monteith, 1977)
	Partitioning/allocation module - Predetermined allocation (Van Keulen and Seligman, 1987)
	Water dynamics module - Water stress index moderated with a drought tolerance parameter
	Nitrogen dynamics modules - Nitrogen stress based on the NNI approach (Lemaire , 1997; Shibu et al., 2010) - Nitrogen stress on RUE (Green , 1987) - Nitrogen stress on RUE and LAI (Vos et al., 2005)
Water uptake component	- Water uptake is defined by using parameters such as root conductance and leaf potential
Soil water component	Two water dynamics modules - Simple cascade approach - Richard’s equation approach
Nitrogen component (i.e. SoilN)	- Soil nitrogen available: nitrogen transformation process is driven only by water and temperature (Johnsson et al., 1987)
Soil CN component	- Soil nitrogen available. The role of soil microorganisms is represented in a mechanistic way through the mineralization-immobilization turnover processes during organic matter decomposition (Corbeels et al., 2005)

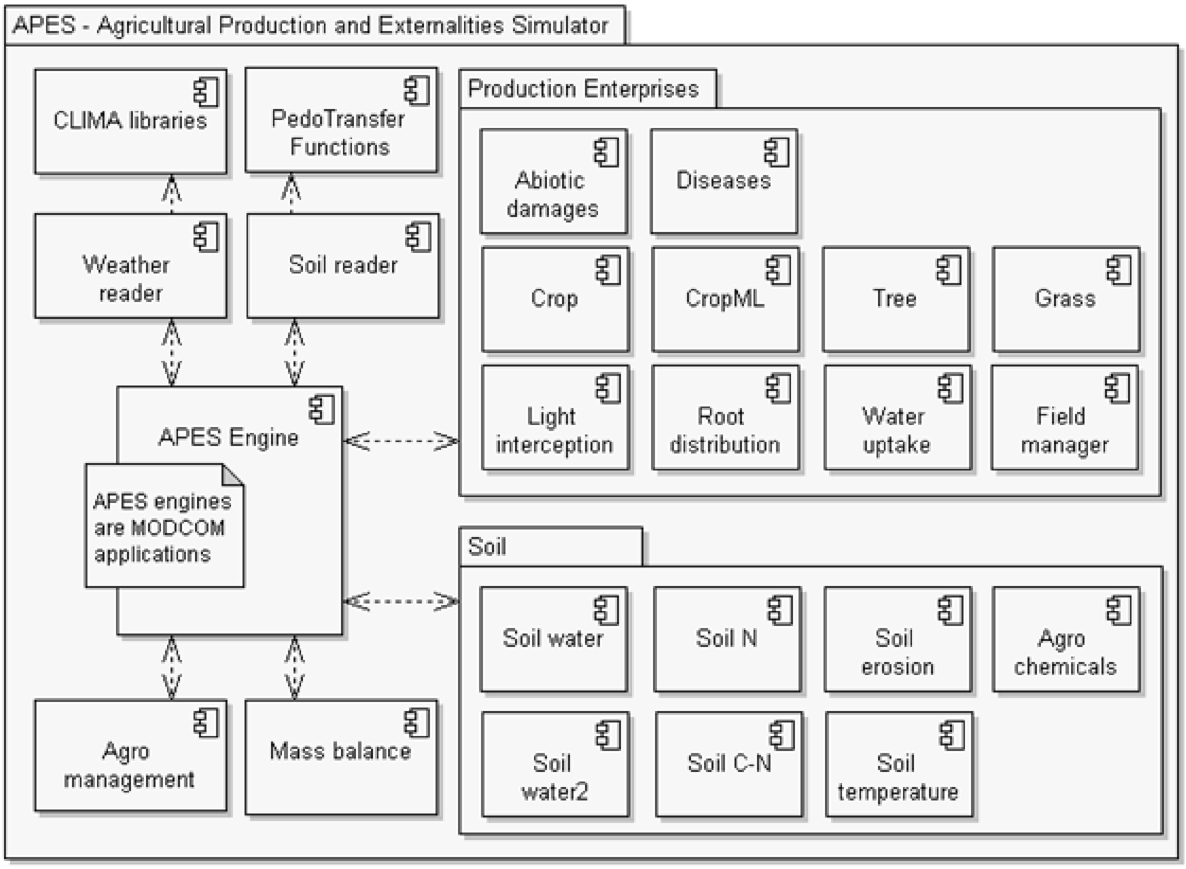

Figure 2.2 : The APES component used for composition. It shows that there are alternate options for simulating soil water, soil nitrogen, and crops; also, within each of the components there can be alternate approaches for simulating processes (Donatelli et al., 2010)

2.2.2. The MODCOM engine

The MODCOM engine is a software framework that facilitates the gathering of simulation models from previously and independently developed component models. It facilitates the exchange of data between model components (Van Evert and Lamaker, 2007). Data are exchanged between model components at a time step of one day; moreover, within each time step, the components can communicate up to three times. The model components can communicate within a time step, for instance to balance supply and demand calculated by two different components, which allow the estimation of actual rates in addition to the potential ones (e.g. for water and nitrogen uptake). For multiple calls within the time step it also allows the intercession of a source between two or more sinks. The fine granularity for different purposes is also shown for adequate accommodation of multiple software calls within a time step, that allow each component to be developed without any dependency on other components or on the modeling framework itself (Donatelli et al., 2010). The model components are linked through adapters to the MODCOM application which serves as the model engine (Figure 2.3).

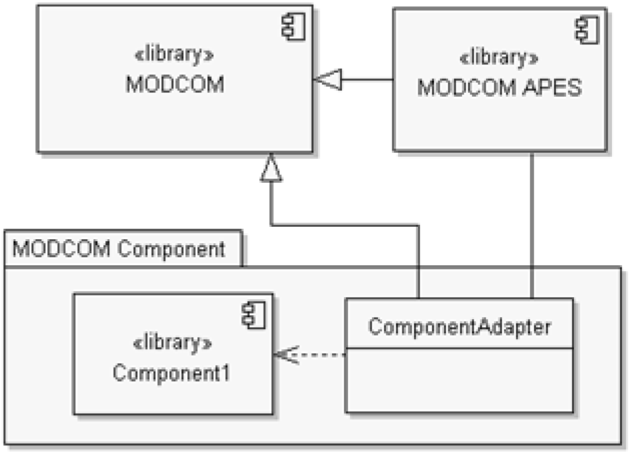

Figure 2.3 : Linkage of a generic component through the adapter pattern in APES applications using MODCOM (Donatelli et al., 2010)

2.3. My contribution in developing the APES model

By using the flexibility and modularity of the APES model, we developed the modeling solution for pea crop, in collaboration with Dr. Myriam ADAM of Wageningen University (Netherlands).

The modeling solution for pea crops was developed by transition of the wheat model (MS_{wheat}) into a pea model (MS_{pea}), following the protocol of Adam et al. (submitted). As a first step, agronomists with good knowledge of crop physiology based on the LINTUL3 model (Shibu et al., 2010) were identified, who helped us to understand the original modeling solution for wheat crops. We held workshops and discussions with crop physiologists, pea experts and legume specialists (e.g. J. Wery, J. Lecoeur, L. Guilioni and M.H. Jeuffroy) and a review of the literature was carried out. The exchange of that information resulted in the construction of a conceptual model for pea crops (Figure 2.4), following the protocol of Lamanda et al. (2011) for the conceptualisation of an agrosystem. For developing the pea conceptual model (Figure 2.4), we assumed that the green cover is homogeneous and we have only one big leaf, the area of this leaf being represented by the leaf area index (LAI). Crop development depends on thermal time and crop growth is based on the radiation interception by green leaf area and its conversion into dry matter. The model simulates both potential and attainable growth, as affected by water and nitrogen limitations. Dry matter and nitrogen are partitioned among the growing organs (storage, roots, stems, leaves) on the basis of partitioning tables with fixed parameters for each phase of the crop cycle.

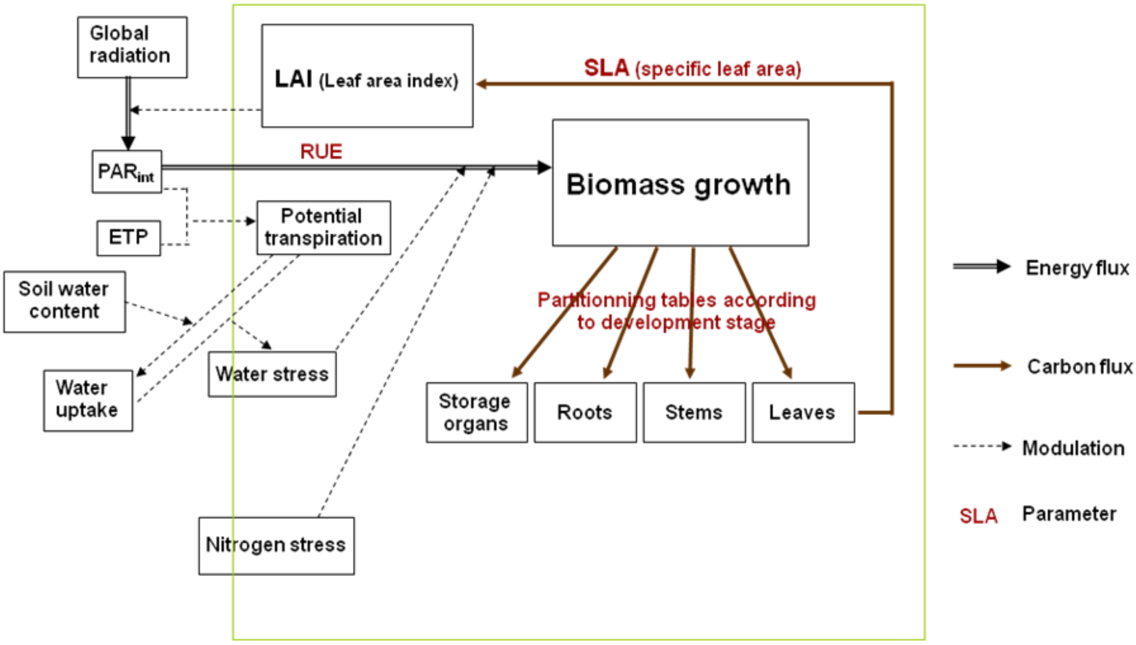

Figure 2.4 : The pea conceptual model in APES.

This conceptual model was then used to identify the modifications needed in the wheat MS to develop a new grain legumes MS, on the example of pea. With the help of the conceptual pea model and expert knowledge, we were able to identify the basic crop processes (Wery, 2005) that needed no change, minor change (i.e. parameter values, or equations) and addition or removal (i.e. as modules). This resulted in an adapted conceptual model, including the following main changes needed in the transition from MS_{wheat} to MS_{pea} :

- Changes in parameter values: different values for SLA (Specific Leaf Area) and RUE (Kaschuk et al., 2009), and modification of biomass allocation as a function of development stage.
- Changes within a module: addition of an equation to limit N uptake from the soil in legumes, compared to cereals (Wery, 1996).
- Changes in the overall structure of the model: addition of a N fixation module (Wery, 1996) and replacement of the phenology module (called indeterminate phenology)

with an indeterminate pattern (i.e. shortened flowering period due to temperature and water stress (Ney et al., 1994).

The evaluation of MS_{pea} was the final step before supplying it to the user. The targeted user of this MS_{pea} was our project. Zander et al. (2010) also tested this new MS by using the weather data for the growing season 2003-2006 from Montpellier, and expert knowledge data from Wery (1996) and Debaecke et al. (2006). Adam et al. (submitted) also tested this MS under potential and water-limited conditions.

2.3.1. Description of the APES crop component for pea

2.3.1.1. Crop phenology

The linear relationship between temperature and development rate has been widely recognized and it has been suggested that thermal units (the summation of daily mean temperature above a base temperature) can predict the phenological development of a crop (Slafer and Savin, 1991). Therefore the crop development, the order and rate of appearance of vegetative and reproductive organs, is determined in APES in terms of phenological developmental stage (DVS) as a function of the temperature sum, i.e. cumulative daily effective temperature[2], with a base temperature of 0 °C. The development stages range from 0 (emergence) to 2 (physiological maturity). The beginning of a stage occurs when the development stage variable reaches 0.7 for beginning of flowering, 1 for beginning of grain filling and 2 for maturity (Figure 2.5). The values of the development stage variable are calculated as the ratio of current temperature sum and the respective T_{sum} parameter, which are T_{sum} emergence, T_{sum} beginning of flowering, T_{sum} anthesis and T_{sum} maturity (Adam, 2010).

[2] Effective temperature of the day = Average temperature of the day – crop specific base Air Temperature.

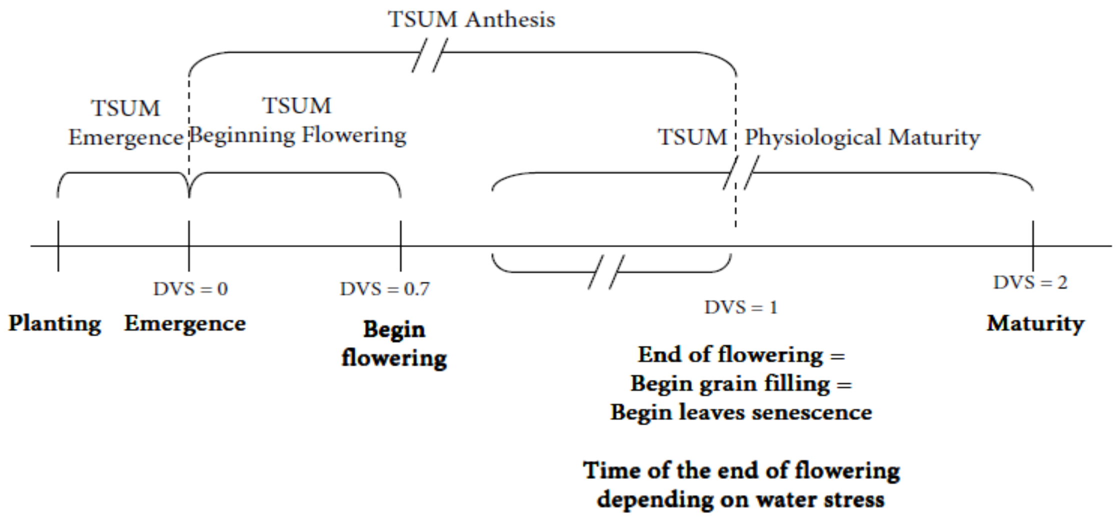

Figure 2.5 : Indeterminate phenology module for pea: representation of the development stages determined by temperature (T_{SUM}) and water stress.

The indeterminate behaviour of peas is affected by water stress (Ney et al., 1994): the length of the flowering period is shortened under water stress conditions considering the beginning of flowering as $T_{sumbeginningflower}$ and the end of flowering as $T_{sumanthesisws}$ (Figure 2.5). It is assumed that the daily water stress since emergence has an impact on the duration of the flowering period. The parameter of water stress impacts on flowering (WS_{impact}), which is the threshold value of water stress effects determines the flowering duration as follows:

If Water stress index j > WS_{impact}

Then $\Delta DS\ j = T°_{sum}\ j / T_{sum}$ beginning flowering (2.1)

But if Water stress index j < WS_{impact}

Then $\Delta DS\ j = T°_{sum}\ j / T_{sum}$ anthesis (2.2)

Where: Water stress index j is the water stress variable for the day j, calculated from the ratio W_{uptake}/W_{demand} (see Figure 14) (unitless), WS_{impact} is the parameter of water stress impact on flowering, ΔDS j is the increase of the development stage variable for the day j (unitless),$T°_{sum}$ is the increase of accumulation of effective temperature ($T°_{sum}$ j = average $T°_{sum}$ j – $T°_{base}$) (°C), Tsum beginning flowering is the thermal time required between emergence and beginning of flowering (°C.day), T_{sum} anthesis is the thermal time required between emergence and end of flowering in well-watered conditions (°C.day).

2.3.1.2. Leaf area development

The time course of leaf area index (LAI) is calculated in two phases: an initial exponential phase during the juvenile phase as a function of temperature and a linear phase, which is dependent on leaf biomass (Figure 2.6)

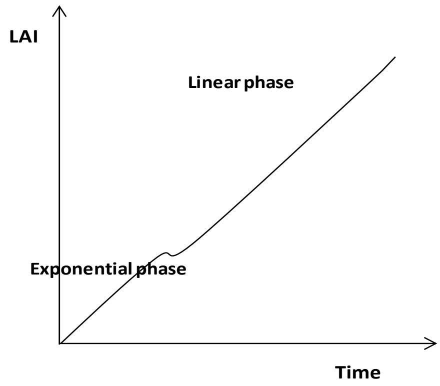

Figure 2.6 : Phases of leaf area development.

At the juvenile phase, growth is sink-limited, determined by the number of cells capable of expansion and their rates of expansion, which stops, somewhat arbitrarily, at development stage > 0.2 or LAI > 0.75. Following the juvenile stage, leaf area growth is assumed 'source-limited', and dependent on leaf weight growth rate and specific leaf area[3] (SLA) (Adam et al., 2010). Sink limitation may result from organ insufficiency to utilize assimilates, while source limitation is due to insufficient assimilate availability for potential organ growth or inability of the translocation system to deliver available assimilates due to long distance or translocation resistance or competition from other sinks (DeJong and Grossman, 1995). Leaf area growth rate during the exponential and source-limited growth stages are calculated as:

$$(dL_g/dt)_{exp} = L_g(t)\, L_r\, T_e \qquad (2.3)$$

$$(dL_g/dt)_{sl} = (dW/dt)_{lv}\, S_{la} \qquad (2.4)$$

Where: $(dLg/dt)_{exp}$ and $(dLg/dt)_{sl}$ are LAI growth rate ($m^2.m^{-2}.d^{-1}$) during the exponential and the source-limited growth stages respectively, $L_g(t)$ is the leaf area at time t (m^2), Lr (°Cd^{-1}) is the maximum relative growth rate of LAI, T_e is the daily effective temperature (°C), $(dW/dt)_{lv}$ is the dry matter growth of leaves ($g.m^{-2}.d^{-1}$), S_{la} is the specific leaf area (m^2.g1)

[3] SLA is the ratio of leaf area index on leaf dry matter, (SLA = LAI / Leaf dry matter). SLA depends upon the morphogenesis (shape and size of leaves) and production of carbon assimilates and can vary during the cycle of the crop (Lecoeur and Sinclair, 1996). However for the time being in APES, only a single value for this parameter is considered.

Finally death of leaves due to ontogenic senescence after anthesis, self shading and stress lead to loss in leaf area, and the net rate of change of leaf area is defined as the difference between growth rate and death rate of leaf area (Adam, 2010).

$$(dL/dt) = (dLg/dt) - (dLs/dt) \qquad (2.5)$$

"In APES senescence is a function of temperature only and it is specified by the following (x,y) pairs: (-10 , 0.03), (10 , 0.03), (15 , 0.04), (30 , 0.09), (50 , 0.09), where -10, 10, 15, 30 and 50 are temperatures and the values 0.03, 0.04 and 0.09 are the corresponding relative death rates due to senescence. Death of leaves due to senescence only occurs after anthesis, as indicated by $T_{sum} \geq T_{sum\text{-}anthesis}$" (Adam, 2010).

2.3.1.3. Dry matter production

In the APES model, as in all crop models (Brisson et al., 2006), dry matter production is based on the interception of radiation by green plant parts and its conversion into dry matter (Donatelli et al., 2008). The produced biomass is calculated as the product of PAR_{int}, RUE parameter and stress index (water and nitrogen stress) (Eq. 2.6). For legume crops, the nitrogen stress index is assumed to be null (Adam et al., submitted).

$$Biomass = PAR_{int} * RUE * Ws * Ns \qquad (2.6)$$

$$Biomass = PAR_{int} * RUE * Ws \quad \text{(For peas)}$$

Radiation interception (PAR_{int})

The intercepted photosynthetic active radiation (PAR_{int}) depends on incident solar radiation. The APES model calculates the daily value of the photosynthetic active radiation intercepted (PAR_{int}) by the classical Beer-Lambert equation (Eq. 2.7) (Monteith and Unsworth, 1990).

$$PAR_{int} = 1 - e^{-k.LAI} \qquad (2.7)$$

Where: k is the crop specific coefficient (coefficient of extinction) and LAI is the leaf area index

Radiation use efficiency (RUE)

RUE is regarded as a crop specific parameter. It serves to convert the intercepted photosynthetic active radiation (PARint) into plant biomass. The efficiency of conversion of absorbed light into biomass varies with time, light intensity, temperature and water availability (Schapendonk et al., 1998). Currently in APES these factors are not considered, RUE being modulated only by water stress (Eq. 2.8)

$$Biomass = PAR_{int} * RUE * (1- water_{stress}) \quad (2.8)$$

2.3.1.4. Dry matter allocation (partitioning)

In the APES model before anthesis, daily production of dry matter is partitioned to leaves, stems, roots and storage organs through a set of allocation tables (Boons-Prins et al., 1993) as a function of development stage. After anthesis, dry matter starts to accumulate mostly in the storage organs (i.e. grains in the case of the annual plants considered in this work). It is assumed that severe water stress will lead to increased allocation of dry matter to the roots, at the expense of allocation to the shoots (Adam, 2010).

$$(dW_i/dt) = P_{ci} * dW/dt \quad (2.9)$$

Where: (dW_i/dt) is the rate of growth (g $m^{-2}d^{-1}$) of the organ i and P_{ci} the biomass partitioning factor to organ i (e.g. roots, stems, leaves and storage organs).

2.3.1.5. Water-limited growth

Biomass production is modulated by the intensity of water stress (Eq. 2.8). The water stress index is calculated as a function of actual transpiration (T_a) (~water uptake) and the potential transpiration of the plant (T_{pot}) (~water demand). It varies from 0 (no water stress) to 1 (maximum water stress) (Figure 2.7). Water stress mainly affects the daily growth via an adjustment of the efficiency of light conversion (RUE) only above a given threshold level. This adjustment is made through a genotypic parameter that represents the ability of the species to resist drought. This parameter is called the drought tolerance factor (Dt). It is defined as the specific value of the ratio “water uptake over water demand”, below which the plant starts to suffer from water deficit (Adam, 2010; Donatelli et al., 2008). It is expressed as:

$$water_{stress} = 1 - \min(1, \frac{T_a}{T_{pot}} \times \frac{1}{D_t}) \quad (2.10)$$

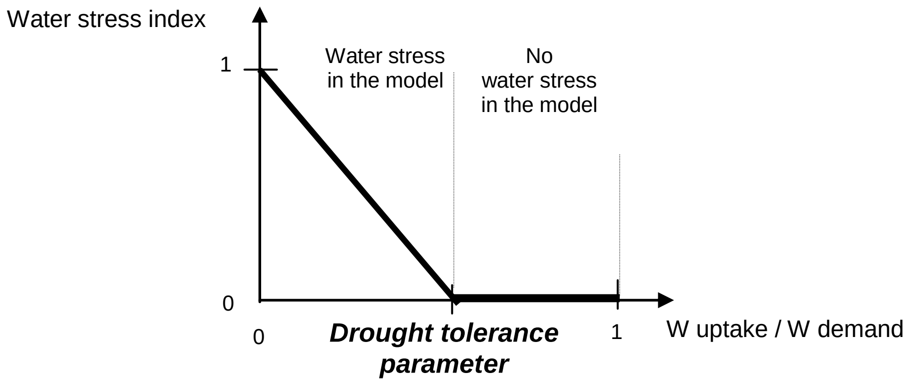

Figure 2.7 : Calculation of the Water stress index variable in APES crop component.

Potential transpiration (T_{pot})

On the basis of the penman equation (Penman, 1956), the potential transpiration is derived from the potential evapo-transpiration (for a reference crop) and the leaf area index is used to distinguish between potential soil evaporation and potential plant transpiration (Donatelli et al., 2005, Donatelli et al., 2008).

$$T_{pot} = ET_{ref} \ (1- \exp^{(-0.5\times LAI)}) \quad (2.11)$$

Where: T_{pot} is the potential transpiration in $mm.d^{-1}$, ET_{ref} is the reference evapotranspiration in mm d^{-1}, 1 take into account the soil and crop albedo, 0.5 takes into account the average extinction coefficient for visible and near infrared radiation as total radiation (rather than PAR) lead to evapotranspiration and LAI is the leaf area index in $m^2.m^{-2}$

Actual transpiration (T_a)

The actual transpiration is derived from the available soil water and the potential transpiration of the plant. The approach to calculate water uptake is based on soil volumetric water contents and fraction of roots in each layer. From plant water demand, APES estimates the local water in each soil layer proportional to the fraction of roots present in the soil layers which are assumed to be homogeneously distributed horizontally in the soil layers (Donatelli et al., 2008). The available water for the crop is the difference between current soil water content and soil water content at wilting point. If in a particular layer, available water exceeds from the local water demand then water uptake from that layer becomes equal to the water demands. However, if available water remains lower than local water demand, then the crop takes up all the water from that layer and unfulfilled demand is distributed to other soil layers. Finally, if crop could not get any more water from any layer then it results in water stress (Adam, 2010).

2.3.1.6. Nitrogen limited growth

It is assumed that nitrogen stress affects crop growth through a proportional reduction in leaf area growth, accelerated leaf senescence, and reduced biomass partitioning to leaves. Nitrogen availability affects photosynthesis by its impact on leaf area and photosynthetic capacity (Novoa and Loomis, 1981) as nitrogen is the major structural component of chlorophyll. In APES the nitrogen condition of the crop is assessed by the nitrogen nutrition index (NNI) ((Lemaire, 1997), which is defined as actual N concentration divided by critical N concentration. Critical crop nitrogen concentration is the lower limit of canopy nitrogen concentration in leaves and stems required for unrestricted growth and fixed to half the maximum nitrogen concentration (Jamieson et al., 1998). Crop experiences N stress when its N concentration in the above-ground part drops below a critical value for unrestricted growth. To calculate a nitrogen nutrition index for the plant as a whole, individual nitrogen concentration of plant organs are considered (Shibu et al., 2010).

Nitrogen demand

Total crop nitrogen demand (g m^{-2} d^{-1}) equals the sum of the nitrogen demands of the individual organs (excluding storage organs, for which nitrogen demand is met by translocation after anthesis from the other organs, i.e. roots, stems and leaves)[4]. Nitrogen demand of individual organs is calculated as the difference between potential and actual organ nitrogen content. Potential nitrogen content is derived from maximum nitrogen concentration in an organ, defined as a function of crop development stage. In the APES model the parameter $\Delta_{UptakeMassflow}$ determines the number of days needed for N uptake from the soil to satisfy the demand of each organ.

[4] Nitrogen demand of the grains (storage organs) is met exclusively by translocation from leaves, stems, and roots, as soon as grain growth starts. Total nitrogen available for translocation in the crop is equal to total nitrogen content of the organs (Ncontent g m^{-2}) minus their residual non-transferable nitrogen content, i.e. the nitrogen incorporated in structural crop components.

Nitrogen uptake

Plant nitrogen uptake is considered as the soil nitrogen supply. It is determined by crop N demand, indigenous soil nitrogen supply (from the carbon-nitrogen component) and fertilizer application and a time coefficient for nitrogen uptake. The time coefficient for nitrogen uptake represents the response time of the system. Mass flow and diffusion are the two major processes of nitrogen uptake by crops. Mass flow takes place with the transpiration stream and is defined as the product of transpiration rate and nitrogen concentration in soil water. Diffusion takes place when crop nitrogen demand cannot be met by mass flow, and when nitrogen is still available in the soil (Seligman et al., 1975). The daily rate of nitrogen uptake by diffusion is calculated as the residual demand after realizing mass flow and a time coefficient for nitrogen uptake by diffusion. Total nitrogen taken up by the crop through mass flow and diffusion is partitioned among the different organs in proportion to their demands Nitrogen uptake stops at anthesis, considering that nitrogen content in the vegetative parts hardly increases after anthesis in annual crops (Groot, 1987; Sinclair and Amir, 1992).

2.3.1.7. Nitrogen nutrition in peas

For developing the pea conceptual model for nitrogen nutrition, we made two assumptions:

i) Peas have a lower potential of N uptake than wheat and the amount of nitrogen demand not satisfied by the soil N uptake can be fulfilled by N_2 fixation.
ii) Peas demand more N from the soil in water-limited conditions than in well-watered conditions (as water stress reduces N fixation).

N fixation

Pea as a legume crop has the capability to supply a part of its nitrogen demand by biological fixation of atmospheric nitrogen. Daily nitrogen fixation is defined as the difference between daily crop nitrogen demand and daily nitrogen uptake from the soil. We assumed that N_2 fixation can fully meet the nitrogen requirements of peas if nitrogen uptake from the soil is insufficient.

$$Nfixed = Ndemand_{plant} - Ndemand_{soil} \tag{2.12}$$

Soil Nitrogen Uptake

It is assumed that peas have a lower potential of N uptake than wheat, which might be related to a lower fine root density in the surface soil layers (Gregory, 1998) and a lower activity of nitrate reductase (Wery, 1996). Similarly to water-limited crop growth, the nitrogen-limited crop model makes use of one soil layer that increases in depth when roots grow over time. It is assumed that peas demand more N from the soil in water-limited conditions as the proportion of N fixed by the plant decreases with increased water stress (Wery, 1996), which is translated as a reduction of coefficient k (Figure 2.8). We therefore adjusted the N demand of the plant to define the total N demand from the soil, by a reduction coefficient (i.e. k = 0.8 for peas). The increase in k under water stress reflects the higher nitrogen uptake from the soil by peas under dry conditions (Mahieu et al., 2009).

$$Ndemand_{soil} = K * Ndemand_{plant} \quad (2.13)$$

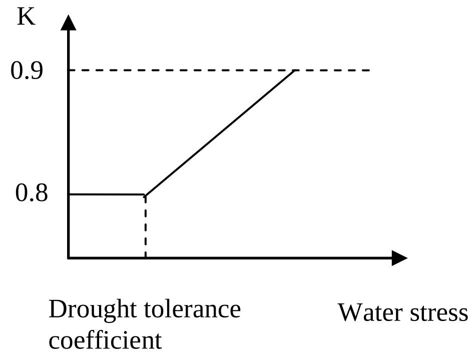

Figure 2.8 : Depiction of reduction coefficient (k) for N uptake dependent on water stress.

2.4. Using expert knowledge data to validate crop models on local situation data

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Abstract

Crop models are widely used tools for simulating the growth and development of crops at field scale. This requires testing crop models under diverse environmental conditions, often for large heterogeneous areas. It is however often difficult to satisfy their detailed input and output data requirements for a proper evaluation of the model prior to use for problem solving. Consequently other sources of information are needed and expert knowledge data is one such substantial source, especially when the model deals with a large range of crops. In this study, expert knowledge data were used as an alternative source to experimental data in order to obtain detailed input (on climate and management) and output data on cumulative and also dynamic variables. The model was first calibrated for the major crops of the study area (durum wheat, sunflower, maize, and pea) on real experimental data. Seven years of experimental data on crop growth and yield were used for this calibration. After this step, evaluation was achieved for the same crops by using expert knowledge data for more biophysical conditions.

The model evaluation results show that model successfully simulated the contrasted biophysical conditions in the Midi-Pyrénées region. Statistical analysis showed that the model accurately simulated above ground biomass and grain yield, with R^2 = 0.89 and 0.92 respectively. On the other hand the simulated results were less satisfactory for N uptake and cumulated evapotranspiration with a R^2 of 0.40 and 0.005 respectively. The model simulated cumulative variables more accurately than dynamic variables. The statistical analysis showed that for dynamic variables, model predicted the later phenological stages (physiological maturity) more accurately than the earlier ones (grain filling and flowering). The results of the study suggest that expert knowledge can be used to get the data for the important intermediate variables, rarely measured in experiments used for calibration (green LAI, actual evapotranspiration, rooting depth), in typical crop management conditions in the region. Moreover, expert knowledge data can also be used to predict the value of variables for a specific phenological stage of a crop cycle under various conditions of soil, climate and management practices, which is otherwise very difficult, expensive and time consuming with experiments. This approach can therefore enable a global and dynamic evaluation of cropping system models in case of unavailability of experimental data for large heterogeneous areas in a region.

Key words: APES model, expert knowledge data, cropping system model, dynamic model evaluation

2.4. Introduction

Cropping system models are useful tools for simulating, at field scale, the growth and development of crops under diverse conditions of soil, climate and management (e.g. CropSyst, Stockle et al., 2003; DSSAT, Jones et al., 2003; STICS, Brisson et al., 1998; APSIM, McCown et al., 1996; EPIC Williams et al., 1989). For such purposes, models should first be evaluated for their ability to simulate the key variables of crop phenology, growth, yield and water and N balances, using experimental data in the range of cropping conditions representative of the targeted use. Calibration and evaluation should be done on two different sets of independent experimental data (Power, 1993; Jorgensen, 1986; Shugart, 1984; Odum, 1983), in order to evaluate the model's performance in simulating the particular biophysical conditions (Poluektov, 1991). However, it is often difficult to find an independent set of data for model evaluation, i.e. data that have not been used for calibration (Stöckle et al., 2003). The main reason is that the observed data needed for model evaluation mainly require destructive observation that are usually time consuming and costly and so performed under limited soil, crop management and climate conditions.

In order to assess model performance in a large range of cropping conditions, two steps are usually followed (Belhouchette et al., 2010, Belhouchette et al., 2008, Oreskes et al., 1994) (i) first the crop model is calibrated with several dynamic and cumulative variables (yield, biomass, LAI, N-leaching…) but under limited cropping conditions, and then (ii) the crop model is validated for a wider range of cropping systems but usually only for crop yield which is the common variable measured in all crop experiments (Therond et al, 2010; Faivre et al., 2004; Van Ittersum et al., 2003; Jagtap and Jones, 2002; Bouman et al., 1996). In many studies dealing with cropping systems analysis at regional scale, i.e. covering a large range of crop, management, soil, and climate conditions (see for example Belhouchette et al., 2010), the input-output data used to describe cropping systems are obtained through farmers surveys, or existing regional databases (Clavel et al., 2011; Therond et al., 2010; Faivre et al., 2004; Middelkoop and Janssen, 1991). These sources of information have many drawbacks, e.g. (i) they lack detailed information on soil-climate conditions such as limited or unlimited water and nitrogen conditions, management practices (e.g. dates and rates of irrigation and fertilization) (Launay and Guérif, 2005); (ii) for surveys they require long and costly data collection (Biarnes et al., 2004); (iii) they do not take into account the interactive effects of soil, climate and management on output data and (iv) the cropping system performance is generally described only with cumulative variables, especially yield.

On the other hand, there are regional experts, who have detailed knowledge on the crop growing conditions in the region, their behaviour during crop cycle and their performances (Clavel et al., 2011). This knowledge, gained during years of field experiments, fields surveys and interactions with farmers is, most often, not expressed in term of input-output variables of a crop model (El Hajj et al., 2009). It is usually used for recommendations and extension services and not for input-output data for model evaluation.

The aim of our paper is to analyze if it is possible to elicit expert knowledge in a model-compatible format, both for cumulative and dynamic variables, in order to use this “expert dataset” to evaluate a cropping system model used at regional level. A specific protocol for this expert knowledge elicitation and its use for model evaluation has been developed and tested in the Midi-Pyrénées region (France).

2.4.1. Materials and methods

2.4.1.1. Description of the study area

The study area is in the Midi-Pyrenees region, in the south-west of France. It is the French region with the highest number of farms, with an agricultural area of 2 540 000 ha, mainly devoted to livestock and arable crops. In this study, we considered only the arable zone (Gers department), which accounts for approximately 40% of the cultivated area of the region (Belhouchette et al., 2010). In this zone a wide range of agronomic conditions including crops, soils, crop management, and weather (rainfall and temperature) can be observed. The main cultivated crops are cereals (durum wheat, soft wheat, maize and barley), legumes (soyabean, peas and fababean) and oilseeds (sunflower and canola). There are mainly two soil types (loam and clay loam), which can be further sub-divided into different types depending on the soil texture and depth. On loamy soil, the major crops are irrigated maize rotated with durum wheat, sunflower and peas, while on clay loam soil; the major crops are durum and soft wheat rotated with sunflower (Nolot and Debaeke, 2003).

The arable zone has a temperate climate with temperatures increasing from south-east to north-west, while rainfall and evapotranspiration increase from east to west. The the maximum irrigated area represents only 9% of the total cultivated area; consequently rainfed annual grain crops are predominant in the region (Louhichi et al., 2008). Long-term meteorological data indicate that the region is characterized by irregular and variable seasonal and yearly rainfall. The mean annual rainfall for the 1996-2002 period was 701 mm/yr (σ = 91 mm/yr). As a consequence, crop yields vary from year to year depending on weather, soil type, and water and nitrogen management (Belhouchette et al., 2010).

2.4.1.2. APES model

The APES (Agricultural Production and Externalities Simulator) model (Donatelli et al., 2010) was used for this study. It is a modular model developed within the SEAMLESS project (Van Ittersum et al., 2008), as part of a modeling chain enabling ex-ante impact assessment of agricultural and environmental policies and technological innovations in different EU regions. It is a multi-year, multi-crop, daily time step, simulation model used for estimating the biophysical behaviour of land-bound agricultural activities at field scale featuring a wide range of climate, soil and agro-technical management options (Donatelli et al., 2010). It can simulate soil-water budget, soil-plant nitrogen budget, crop phenology, crop canopy development, root growth, biomass production and partitioning, crop yield, soil erosion and soil carbon budget. It is a flexible and generic model which facilitates the adjustment of model structure depending on the simulation goal and can be adapted to different environments and management practices for a wide range of crops (Adam et al., 2010). In this study, due to these particular features, it was chosen because it enables the simulation of crop production, as observed in the study area, under a wide range of biophysical conditions (soil, rainfall), type of crops, land use or agro management systems (cereal, legume crops, and oil crops).

Model evaluation

The model was evaluated in two phases (Figure 2.9). In the first phase it was calibrated by using experimental data for the main crops (durum wheat, maize, sunflower, and peas) cultivated in the arable zone. In the second phase it was evaluated (for cumulative and dynamic variables) for the same crops but for more contrasted crop management and rainfall conditions by using data produced with an expert knowledge elicitation protocol.

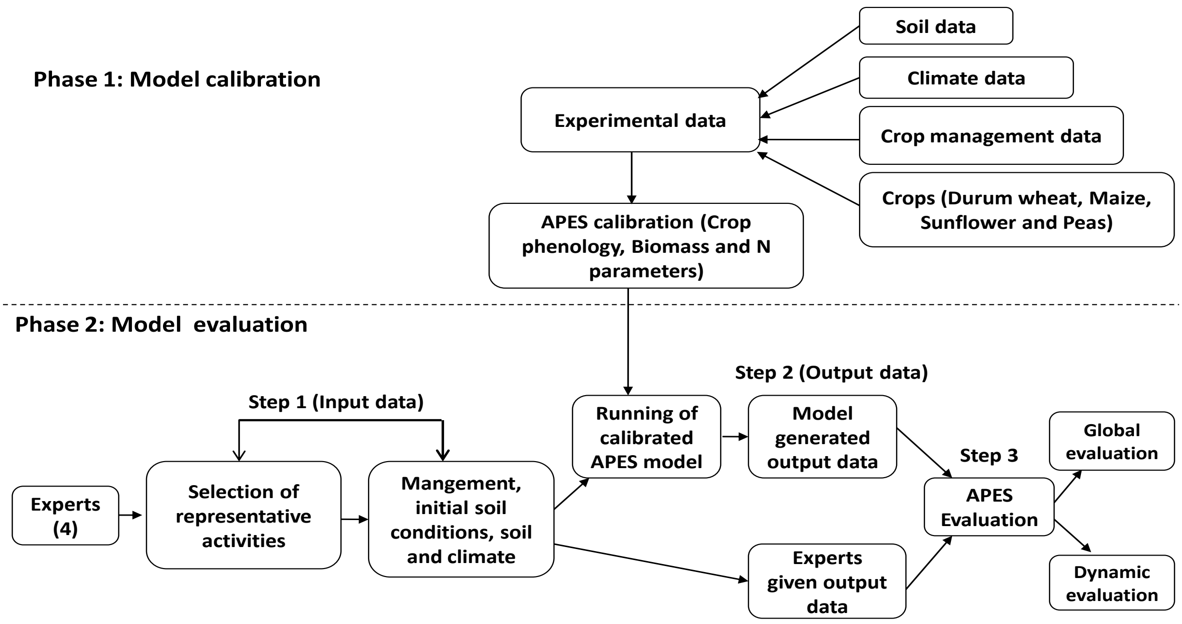

Figure 2.9 : Methodology for calibration and validation of the model; using experimental and expert knowledge data. *In Phase 1 the model was calibrated classically by using experimental data. In Phase 2, which is further divided into 3 steps, the global and dynamic evaluation of model was achieved by using expert knowledge d*ata.

Model calibration (Phase 1)

2.4.1.3. Experimental data

The cropping system experiment conducted by INRA in the region (Auzeville near Toulouse, latitude 43° 32’ N, longitude 1° 28’ E) between 1996 and 2002 (Nolot and Debaeke, 2003) was used to calibrate the APES model. We extracted the data for the major crops of the region, i.e. durum wheat (*Triticum durum*), sunflower (*Helianthus annuus*), maize (*Zea mays*) and pea (*Pisum sativum*). Soil samples were taken up to 1.5 m in depth before sowing in order to determine the initial soil moisture, soil mineral nitrogen (NO_3-N) and organic matter content. Soil texture in percentage of sand, silt and clay was measured for two layers i.e. 0-30 cm and for maximum depth of the soil. Two types of soils were identified; clay loam and loam, with organic matter content ranging from 0.8 to 1.41% for the 0-30cm soil layer (Table 2.2). Volumetric water content at wilting point (PWP) and field capacity (FC), and maximum bulk density (BD) were estimated from soil texture using the pedotransfer functions provided by SoilPAR (Acutis and Donatelli., 2003) (Table 2.2). The weather data concerning daily maximum and minimum temperature, precipitation, wind speed, global solar radiation and maximum and minimum relative air humidity were recorded at the experimental site. Management practices were described such as sowing and harvesting dates, dates and amounts of irrigation and fertilization. The key phenological stages such as emergence, flowering and maturity have been noted and grain yield, above ground biomass and above ground N uptake were measured at harvest (Table 2.3).

Table 2.2 : Experimental (INRA Toulouse) soil data used for calibration of the model on 1 meter soil depth

Soil Characteristics	Soil types (average value for all layers)	
	Clay loam	Loam
Sand (%)	26	35
Silt (%)	40	37
Clay (%)	34	28
Bulk density (g/cm^3)	1.3	1.3
Permanent wilting point (m^3/m^3)	0.19	0.16
Field capacity (m^3/m^3)	0.34	0.30
Organic matter (%)	1.34	1.41
Maxi. Depth (m)	0.95	0.94
Initial soil conditions		
Crops	Water content (m^3/m^3)	Nitrogen content (kg N/ha)
Durum wheat	0.34	22
Maize	0.23	15
Sunflower	0.38	9
Peas	0.34	18

Table 2.3 : Experimental crop data (INRA Toulouse) used for calibration of the APES model.

Crops	N*	Soil types		Management data					Output data					
				Sowing date	Fertilization (kg N/ha)		Irrigation (mm)		Above ground biomass (t/ha		Grain yield (t/ha)		Above ground N uptake (kg/ha)	
		Plots with clay loam soil	Plots with loam soil		Average	σ	Average	σ	Average	σ	Average	σ	Average	σ
Durum wheat	7	4	3	4-21 November	119	56	Rainfed	-	13.70	3.4	6	1.5	167	40
Maize	7	3	4	8-22 April	196	18	214	74	22.4	3	11	1	216	20
Sunflower	6	3	3	7-10 April	63	3	Rainfed	-	8.7	1.5	3.4	0.8	101	35
Peas	7	4	3	24 November and 1-10 December	0	-	50	3	7.5	0.7	3.4	0.6	196	14

2.4.1.4. Calibration procedure

First the model was calibrated for phenological stages of emergence, flowering and harvesting time by using the observed data. Then the model was calibrated for light interception, biomass production and nitrogen parameters to match the observed and simulated data of above ground biomass (AGB) grain yield and N uptake (Table 2.4). The values of all parameters were adjusted within a reasonable range of variation based on previous research and expert knowledge (Donatelli et al., 2002). In order to ensure a good correlation between observed and simulated data sets, the adjustment process was stopped when further modification of crop parameters values generate little or no change on the basis of the relative root mean square error (RRMSE) (Loague and Green, 1991).

$$\text{RRMSE} = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(Oi - Si)^2}}{\bar{O}i} \times 100$$

Where:

Si: simulated data, Oi: observed data, Ō: average observed data and n: observation number

Table 2.4 : Crop input parameters, which are fixed as default values in the APES model, or calibrated to match model output against observed data (*).

Parameters	Parameter values used in APES model			
Phenology	**Durum wheat**	**Maize**	**Sunflower**	**Peas**
Air Temperature Base (°C)	0	8	6	0
Air Temperature Sum Emergence (°C d)	146*	42*	68*	140*
Air Temperature Anthesis Sum (°C d)	510*	1185*	1100*	1380*
Air Temperature Begin of flowering Sum (°C d)	-	-	-	1050*
Air Temperature Ageing Sum (°C d)	510	1400	780	1380*
Air Temperature Maturity Sum (°C d)	800*	740*	700*	700*
Air Temperature Terminal Spikelet (°C d)	204*	-	-	-
Air Temperature Term Spik To Anthesis (°C d)	306*	-	-	-
Temperature Maximal Vernalization (°C)	10	-	-	-
Temperature Minimal Vernalization (°C)	3	-	-	-
Temperature Optimal Vernalization (°C)	5	-	-	-
Vern Day Max (d)	50	-	-	-
Biomass production				
Leaf Area Index Growth Rate Relative Exponential ($°Cd^{-1}$)	0.005	0.007*	0.009	0.0065*
LAI Critical ($m^2.m^{-2}$)	4	3	4	4
Specific Leaf Area ($cm^2.g^{-1}$)	0.018	0.018*	0.022	0.018*
Radiation Extinction Coefficient	0.6	0.48*	0.6	0.4*
Radiation Use Efficiency ($g.MJ^{-1}$)	2.7*	3.3	2.2*	1.8*
Drought Tolerance	0.25*	0.5	0.5	0.4*
Fraction Reallocated Leaves to SO	0.3	0.3	0.2*	0.4*
Fraction Reallocated Stems to SO	0.2	0.2	0.2	0.2
Nitrogen parameters				
Non Translocatable Residual N Concentrations Stem	0.0015	0.0015	0.0015	0.0015
Non Translocatable Residual N Concentrations Root	0.002	0.002	0.002	0.002
Translocation Fraction N Roots Total N Concentration	0.15	0.15	0.15	0.15
N Max Concentration Storage Organs	0.02	0.012*	0.012*	0.05
Fraction Max N Concentration Root from N Concentration Leaves	0.37	0.37	0.2*	0.37
Fraction Max N Concentration Stem from N Concentration Leaves	0.35	0.3*	0.3*	0.5
Time Coefficient N Uptake Mass flow (days)	3	3	3	3
Non Translocatable Residual N Concentrations Leaves	0.004	0.004	0.004	0.004
Translocation N Time Coefficient (days)	10	10	10	10
N Optimal Fraction	0.5	0.5	0.5	0.5

Model evaluation (Phase 2)

The model was evaluated for the same four crops (durum wheat, sunflower, peas and maize grain), under typical combinations of soil and management of the Midi-Pyrenees region, for specific type of climatic years. A 3-step evaluation protocol was defined and applied in interaction with four experts from the region (Table 2.5). The work with the experts was accomplished during a one-day workshop. It is assumed that, if experts are properly chosen, then this local knowledge is accurate and reliable enough to be used as a reference to which the model simulation are compared.

Table 2.5 : Skills and nature of expertise of experts and concerned crops.

Expert n°	Skills and Expertise	crop
1	Cereal and legume crops behaviour based mainly on various surveys	durum wheat
2	Crop behaviour based on various experiments generally conducted under real conditions	durum wheat, peas, sunflower
3	Sunflower behaviour based mainly on experiments	sunflower
4	Irrigated maize behavior based on experiments	maize

2.4.1.5. Input data (Step 1)

Selection of representative agricultural activities in the region

In order to represent the cropping system diversity of the arable zone (Gers department), the representative activities (i.e. combinations of crop, crop management and soil), as defined by Belhouchette et al. (2010) were selected by the experts. Initially three crop families, i.e. cereals; oils and proteins crops were identified. Then, the major crops of each family in the region were selected (Table 2.6). Each expert identified activities for which he had enough confidence to characterize them in terms of crop management and then of crop behavior (yield, biomass…).

Table 2.6 : Percentage area and production of major crops in each crop families.

Crop families	Major crops in each family	Area and production of major crop in each family	
		Area (%)	Production (%)
Cereal	Maize	32	16
	Durum wheat	16	12
Oil	Sunflower	72	68
Protein	Peas	43	52

Overall, twelve representative agricultural activities were selected (Table 2.7). These activities included the four crops (maize, durum wheat, sunflower, and peas), two soil types (loam and clay loam) and, except for maize, two climatic conditions (wet and dry year). Maize crop, being a summer crop, is cultivated under potential and limited water conditions. Durum wheat and sunflower are cultivated on both soil types, while peas and maize are cultivated only on loam soil (Table 2.7).

Crop management data

The experts also provided average crop management data, i.e. sowing dates and dates and amounts of fertilization and irrigation (Table 2.7) for each individual activity. The management data were specified by taking into account the soil type (clay loam, loam), year type for rainfed crops (wet, dry) and water condition (limited and unlimited) for maize. Expert identified recent real year that they have in mind, corresponding to the two year types (wet, dry).

Initial soil conditions, soil and climate data

The initial water and nitrogen conditions are difficult to measure and rarely assessed in experiments and farmers fields. They depend mainly on the previous crop in the rotation cycle, the capacity of the soil to retain water and nitrogen, the rainfall pattern during the intercropping period (Leenhardt et al., 2006). Consequently the initial soil conditions were fixed for each crop by soil type at the value used for calibration (Table 2.2). Each soil type was also described with the same parameters than in model calibration (Table 2.2). The weather data of the climatic year specified by each expert were provided by the local meteorological station (Table 2.7). We used daily values of rainfall, minimum and maximum temperature and minimum and maximum relative air humidity, solar radiation and wind speed.

Table 2.7: Typical agricultural activities selected by experts in the arable zone of the Midi-Pyrénées region.

Selected activities					Crop input data			Crop output data				Expert
					Management			Cumulative variables				
Crops	Soil types	Climate condition	Real year specified by experts	Activities	Average sowing date	Fertilization (Kg N/ha)	Irrigation (mm)	Above ground biomass (t/ha)	Grain yield (t/ha)	Above ground N uptake (kg/ha)	Actual accumulated evapotranspiration (mm)	
Durum wheat	Clay loam	Wet year	1996-1997	1	Ist Nov	200	Rainfed	15	7	220	400	1
		Dry year	2004-2005	2	Ist Dec	150	Rainfed	10	4.5	160	300	1
	Loam	Wet year	1997-1998	3	11-Nov	220	Rainfed	14	5.5	200	450	2
		Dry year	2002-2003	4	11-Nov	150	Rainfed	12	6	200	450	2
Peas	Loam	Wet year	2001-2002	5	15-Dec	0	Rainfed	10	4.5	250	250	2
		Dry year	2006-2007	6	15-Dec	0	90	10	5	250	245	2
Sunflower	Loam	Wet year	2002	7	20-Apr	50	Rainfed	9	3	150	450	2
		Dry year	2003	8	20-Apr	0	Rainfed	5.5	2.5	130	350	2
	Clay loam	Wet year	2008	9	15-Apr	60	Rainfed	8	3	125	450	3
		Dry year	2009	10	15-Apr	60	Rainfed	7	2.5	115	400	3
Maize	Loam	Unlimited water conditions	2009	11	20-Apr	200	240	22	11	260	580	4
		water limited conditions	2009	12	20-Apr	200	170	18	9	240	500	4

2.4.1.6. Output data (Step 2)

For each activity (crop by soil, climate and management type), each expert was also asked to fill specific tables and graphs for an imposed set of output variables of the model:

- Cumulative variables in the form of table: above ground biomass, grain yield, above ground N uptake and cumulated evapotranspiration at harvest (Table 2.7),

- Dynamic variables in the form of curves hand-drawn by the expert on a normalized grid: above ground biomass, leaf area index, above ground N uptake, cumulated evapotranspiration and rooting depth (see an example in Figure 2.10).

They had to provide these data before we run the APES model for the specific situation, in order to ensure that the expert elicited data are independent of the simulated data.

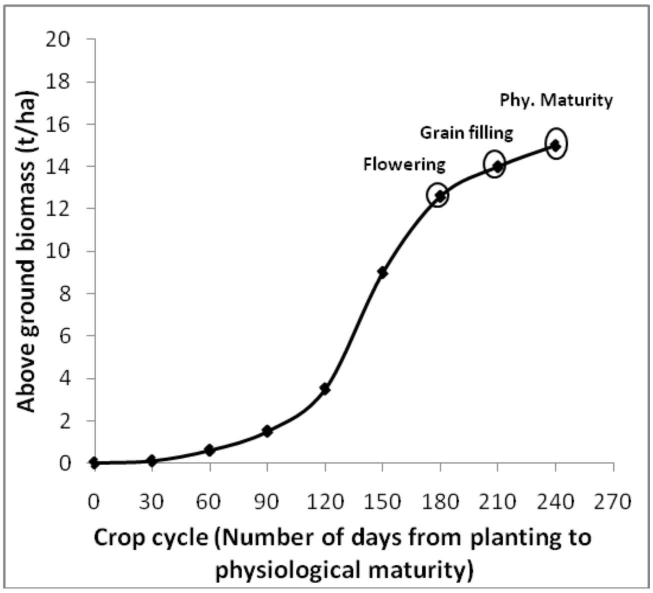

Figure 2.10 : An example of expert drawn dynamic curve for activity 1 (durum wheat cultivated on clay loam soil under wet climatic conditions).

The experts were allowed to communicate during the identification of the activities and the description of the input data, in order to ensure complimentary and consistency among the situations described as well as exchange of information on soils and climate. But they were not allowed to communicate during the description of the output variables, in order to avoid interactions in the way they expressed their results. After this process we then asked each expert to describe what was the approach he considered to draw the curves for the dynamic variables? We found that all the four experts used a similar approach: i) determines the number of days required to reach a specific stage of crop cycle, i.e. flowering, grain filling and physiological maturity; ii) determines the value of the cumulative variable at each phenological stage and mark it; iii) plot the curve between these mark points and the origin with a sigmoid type of curve.

2.4.1.7. Criteria for model evaluation (Step 3)

The method for global and dynamic model evaluation was also determined through discussions with the experts. For each activity, the APES model calibrated after Phase 1 (Figure 2.9) was run in Phase 2 (evaluation) using the input data collected in step 1. Simulated output data were then compared with the experts' output data derived from step 2, both for cumulative and dynamic variables. A global evaluation of the model, conducted on cumulative variables, was achieved by using R^2 (Loague and Green, 1991). The over and underestimation of simulated variables, compared to the expert values, were calculated by the coefficient of residual mass (CRM).

$$\text{CRM} \quad \frac{\left(\sum_{i=1}^{n} Oi - \sum_{i=1}^{n} Si \right)}{\sum_{i=1}^{n} Oi} \times 100$$

Where:

Si: simulated data, Oi: observed data

Wherever possible, simulated and expert data were evaluated by using other data provided by the literature for biophysical and management conditions similar to the simulated activity. The dynamic evaluation of the model, was done with dynamic variables (above ground biomass, green LAI, cumulated evapotranspiration, above ground N uptake and root depth) at key phenological stages (flowering, grain filling and physiological maturity).

2.4.2. Results

2.4.2.1. Model calibration

Statistical analysis shows that the model predicted well the crop phenology with a RRMSE ranging from 3% to 19% for all phenological stages, except for maize, for which the model predicted the crop emergence with less accuracy (RRMSE of 39%), (Table 2.8). The calibrated model also successfully simulated the above ground biomass, grain yield and N uptake for all crops of the experiment, with a RRMSE ranging from 6% to 15% for biomass, 8% to 14% for grain yield and 6% to 14% for N uptake. For the latter variable (N uptake), sunflower and pea were poorly simulated, with an RRMSE of 28% (Table 2.9).

Table 2.8 : Statistical analysis of the calibration results for phenological stages.

	Number of days for different phenological stages			
Crops	Number of plots	Planting-Emergence	Start of flowering-Start of grain filling	Start of grain filling - Phy. maturity
		RRMSE (%)	RRMSE (%)	RRMSE (%)
Durum wheat	6	3	1	12
Maize	6	39	3	19
Sunflower	5	19	6	3
Pea	6	4	8	5

Table 2.9 : Statistical analysis of the calibration results for above ground biomass, grain yield and above ground N uptake.

Crops	N	Variable	Ô	Ŝ	RRMSE (%)
Durum wheat	7	Above ground biomass (t/ha)	13.70	15.33	15
		Grain yield (t/ha)	5.98	6.44	14
		Above ground N uptake (kg/ha)	167	184	14
Maize	7	Above ground biomass (t/ha)	22.4	22.2	8
		Grain yield (t/ha)	11.08	10.64	8
		Above ground N uptake (kg/ha)	216	218	6
Sunflower	6	Above ground biomass (t/ha)	8.7	8.2	13
		Grain yield (t/ha)	3.4	3.1	14
		Above ground N uptake (kg/ha)	101	108	28
Pea	7	Above ground biomass (t/ha)	7.5	8.2	15
		Grain yield (t/ha)	3.4	3.5	13
		Above ground N uptake (kg/ha)	196	143	28

N: Number of plots, Ô: average observed value Ŝ: average simulated value, RRMSE: Relative root mean square error.

2.4.2.2. Model evaluation

- Cumulative variables

Above ground biomass (AGB) and grain yield

Figures 2.11 (a) and (b) show that the model simulated well the AGB and grain yield for all activities with a R^2 of 0.89 and 0.92 for AGB and grain yield respectively. All the data pairs are close to the 1:1 line and the activities with over or under-estimation are the same for grain yield and above ground biomass.

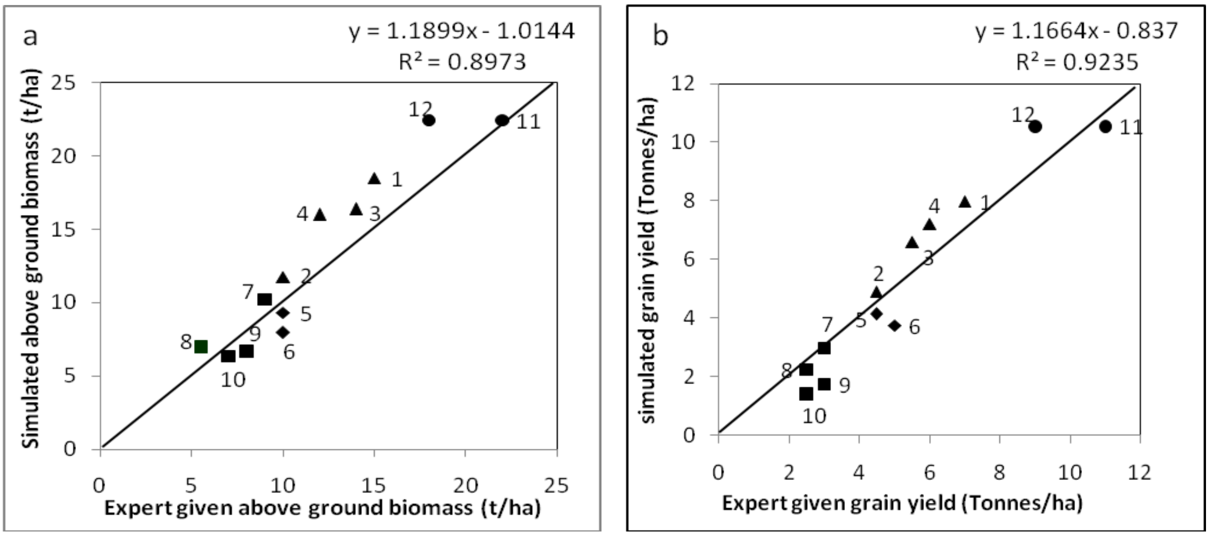

Figure 2.11 (a), (b): Correlation of simulated and experts' values for above ground biomass at harvest and grain yield respectively for all activities

Above ground N uptake

Statistical analysis shows that for all the activities, the model simulated N uptake less accurately (R^2 = 0.42) than for biomass and grain yield (Figure 2.12). Overall, the model underestimated N uptake with an average CRM value of 16% (Table 2.10). Figure 2.12 shows that most of the data pairs are close to the 1:1 line, except for activities 5, 6, 11, 12, for which the model significantly underestimated the N uptake with a CRM value of 28%, 40%, 32%, 35% respectively (data not shown). Those activities correspond to the pea crop (cultivated in loam soil under wet and dry conditions) and maize crop (cultivated in loam soil under unlimited and limited water conditions) respectively (Table 2.7).

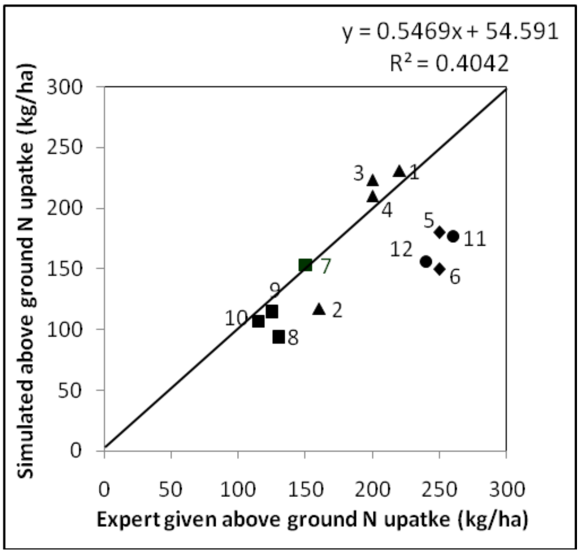

Figure 2.12 : Correlation of simulated and experts' values for above ground N uptake for all activities.

Table 2.10 : Statistical analysis of the model validation for cumulative variables.

Climate conditions	Activities	Variables	Ô	Ŝ	CRM (%)	R^2
Wet and dry together	12	Above ground biomass (t/ha)	12	13	-8	0.89
		Grain yield (t/ha)	5.29	5.33	-1	0.92
		Above ground N uptake (kg/ha)	191	159	16	0.40
		Actual accumulated evapotraspiration (mm)	402	339	15	0.005
Wet	6	Above ground biomass (t/ha)	13	14	-7	0.92
		Grain yield (t/ha)	5.66	5.66	0	0.93
		Above ground N uptake (kg/ha)	200	179	10	0.36
		Actual accumulated evapotraspiration (mm)	400	362	10	0.05
Dry	6	Above ground biomass (t/ha)	10	12	-20	0.90
		Grain yield (t/ha)	4.91	5.01	-2	0.94
		Above ground N uptake (kg/ha)	182	139	23	0.49
		Actual accumulated evapotraspiration (mm)	374	316	15	0.04

Cumulated evapotranspiration (ETC)

Statistical analysis showed a discrepancy between simulation and expert data for ETC with a very poor correlation of $R^2 = 0.005$. Most of the data pairs are far away from the 1:1 line (Figure 2.13). Overall the model underestimated the ETC with a CRM value of 15% (Table 2.10). As shown in figure 2.13, the model underestimated the ETC for all activities, except for activities 5 and 6, for which the model significantly over-estimated the ETC with a CRM value of 51% and 78% respectively (data not shown). Exclusion of these two activities significantly improved the correlation between simulated and expert data (R2 = 0.59), but the underestimation of ETC by the model remains at a high level (CRM = 25%).

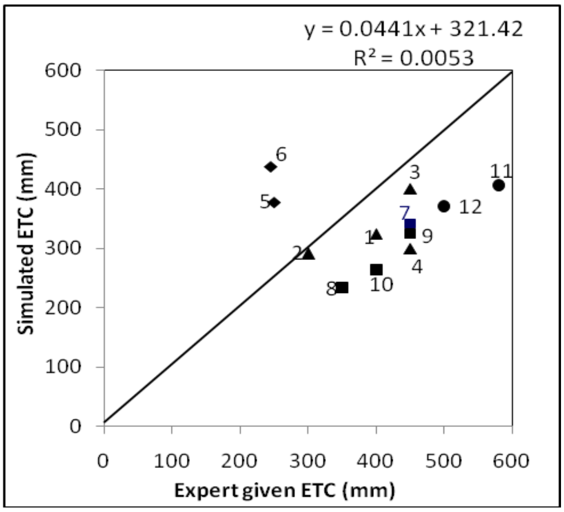

Figure 2.13 : Correlation of simulated and experts' values for cumulated evapotranspiration for all activities.

- Dynamic variables

The comparison of the simulated and experts' dynamic curves of above ground biomass, above ground N uptake, green leaf area index (LAI) and rooting depth show that in most of the activities both curves have the same shape throughout the crop cycle except for the cumulated evapotranspiration (ETC). For all the activities the difference between simulated and experts' curves are shown at key phenological stages (flowering, grain filling and physiological maturity) and the comparison was done by using R^2.

Above ground biomass (AGB)

The statistical analysis shows that the model simulate well the AGB dynamic in most of the activities with R^2 of 0.58, 0.70 and 0.93 for flowering, grain filling and physiological maturity respectively (Figure 2.14).

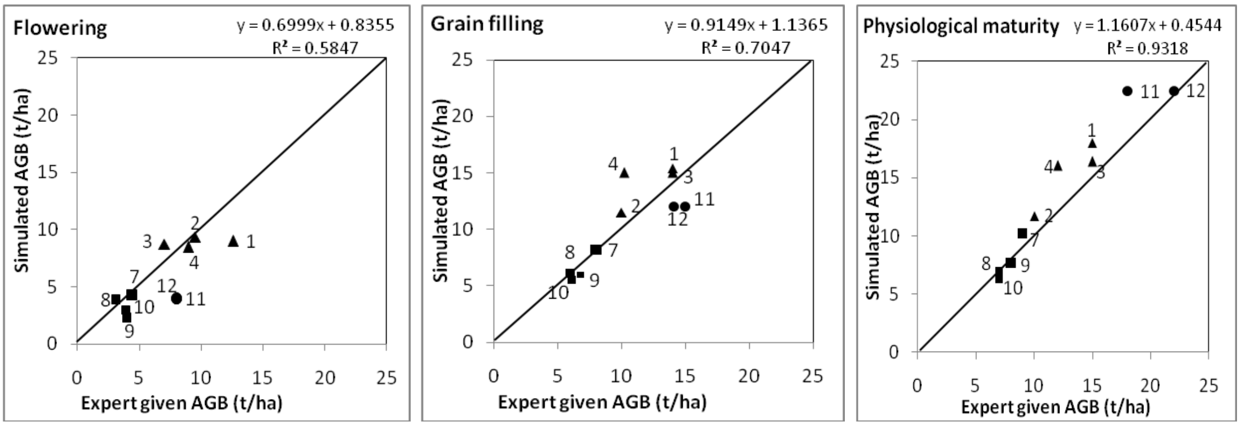

Figure 2.14 : Correlation of simulated and experts' values for the dynamic of AGB across different phenological stages.

Above ground N uptake

The model simulates N uptake with a lower R^2 than for AGB for all activities, with R^2 of 0.42, 0.51, 0.54 respectively for flowering, grain filling and physiological maturity stages (Figure 2.15). Overall, the model underestimates N uptake for all activities with a CRM value of 20% for all phenological stages. These results are consistent with cumulative evaluation of total N uptake, where model also underestimated the N uptake with CRM value of 16% for all activities. The underestimation was more pronounced at flowering (CRM = 31%) and decreased at grain filling (CRM = 19%) and physiological maturity (CRM = 10%).

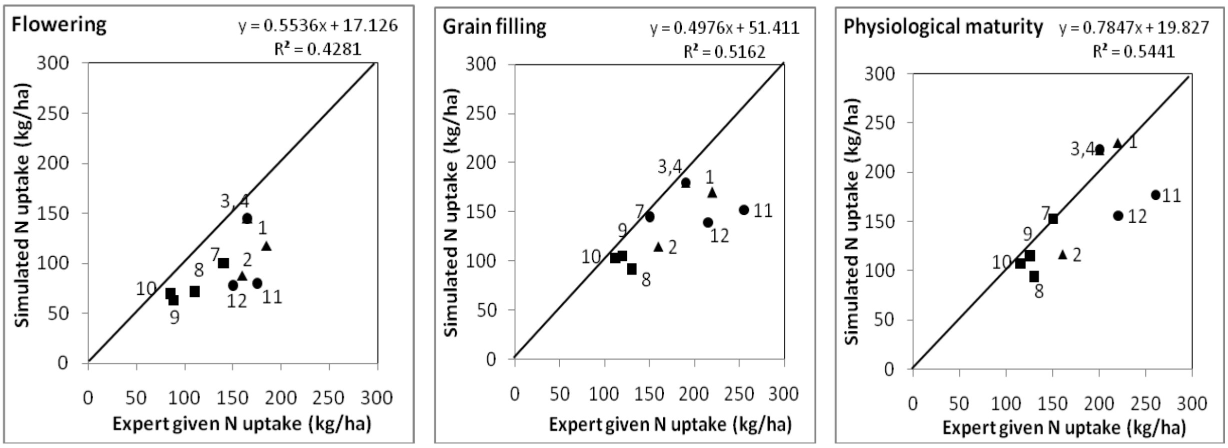

Figure 2.15 : Correlation of simulated and experts' values for the dynamic of N uptake across different phenological stages.

Green Leaf area index (LAI)

For all the activities, the model simulates well the LAI dynamic with a R^2 of 0.64, 0.87 respectively for flowering and grain filling stages. Most of the data pairs are close to the 1:1 line with a higher correlation at grain filling stage than at flowering (Figure 2.16).

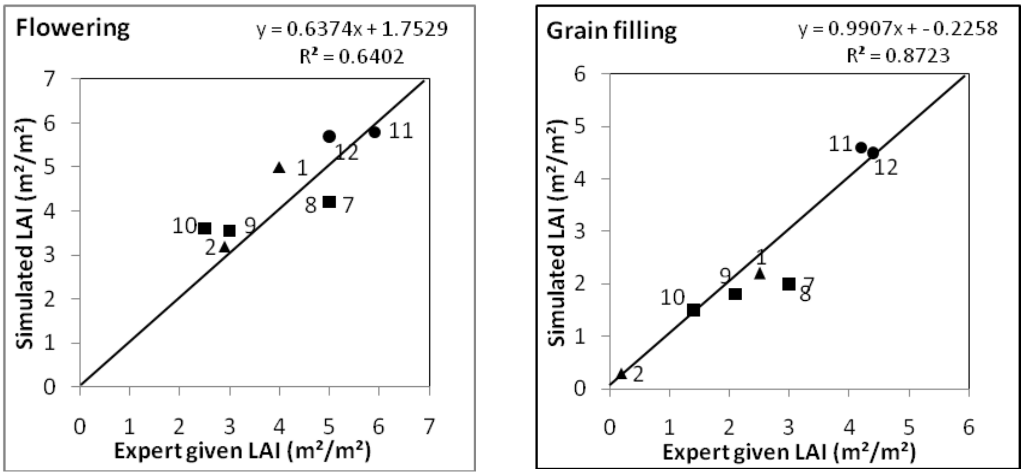

Figure 2.16 : Correlation of simulated and experts' values for the dynamic of LAI across different phenological stages.

Actual cumulated evapotranspiration (ETC)

A large difference was observed between simulated and experts' ETC curves. Statistical analysis showed that for all activities, the model simulated the ETC at all phenological stages with a non-significant R^2 of 0.05 and 0.13 at flowering and grain filling stages respectively

(Figure 2.17). However, a comparatively better correlation (R^2= 0.57) was observed at physiological maturity (Figure 2.17). In all activities, for all phenological stages, the model underestimated the ETC with a CRM value of 32%, but this underestimation was higher at flowering (CRM of 38%) than at grain filling (CRM of 33%) and physiological maturity (CRM of 25%). These results are very close to cumulative evaluation of cumulated evapotranspiration, where in most of the activities, the model also underestimated the ETC amounts with CRM value of 15%.

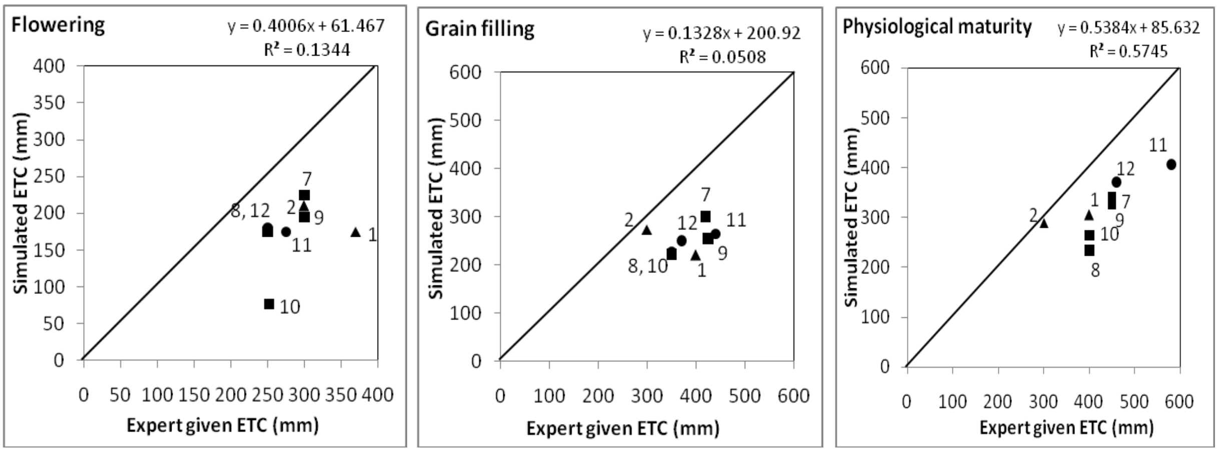

Figure 2.17: Correlation of simulated and experts' values for the dynamic of ETC across different phenological stages.

Rooting depth

The model simulates the rooting depth dynamic correctly at all phenological stages with a R^2 of 0.67, 0.68 and 0.70 respectively for flowering, grain filling and physiological maturity (Figure 2.18).

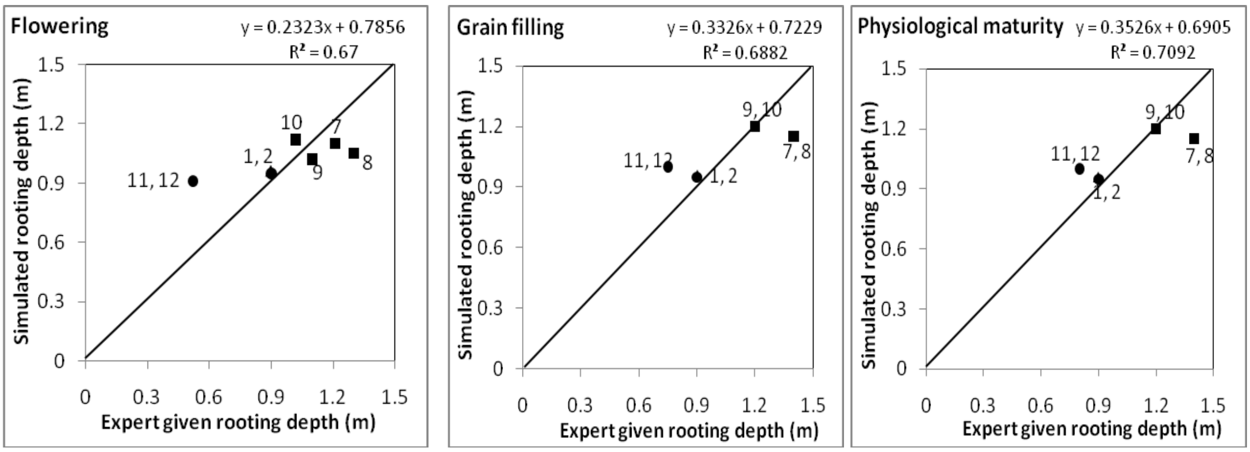

Figure 2.18 : Correlation of simulated and experts' values for the dynamic of rooting depth across different phenological stages.

2.4.3. Discussion

2.4.3.1. Model evaluation

Statistical analysis shows that the model accurately simulated the contrasted soil-climate-management combinations and the evaluation results were fairly satisfactory for cumulative as well as dynamic variables. The experts not only provided the input (management, climate) data for running the model but also the output data for cumulative and dynamic variables for model evaluation. However, we noted that some dynamic curves were missing, as experts felt that they were unable to plot the curves for some dynamic variables, i.e. green LAI, cumulated evapotranspiration, and root depth for durum wheat (activities 3 and 4) and all the curves for the peas crop (activities 5 and 6). The values of variables obtained with the experts' knowledge elicitation were considered as relative reference values and confronted to values published in other studies with similar biophysical conditions.

Statistical analysis shows that model simulated values were closer to the expert given values for grain yield and above ground biomass as compared to N uptake and cumulated evapotranspiration. The consistency of over and under-estimation of grain yield and above ground biomass for similar data pairs might be due to the fact that experts declared after filling the table that they were generally estimating grain yield for the given activity, then by using a typical crop harvest index, the above ground biomass.

The discrepancy between simulated and expert given N uptake was much higher for the pea and maize crops (activities 5, 6 and 11, 12 respectively). The simulated data for pea crop shows that total N uptake ranged from 150 to 180 kg/ha, which is lower than the average value of 250 kg/ha provided by experts. However, for similar environmental and biophysical conditions, Beck et al. (1991) reported a total N uptake of 161 kg/ha, which is more consistent with the simulated values and much lower than the expert given values. For maize crop, the simulated data showed a total N uptake ranging from 155 to 180 kg/ha which is systematically lower than the values provided by experts, which ranged from 240 to 260 kg/ha. In similar environmental and soil conditions, Kirda et al. (2005) and Gabriel and Quemada (2011) reported maize N uptake of 220-230 kg N ha^{-1} which is consistent with the experts values and much higher than the model output.

For all crops, the bad prediction of cumulated evapotranspiration was probably due to the model, as for similar environmental and soil conditions, the ETC values reported in literature are similar to the values given by the experts. For example Nolot and Debaeke (2003) reported average ETC of 560 mm for durum wheat, 715 mm for maize, 586 mm for sunflower and 562 mm for pea. Other studies also showed the same range of ETC for almost similar biophysical conditions, e.g. 444 to 570 mm for durum wheat, 483 to 660 mm for maize and 470 mm for sunflower (Calvet et al., 2008; Utset et al., 2004; Claude Mailhol et al., 1997; Ruget et al., 2002; Kirda et al., 2005). For all crops, except for pea these amounts are close to the value given by the experts. The underestimation of ETC by the APES model is consistent with the observation done by Adam et al. (2009) that the plant available water is usually underestimated in the APES model.

Global evaluation of cumulative variables for all activities showed that the model simulated wet climatic conditions relatively more accurately than dry ones. For all cumulative variables, the difference (CRM) between simulated and experts given variable values were higher for dry conditions as compared to wet conditions. Moreover this difference was more prominent for above ground biomass and N uptake (13%) as compared to grain yield and cumulated evapotranspiration, where the difference was less than 5% for wet and dry conditions. Adam et al. (2009) also found that APES is less sensitive to water stress conditions for above ground biomass and for its induced effect on N uptake.

Statistical analysis shows that same trend was observed for simulated and expert given dynamic curves of above ground biomass, LAI and rooting depth as compared to N uptake and cumulated evapotranspiration. For N uptake and ETC the simulated results were consistent with the simulated results of cumulative variables. Moreover, the better simulation of later stages (physiological maturity) of crop development than the earlier ones (flowering and grain filling) might be due to the fact that for drawing the dynamic curves for all variables the experts kept in their mind, the cumulative variable value at main phenological stages, which obviously resulted in better simulation of later stages (physiological maturity) of crop development than the earlier ones.

2.4.3.2. Methodology analysis

When looking for data to calibrate and evaluate the model, we found only one seven years dataset for four major crops in one location of the region (INRA experimental station in Toulouse) with several key crop variables measured at harvest and at some phenological stages (Nolot and Debaeke, 2003). These data were precious to conduct the necessary work of parameterization of crop specific parameters (Wallach et al., 2002). Now a day, for model-based assessment of agricultural systems in a region, it is a common practice to use the simplified regional data sets for the evaluation of the models (Therond et al., 2010, Leenhardt et al., 2006). However, these regional data focus mainly on yield and phenology, while local experts with a good knowledge of regional crops, soils and farms can provide not only the detailed input (climate, management) and output data but also the intermediate variables data of shoot and root growth and water and nitrogen balances. In this study we used the experts to build these datasets for the evaluation of the model. The initial soil water and nitrogen status was an exception because the experts were not able to provide them, but this type of data is rarely available anyway in regional databases also (Therond et al., 2010, Leenhardt et al., 2006). Moreover it was easier and less time consuming to get a complete data set for contrasted soil, crop, management and climatic combinations during a one day meeting with local experts, than from experimental network not aimed for model evaluation.

On the other hand, it is very important to identify the most widely-acknowledged, experienced and skilled experts from the study area. The interpretation and transformation of qualitative information into quantitative data, called defuzzification problem (Alcamo., 2008), is an important challenge when using experts' knowledge data. For example, the meaning of wet and dry year was found to be different for different experts. The experts considered a year wet and dry, when the average rainfall ranged respectively from 700 to 920 mm/year and 530 to 670 mm/year. It is well known that such assumptions on rainfall variation can affect crop growth and development differently. The key aspect of the approach (Figure 2.9) is the assumption that the data produced with expert knowledge can be considered as a reference for the model assessment. To ensure quality of expert data the protocol of elicitation of expert knowledge in a compatible form with the model input and output, included the following elements:

- the expert need to be as much as possible confident with the situations for which they provide the dynamic and cumulative variables. This is why, during the workshop, we left the experts select the crop, the climatic year, the soil and the crop management of the first situation they described. In a second phase we asked them to complete the datasets with contrasted situation representative of the region. The experts were asked to provide, on a 1 to 5 range, the confidence level for each variable in each situation. This information was difficult to use as most of the answers were in the 3-4 range and no curve or table value was provided by the experts when they were not confident enough with the variable, e.g. as in case of pea crop for dynamic curves.

- in order to ensure independence of the evaluation dataset, compared to the model, and also possibility of imposing the opinions and decisions of one expert on another (Koehler and Koontz, 2008), the experts were not allowed to use the model or to see simulation results with the model prior to the workshop when they provided the variables for the various situations.

- before simulation of the situations described by the experts we checked in the literature, when data on similar situations were available, that the values given by the experts were similar. As shown in the results we identified only two cases (N uptake and cumulated evapotranspiration in pea crop) where the expert provided data inconsistent with the literature.

2.4.4. Conclusion

This methodology is valuable for global and dynamic evaluation of cropping system models in case of unavailability of experimental data for typical crop-soil-management-climate conditions of a region. Often several regional experts are able to provide detailed knowledge on the crop growing conditions, their behaviour and performances during the crop cycle. This expert knowledge, which is generally used for recommendations and extension services can be elicited into model compatible format and can be used as input-output variables of a crop model. Local experts with a good knowledge of regional crops, soils and farms can not only provide the data for key cumulative variables but also the important intermediate variables (green LAI, actual evapotranspiration, and rooting depth) rarely measured in long term or multi-crops experiments. The results of the study show that if experts are properly chosen their local knowledge can be used as a reference for evaluation of the crop models.

Acknowledgement

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2.5. Concluding remarks

This chapter describes in detail the modifications have been considered for developing the pea crop module adapted from wheat crop module. Then the APES model was calibrated and evaluated for main crops (durum wheat, sunflower, maize, peas) cultivated in the study area. The evaluation results show that model can simulate well the growth and development of the crops with satisfactory results. In addition the model can also simulate well the variables of externalities (N leaching, soil erosion, water consumption…), which will be used as inputs in the FSSIM model (Chapter 3, section 3.2.2.1). At the biophysical part, all the diversity related to crops, crop varieties, climates, soil types, management practices, which can be observed in the region have not been considered due to the deficiency of experimental data. Some simplifications concerning the crops, soil type's management practices etc. were considered. The intensity of these simplifications was based on the availability of the experimental data, minimum data on activities, which is sufficient to proceed to the next step.

CHAPTER 3

MODELING CHAIN APES-FSSIM-INDICATORS AND ITS APPLICATION

Outlines of the chapter

This chapter, presented as publication, is an integration of ideas and results of the previous chapters in a bio-economic model (FSSIM) linked to scenarios and indicators. It starts from the problem of small area of grain legumes in the Midi-Pyrénées region (MP) (for details see chapter 1 section, 1.4). This chapter analyses how these constraints can be removed or reduced by testing different alternative scenarios, in comparison with the projected current situation. The material and methods part provides the description of the MP region with main crops, soil types and current area of grain legumes. It also describes the main methodological steps needed to get objective of the paper. Then it describes the farm types selected for this study, list of alternative scenarios, the procedure for their construction and main measures for each scenario. The materials and methods part ends with the list of indicators needed to assess the impact of above mentioned alternative scenarios and the procedure for the calculation of these indicators. We then present and analyze the main results of the sensitivity analysis for various levels of premiums and increase in price and yield. This part also describes the main outcome of the simulated scenarios in term of change in grain legumes area as well as for the selected indicators and expected and unexpected results and their explanation through bibliography. The chapter ends with conclusion on the results and this approach for further use at regional scale.

Assessing the economic and environmental impacts of introducing grain legumes in farming systems of the Midi-Pyrénées region

(Paper to be submitted in Agriculture Ecosystems and Environment)

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Abstract

Grain legumes are the only cultivated grain crops which can fix Nitrogen from the atmosphere and makes them an important component of a sustainable agriculture combining food production and reduced environmental impacts. The introduction of grain legumes in intensive cereal-based cropping systems can result in several agronomic, socio-economic and environmental benefits. Despite these advantages, their share in agricultural land area is low, e.g. 1 to 3% in the Midi-Pyrénées region (France), where this study has been conducted. Many climatic, soil, agronomic, technical and economic constrains hinder their development. These constraints can be analysed, and possibly overcome, by identifying the strategies (alternative scenarios) allowing the adoption of these crops by the farmers in the future. These strategies and their impact on farming systems sustainability have been tested with the modelling chain APES-FSSIM-Indicators, which has the ability to simulate the policy changes and technological innovation through sustainability indicators for EU farming systems. Alternative scenarios, defined in collaboration with local experts, includes: proposition of new grain legumes (peas) based cereals rotations ($S_{tec.innov}$), provision of higher premiums to grain legumes compared to other crops ($S_{premium}$), increase in sale price (S_{price}) and yield (S_{yield}) of grain legumes, reduction in price ($S_{price.var}$) and yield ($S_{yield.var}$) variability of grain legumes, and combination of these alternative scenarios (S_{comb}). The FSSIM model simulates farmer's decisions in response to these scenarios and assessed them with economic and environmental indicators of sustainability. These indicators were identified based on the advantages and disadvantages of legumes-based cereals rotations.

Results show that simulation of $S_{tec.innov}$, $S_{price.var}$, $S_{yield.var}$ scenarios have no effect on pea area in the region, while $S_{premium}$, $S_{price,}$ S_{yield} have a positive effect on pea area. The $S_{premium}$ scenario was found to be more effectient than $S_{price,}$ S_{yield} scenarios. Moreover for several levels of premium, overall the increase in pea area was more important for FT2 and FT3 than FT1. This was mainly due to the difference the initial allocation of crops to the farm area allowing more flexibility for rotation changes in FT2 and FT3 than on FT1. With the more complex scenario S_{comb}, the increase in pea area was higher for FT2 (34 ha) and FT3 (32 ha) than for FT1 (7 ha). Farm income also increased by 11%, 26% and 20 % and energy consumption decreased by 4%, 9% and 8% respectively for FT1, FT2 and FT3. The increase in farm income was mainly due to replacement of less profitable rotations with more profitable ones and reduction of energy use was mainly due to the reduce in area of more fertilizer and water used maize with un-fertilized and less water used peas.

The results obtained from this study show that grain legumes area on Midi-Pyrénées farming systems can be increased by a combination of slight new policy changes (respective premiums between peas and other crops) and slight price and yield increase of grain legumes. The methodology can easily be adapted to other regions and legume crops, provided sufficient data and expert knowledge are mobilized for the modeling chain parameterization.

Key words: cropping systems, crop model, bio-economic model, indicators, scenarios, expert's knowledge.

3.1. Introduction

Grain legumes belong to the Leguminosae family (subfamily Fabaceae) and are considered as the cheapest sources of supplementary proteins (MP3-Grain Legumes, 2010). Their grains are used either for human consumption (food legumes) or for animal feed (Nemecek et al., 2008**;** Singh et al., 2007; Schneider, 2008; AEP, 2004). The unique characteristic of grain legumes as nitrogen-fixing plants makes them economical and environmentally-friendly compared to other arable crops (Graham and Vance, 2003). Previous studies showed that introducing grain legumes into European cropping systems offer many economic, agronomic and environmental benefits (Nemecek et al., 2008; Ncube et al., 2008; Von Richthofen et al., 2006; Carrouee et al., 2000; Campbell et al., 2000; Rao et al., 1999; Rego and Seeling, 1996; Wani et al., 1996; Haque et al., 1995). Despite, these advantages, as compared to other word regions (Wery and Ahlawat, 2007), where their area varies from 10 to 44 %, in European agriculture their share in the total cultivated area is still very limited (1 to 7%) (UNIP, 2009; Schneider, 2008). In contrast, there is a substantial deficiency of vegetable proteins in France and in the whole of Europe, and every year this deficiency is compensated by importing about 75% of the proteins used, mostly from America, which is equivalent to 35 million tonnes of soyabean meal used (UNIP, 2009). Moreover, farmers also show little interest in growing grain legumes on their farms, as a response to institutional, agronomic, technical, climatic, and economic constraints (Von Richthofen et al., 2006). The most frequent problems cited for legumes are: provision of less subsidies compared to other grain crops (UNIP, 2009), higher susceptibility to pest and diseases (Gueguen et al., 2008; Wery and Ahlawat, 2007), need of greater technicality for their production (Carroué et al., 2003)**,** low competition with cereal crops and low and fluctuating prices and crop yield (Jeuffroy, 2006). Due to these constraints, the EU grain legumes sector has declined over recent decades with 30% decrease of grain legume area. In France their area has now reached its lowest level (165 000 ha) since the 80s with 63% decrease only between 2004 and 2008 (Schneider, 2008).

In this context, it is challenging to propose and evaluate strategies that would allow the promotion of grain legumes by acting simultaneously on several of these constraints. This question should be addressed in term of diversity of the contexts (institutional, socio-economic and environmental) and of the farming systems. The review of literature shows that few studies propose quantitative approaches to assess the impact of policies aiming to promote grain legumes area and to assess their impacts at farm and small region levels (Schneider, 2008). Usually the behaviour of agricultural systems in front of cultivation of legumes-based cereals rotations are analyzed by using two types of approaches. The first focuses on socio-economic factors, mainly with econometric models, and helps to quantify which economic incentive (price, premium) affects significantly the farm income (von Richthofen and GL-Pro partners, 2006). In such type of approach, the integration of biophysical components is usually limited to a few quantitative agronomic variables (mainly yield) that are extracted from experiments or specific farm survey. The second type of approach is based mainly on experiments, in specific soil-climate conditions, for assessing the agronomic and environmental performances of legume crops under various crop practices (Nemecek et al., 2008). In both cases, the tendency is to unravel the integrated problem of promoting legume crops as an agronomic and socio-economic issue, in order to reach a compromise solution between different criteria (economic, social, environmental…).

Therefore the objective of this study is to assess the impacts of combined strategies (technical and socio-economic) targeting the promotion of the grain legumes in the Midi-Pyrénées region of France, selected here as a typical example of an EU region with a high agronomic potential for the cultivation of grain legumes. These strategies are expressed as scenarios defined as constraints/opportunity applied to farming systems simulated by the FSSIM bio-economic model (Therond et al., 2009). These scenarios were identified through consultation with local experts and have been assessed through a relevant set of economic and environmental indicators.

3.2. Materials and methods

3.2.1. Study area

Midi-Pyrénées is one of the largest regions of France with an area of 45350 square kilometres and 8.3% of the national territory. A wide range of agronomic conditions including crops, soils, crop management (mainly water and nitrogen) and weather (rainfall) can be observed in this region. Almost all temperate grain crops are cultivated in this region: cereals (durum wheat, soft wheat, maize, and barley), legumes (soyabean, peas, and fababean) and oilseeds (sunflower and canola). The soil types in the region can be splited into loam and clay loam, and further sub-divided into different types depending on soil depth and slope. Irrigated maize rotated with durum wheat, sunflower and peas are cultivated mainly on loam soil, while on clay loam soils, durum and soft wheat rotated with sunflower can be observed (Nolot and Debaeke, 2003). Cereals represent 29% of the Utilized Agricultural Area (UAA) in the region and most of the farms grow cereal crops (Agreste, 2009). Grain legumes have a very small share of the UAA, varying between 1% and 3% of the UAA, depending on farm types and sub-regions (GL-Pro, 2007), while the potential is estimated to be between 15 and 25% (GL-Pro, 2007). Between 2001 to 2009, the regional grain legumes area and production has been decreased by 64% and 68% respectively (data of INRA Toulouse) due to political (CAP reforms), agronomic, technical, climatic, and economic constraints.

3.2.2. Scenario simulation methodology

A 4-steps framework derived from the regional component of the SEAMLESS platform (Belhouchette et al., 2011) has been used in this study to assess farm behaviour under innovative strategies and economic incentives for promoting grain legumes in the Midi-Pyrénées region (MP):

1. <u>Description of current activities:</u> the aim is to describe the main crop-based activities (e.g. a crop species, in a rotation, on a soil, with a specific management) in the MP region for a wide range of farming systems, biophysical conditions and management practices and then to identify for each activity the yields and externalities in order to use them as input into the FSSIM model.
2. <u>Description of the farm types</u>: this step describes the representative farming systems (farm types) in the MP region, which will be considered in the scenario study. These farm types

have been identified using the SEAMLESS database and typology criteria for farming systems in EU (Andersen et al., 2007).

3. Calibration of the FSSIM model: this bio-economic model (Louhichi et al., 2011), which is capable of simulating the farmer's decisions and farm performances indicators, is calibrated for each farm type in order to reproduce the current situation.

4. Definition and simulation of the scenarios: this step targets the definition of the scenarios, which are established in consultation with regional experts to address their questions of interest on grain legumes in a format compatible with the FSSIM model structure and input (Therond et al., 2010).

5. Indicator selection and description: the objective of this step is to describe the procedure for indicator selection and the list of the indicators which will be used to assess the impact of the each selected scenarios for each selected farm types.
6. Sensitivity analysis: this step completes the previous one to analyse how output of the scenarios (Indicators values) are sensitive to minor changes in some scenario parameters (e.g. premium level).

3.2.2.1. Description of current activities (Step 1)

Data for current activities in the MP region (crop rotations and crop management: fertilization, irrigation…) were collected through a survey of 10 local experts reported by Zander et al. (2009). Through this survey, 65 rotations with 11 different crops were identified (Belhouchette et al., 2011). The most frequent are the 2 year rotations with soft wheat–sunflower, durum wheat–sunflower, and maize–maize. The 3 year (barley-sunflower-durum wheat) and 4 years (durum wheat–rape -durum wheat-sunflower) rotations can also be found. Only few grain legumes 2 years rotations have been found: winter barley-peas, winter soft wheat-peas and winter durum wheat-peas, maize-soyabean, winter soft and durum wheat-soyabean, for a total area of less than 3% of regional UAA (UNIP, 2009). Combined with management types, soil types and production systems, these 65 rotations yield a total of 103 current agricultural activities. For each crop and its current activities, a set of data has been collected for running the FSSIM model. It includes the data on: i) management practices i.e. tillage events, amounts of irrigation water, fertilizers and pesticide applications; ii) soil characteristics i.e. clay loam and clay soils; iii) crop performances such as yield and externalities (e.g. nitrate leaching). The first two types of data have been used, together with climatic data, to run the APES crop model, previously calibrated (Mahmood et al., submitted), in order to produce the third type of data as described by Belhouchette et al. (2011). In addition, local statistics for years 1999-2003, have been used to derive a set of economic data, such as product sale price, variable costs of cropping and premiums. Variable costs have been calculated with the input costs of fertilizers, seeds, irrigation, biocides and other crop management practices (Belhouchette et al., 2011). These data were used as input for running the FSSIM model (Table 3.1).

Table 3.1 : Set of input-output coefficients used in the bio-economic FSSIM model (Source: SEAMLESS database).

Crops	Production techniques	Yield (T/ha)		Fertlizer (Kg N/ha)		Irrigation (mm/ha)		Labour (Hours)		Variable costs (Euro/ha)		Prices (Euros/T)	Premiums Agenda 2000 (Euro/ha)
		Soil loam	Soil Clay Loam	Soil loam	Soil Clay Loam	Soil loam	Soil Clay Loam	Soil loam	Soil Clay Loam	Soil loam	Soil Clay Loam		
Soft wheat	rainfed	4.35	-	150	-	-	-	3.10	-	467	-	116.23	309
	irrigated	-	-	-	-		-	-	-	-	-		
Durum wheat	rainfed		4.35	-	150	-	-	-	3.10	-	467	135.3	613
	irrigated	-	-	-	-		-	-	-	-	-		
Barley	rainfed	4.5	4	100	100	-	-	2.55	2.70	206	310	93.75	309
	irrigated	-	-		-	-	-	-	-	-	-		
Maize	rainfed	5	-	120		-		4.27	-	421	-	119.66	309
	irrigated	10.3	10.3	150	150	250	260	49.72	49.72	739	829		469
Sunflower	rainfed	-	1.90	-	-	-	-	-	3.93	-	263	213.27	363
	irrigated	-	-	-	-	-	-	-	-	-	-		
Soya	rainfed	2.59	2.8	0	0	-	-	3.93	3.93	263	297	196.30	363
	irrigated	3.03	2.9	0	0	110	110	40.29	40.29	512	380		523
Rapeseed	rainfed	3.20	3	140	140	-	-	2.67	2.67	211	416	203.78	363
	irrigated	-	-	-	-	-	-	-	-	-	-		
Peas	rainfed	2.39	2.36	0	0		-	2.47	2.47	365	365	132.68	364
	irrigated	4.34	4.32	0	0	40	40	11.56	11.56	423	383		549

3.2.2.2. Farm types description (Step 2)

Midi-pyrénées region is one of the largest regions in France with 47451 farms (Agreste, 2009). Modeling all individual farms is not feasible because of the large number and variability of field and farm in terms of biophysical, economical and social characteristics. Therefore we used the SEAMLESS farm typology (Andersen et al., 2007), based on Farm Accountancy Data Network (FADN) and Farm Structural Survey (FSS), to select the most representative arable farm types of the MP region. It allowed selecting three farm types (FT1, FT2 and FT3), representing respectively 2330, 990 and 1736 real farms of the MP region (Table 3.2). They are characterized by cereal (FT1), cereal/fallow (FT2) and mixed (FT3) farms. FT1 is mainly dominated by cereals (37% of UAA) and oilseeds (21%), FT2 by oilseeds (30%) and FT3 by oilseeds (38 %) and cereals (36%). The available irrigable area is variable and accounts 40%, 28% and 15% of UAA respectively for FT1, FT2 and FT3. As indicated in table 3.2, grain legumes are only cultivated on FT1.

Table 3.2: Main characteristics of the three arable farm types in the Midi-Pyrénées region.

Specialisation land use	Farm type 1	Farm type 2	Farm type 3
	Cereal	Cereal/Fallow	Mixed
Farm represented (number)	2330	990	1736
Area by Farm (ha)	111	107	110
Irrigable area by Farm (%)	40	28	15
Soil Types (% of texture)	Loam (40%)	Loam (36%)	Loam (41%)
	Clay-loam (60%)	Clay-loam (64%)	Clay-loam (59%)
Available labour (hours)	2901.6	3260.3	3179
Observed Crop pattern (ha)			
Cereals (winter soft wheat, winter durum wheat, barley, oat)	37	21	36
Maize	14	21	15
Oilseeds (sunflower, rapeseed)	21	30	38
Grain legumes (mainly peas)	8	0	0
Fallow and other crops (Fruits…)	20	22	10

3.2.2.3. Calibration of the FSSIM model (Step 3)

FSSIM is a generic and modular bio-economic farming system model (Janssen et al., 2007), developed to assess, at farm level, the economic and ecological impact of agricultural and environmental policies on performance of farms through sustainable development indicators (Louhichi et al., 2009). It was designed for simulating a wide range of farmers systems across Europe and elsewhere for addressing a variety of policies and innovation questions related to agricultural systems (Belhouchette et al., 2011). It is an optimization model that maximizes the farm's utility, when subjected to a set of biophysical, socio-economic and policy constraints (Louhichi et al., 2009). Being a mono-periodic model it can optimizes an objective function only over one year, for which decisions are taken (Belhouchette et al., 2010). The main outputs generated from FSSIM are the forecasts on farm income, land use, labor use and environmental externalities (e.g., nitrate leaching, pesticide use, soil erosion, pesticide consumption, organic matter, water use…).

The mathematical structure of FSSIM can be formulated as follows:

Maximise: $U = Z - \phi\sigma$ (3.1)

Subject to: $Ax \leq B \; ; x \geq 0$ (3.2)

Where: **U** is the variable to be maximised (i.e. utility), **Z** is the expected income, **x** is a (n x 1) vector of agricultural activity levels, **A** is a (m x n) matrix of technical coefficients, **B** is a (m x 1) vector of levels of available resources, $\boldsymbol{\phi}$ is a scalar for the risk aversion coefficient and $\boldsymbol{\sigma}$ is the standard deviation of income according to states of nature defined under two different sources of variation: yield (due to climatic conditions) and prices (Belhouchette et al., 2010). Overall, FSSIM considers farmer's behaviour toward two types of risk: i) yield variability due to climate (rainfall and temperature) and, ii) economic variability due to changes in market prices for inputs of agricultural activities and the implementation into the farming system of new activities.

Already calibrated FSSIM was used in this study (Belhouchette et al., 2011). The calibration was achieved in two steps by using the data given in table 3.1. In 1st step, the risk aversion coefficient was considered as single unknown parameter (Kanellopoulos et al., 2010). The value of risk aversion parameters was estimated by multiple model run, in order to get the best fit between the simulated and the observed crop pattern. The value of risk aversion coefficient has been obtained in this way, was selected for further simulations. This step did not gurantee the exact calibration of the model (Belhouchette et al., 2011; Kanellopoulos et al., 2010). Therefore, in second step, the positive Mathematical Programming (PMP) approach presented by Howitt (1995a) was used for this purpose, which guarantees the exact reproduction of the base year situation (Paris and Howitt, 1998). PMP approach can be divided into two steps: i) addition a number of calibrations constrain (Annex 3) in first step, in order to ensure the reproduction of base year situation and calculate the price of the binding calibration constraints, ii) removal the calibration constraints in order to use their shadow price to specify and calculate the nonlinear costs in the objective function (Howitt, 1995; Heckelei, 2003). The salient features of using PMP includes: exact reproduction of the observed reality, generic procedure fully automated which can be easily adopted and used for different farm types, regional, national and higher level analysis without additional site specific information with limited available data (Kanellopoulos et al., 2010).

3.2.2.4. Definition and simulation of the scenarios (Step 4)

- Reference scenario (RS)

The reference scenario interprets the projection in time with possible future development in term of technological, structural and market changes. It represents the reference for interpretation and analysis of the alternative scenarios (Therond et al., 2010). In this study, the reference scenario (table 3.6) refers to the implementation of the CAP reform as decided in 2003 with national and regional adjustments and a time horizon up to 2013.

- Set-aside: minimum of 10% of UAA as fallow.
- Modulation: 3% reduction of premiums between 2003 and 2013
- Decoupling: decoupling of premiums as currently implemented in the MP region.

In term of technological and market change, three exogenous assumptions are adopted between 2003 and 2013:

- Inflation rate: 1.19 % per year
- Yield trend: long term evolution of crop yield reflecting the projection of current genetic and technical progress based on CAPRI database (Britz et al., 2006)
- Price trend: the evolution of agricultural products prices derived from the CAPRI database (Britz et al., 2006).

  All other parameters are assumed to be unchanged up to 2013.

- Alternative scenarios (AS)

Procedure for identification of alternative scenarios

The identification of alternative scenarios has been acomplished through consultation with five local experts with intensive knowledge of the farming and cropping systems of the region (Table 3.3). The identification of alternative scenarios was completed in two 2 steps:

1- Present the study objective: A first document presenting the study area and the objective of the study has been sent to all experts. This document presented also a summary of the method that can be followed to assess the impacts of the scenarios targeting the promotion of legume crops area in the MP region.

2- Identification of alternative scenarios: a half day meeting was held with all experts in the region, with the aims to identify: (i) the main biophysical, technical and socio-economic constraints for grain legumes production in the study area (table 3.4) and (ii) a list of alternative scenarios which can remove or reduce these constraints. For this purpose the expert were asked to answer the following three main questions:

- What are the main biophysical, agro-environmental (soils, sensitivity to frost, pest and diseases, sensitivity to excess and deficit of water etc.) and technical (sowing, harvesting…) problems faced by farmers during both sowing seasons (spring and winter) of the main grain legumes?
- In which types of cereal activities do farmers prefer to introduce grain legumes?
- What are the grain legume that can be irrigated and in which activities?

From the answers and a checking of what can be done with the FSSIM model and the available data, we identified a set of alternative scenarios described below.

Table 3.3 : Skills, expertise and functions of the regional experts.

Experts n°	Skills/Expertise	Function
1	- Adviser for technical and inputs control	Agricultural adviser for the Ariège Agricultural department
2	- Implementation of the strategy work - Design of actions and individual services to help farmers to anticipate the regulatory requirements for the orientation of their farms	Head of Agronomy and Environment of Haute-Garonne Agricultural department
3	- Implementation and monitoring of experiments - Participation in the regional program for the development of cultivation techniques	Technical advice for the Gers Agricultural department
4	- Expertise in growing conditions of pea, fababean and lupins	Researcher in the institute of crops (ARVALIS)
5	- Crop behavior based on various experiments generally conducted under real conditions	Responsible for field experiments in a research station (INRA Toulouse)

Table 3.4: Major constraints identified by experts for grain legumes production in the Midi-Pyrénées region.

Main constraints	Adaptability and tolerance	Peas	Fababean	Lupins	Soyabean
Climate	Tolerance to high temperature	+	-	+	+++
	Tolerance to drought stress	+	++	+	-
	Frost resistance	++ to +++	+ to ++	nd	- -
Soil	Calcareous soils with $CaCO_3$ > 2%	+ +	+ +	--	++
	Shallow soils susceptible to drought	+	-	++	-
	Tolerance to waterlogged soil	+	++	+	++
Technical and agronomic	Lodging problem	+	++	++	+
	Problem during sowing and harvesting (Large seed size)	nd	-	nd	nd
	Tolerance diseases	-	-	-	-
Economic (as compared to non-legume crops)	Premium	↘	↘	↘	↘
	Yield and sale price	↘	↘	↘	↘
	Price and yield variability	↗	↗	↗	↗
	Total cost	↗	↗	↗	↗

Tolerance sensitivity: +++ (perfect tolerant), ++ (good tolerant), + (moderate tolerant), - (low tolerant), -- (avoid), nd (not determind), ↗ Or ↘ (high or low),

Scenario based on technological innovation: $S_{tec.innov}$

According to the experts the main grain legumes cultivated in the study area is the peas and soyabean, fababean and lupin can also be found in some places. We therefore focused for this study on peas only in the absence of data for crop and farm models calibration for the others. Pea is mainly cultivated in bi-annual rotations with cereals. The experts identified nine legumes-based activities suitable to the biophysical conditions of the region (Table 3.5) that were provided as technological innovation at the farm gate (Table 3.6), to be further selected or not by the FSSIM model in the optimization process. Then for each activity, we specified crop management practices, total cost and prices based on the SEAMLESS database (Andersen et al., 2007). Finally the APES model, previously calibrated for some of these crops in the region (Mahmood et al., submitted), was run for each activity to generate externalities such as nitrate leaching and soil erosion. In this study, we assumed fababean as similar to pea crop due to non-avaiabaility of fababean module in the APES model and same externalities and statistical data were used in the FSSIM model.

Table 3.5 : New grain legumes-based cereal rotations identified by the experts.

Climate condition	Rotations
Rainfed	S-DW-P-DW
	S-DW-P-DW-RS
	S-DW-P-DW-FB-DW
	S-DW-FB-DW
Irrigated	M-SJ-DW
	M-DW-P-DW
	M-DW-FB-DW
	M-DW-P-M
	M-SJ-M-P

S= Sunflower, DW= Durum wheat, P= Peas, RS= Rapeseed, FB= Fababean, SJ= Soyabean, M= Maize

Table 3.6 : Summary of alternative scenarios with their assumptions and measures.

Scenarios		Assumptions	Measures
Technological innovation	$S_{tec.innov}$	Biophysically suitable new rotations can increase the grain legumes area	Nine new rotations with 4 for rainfed and 5 for irrigated conditions
Economic	$S_{premium}$	More premium can make the grain legumes more profitable	Sensitivity analysis (0 to 5000 €/ha)
	S_{price} and S_{yield}	Increase in sale price and crop yield can make grain legumes more competitive with non-legumes	Sensitivity analysis (0 to 100 % increase in price and yield than current one)
	$S_{price.var}$ and $S_{yield.var}$	Decrease in price and yield variability can attract the farmers attention to grow more grain legumes and hence their area	20 % and 50% decrease in price and yield variability than current one
	S_{comb}	The combined scenario would be more effective and realistic	$S_{tec.innov}$ (nine new rotations) + $S_{premium}$ (400 €/ha) + S_{price} and S_{yield} (50 % increase)

Scenario based on provision of more premiums to grain legumes: $S_{premium}$

The review of literature showed that during the CAP reforms of 1992 and 2003, the potential of grain legumes has been ignored leading to more premiums provided to non N-fixing crops (UNIP, 2009; Von Richthofen et al., 2006). As a consequence, the legumes area decreased drastically **(**Schneider, 2008; UNIP, 2009). According to the experts, the provision of higher premiums for grain legumes would be the primary incentive for the adoption of these crops by farmers. In agreement with this argument, the EU commission projected a total of 40 million Euros per year between 2010 and 2012 to rapidly achieve a legume area of at least 400 000 ha in EU (Le syndicat Agricole, 2009). This gives a premium per ha of legumes of:

- 150 € / ha in 2010 to achieve an area of 267 000 ha
- 125 € / ha in 2011 to achieve an area of 320 000 ha
- 100 € / ha in 2012 to achieve an area of 400 000 ha

These amounts should be added to the European aid of 55.57 €/ha specific for legumes as specified in the CAP reform of 2003. But during our meeting with local experts, they claimed that these amounts of premiums would be insufficient for increasing significantly the grain legumes area in the MP region. With their experience they acknowledged that peas can be more profitable than wheat, only if it receives a premium higher than 800 €/ha. Therefore, in this study, instead of using the EU or experts amounts, we conducted a sensitivity analysis for a wide range of premium (Table 3.6).

Scenario based on sale price (S_{price}) and crop yield (S_{yield})

Von Richthofen et al. (2006) reported that farmers in EU and France believe lower sale price and grain yields are two of the major obstacle for legume production. This opinion was also expressed by experts during the meeting. Moreover, according to Chambre d'Agriculture de l'Ariège (2009), in rainfed conditions, average yields of wheat and peas are respectively 5 and 2.5 t ha^{-1}. On average, farmers sold the product (grains) at market price of 180 €/t for wheat and 140 €/t for peas. For growing both crops they spend almost the same amount of money: 460 and 480 €/ha respectively for wheat and peas. Obviously this makes wheat more profitable than pea in these conditions, with a difference of gross margin of 516 €/ha (741-225). It is therefore assumed that increase in sale price and/or crop yield could make grain legumes competitive compared to cereal. Therefore, we conducted a sensitivity analysis combining product prices and yields of grain legumes (Table 3.6).

Scenario based on price ($S_{price.var}$) and yield ($S_{yied.var}$) variability

Von Richthofen et al. (2006) reported that in some cases the choices of crops are mainly determined by their yield and price stability across years. The experts confirmed this hypothesis and considered that, compared to other regional crops like rapeseed and wheat; grain legumes are more risky in economic terms because of yield and price instability. We therefore assumed that a reduction of yield and price variability could make grain legumes more attractive to farmers. A sensitivity analysis was conducted with a reduction of 20% and 50% of yield and price inter-annual variability (Table 3.6).

Scenarios combining the previous components: S_{comb}

The idea behind this scenario, which arose as a conclusion of the experts meeting, is that implementing one measure (e.g. premium) can only be partially effective and would never lead to significant increase in the grain legumes area. The hypothesis is that an increase in grain legumes area on MP farm can only be achieved by acting both on several components of the farming system's economic environment (price, premium) and on the grain legume crop innovations (e.g. rotations, management) to improve yield. Therefore this scenario was built as a combination of the previous ones, except $S_{price.var}$ and $S_{yied.var}$. As described in table 3.6, the level of premium was fixed at 400 €/ha and the increase in price and yield were fixed at 50% compared to the current one. These levels were defined using the results of the sensitivity analysis conducted for the corresponding scenarios (S_{price} and S_{yield}).

3.2.2.5. Indicators selection and calculation (Step 5)

The impact of the above described reference and alternative scenarios on the three farm types were assessed through relevant socio-economic and environmental indicators. These indicators were identified on the basis of the advantages and disadvantages of legumes-based cereals rotations (Table 3.7), taking into account the capability of the modelling chain with the available data. All these indicators, except energy consumption, are calculated by the bio-economic FSSIM model and expressed at farm scale. The indicators and their calculation method in FSSIM model are summarized in table 3.8 and more details can be found in Louhichi et al., 2009).

Table 3.7 : Indicators relevant to assess advantages and disadvantages of legumes-based cereal rotations according to literature.

Criteria for indicator selection		Relevant indicator
Advantages	Less or no need of N fertilizer and ultimately saving of energy, (Nemecek et al.,2008; Nemecek and Erzinger, 2005)	N fertilize use, Total cost, Farm income, Energy consumption
	Reduction in amount of fertilizer for following crop in the rotation (Ncube et al., 2008; Nemecek et al. 2008; Wery and Ahlawat, 2007)	Fertilizer use, Farm income, Total cost,
	Increase in yield of following crop in the rotation (Von Richthofen et al.,2006; Haque et al.,1995; Dakora et al., 1987)	Farm income
	Increase in gross margin at rotational level and ultimately farm income (Von Richthofen et al., 2006; Rao et al.,1999)	Farm income

	Addition of organic matter, which could change the soil chemical, physical and biological properties and could help in soil stability, but it is not only specific to grain legumes (Mvondo et al. 2007; Haque et al.,1995)	Soil erosion
Disadvantages	Higher N leaching in winter (Nemecek et al., 2008; Crews and Peoples, 2004; Fillery, 2001)	N leaching
	Higher labour requirement (Wery and Ahlawat, 2007; Rao et al., 1999)	Labour use
Both	Change in water use (depending on the conditions)	Water use
	Can be used as break crop, which could help in reducing pesticides use (Nemecek et al., 2008; Robson, 1990). On other hand, it can also increase cost of plant protection due to more susceptible to pests and diseases (Beaver et al., 2003; Coyne et al., 2003)	Total cost, Farm income

Table 3.8 : Methods of indicators calculation by the bio-economic FSSIM model (according to Louhichi et al., 2009).

Selected indicators	Method of calculation
Farm income	It includes crop income without premiums + EU premium + PMP terms given in Euros + risk (yield + price)
Share of premium in income	It is the percent of EU premium which become part of farm income
Total cost	It represents variable costs for crops + N and P fertilizer costs + harvest costs of grass + average labour cost.
Water and N fertilizer use	It includes the amount of water and N fertilizer that is actually used to satisfy the water and N requirements of crops and grasses grown on the farm.
Externalities (N leaching, Soil erosion...)	For each activity, it includes the environmental indicators that were simulated at field scale by using the CropSyst model (Belhouchette et al., 2010). Then for each selected scenario, the FSSIM model was run in order to select most profitable activities. At the end the average value of each environmental indicator simulated by CropSyt is calculated at farm scale by aggregating values of FSSIM selected most profitable activities (Belhouchette et al., 2011).

The indicator of total energy use (E_t) was calculated outside the bio-economic FSSIM model. For this purpose, the INDIGO method of energy proposed by Bockstaller and Girardin (2003) and Pervanchon et al. (2002) was used. Because of the lack of data we took into account only four of the seven sources of energy consumption proposed in the INDIGO method: fertilization, machinery, irrigation and pesticides. We assume that this does not impair the use of this indicator for relative changes analysis between scenarios, because the three remaining components (seeds, fuel and electricity) are likely to be only slightly modified by the rotation changes. The indicator of total energy use was calculated as the sum of the four components using the conversion factors described in the annex 2. Table 3.9 shows the energy used for these four components for an area of 1 ha for each crop.

Table 3.9 : Energy used for an area of 1 ha of each crop; calculated by using INDIGO method of energy indicator.

	All types of machinary	N Fertilization	Pesticides	Irrigation	E_t
Crop	MJ/ha	MJ/ha	MJ/ha	MJ/ha	MJ/ha
Winter soft wheat	2282	413	225	-	2920
Winter durum wheat	2282	310	225	-	2817
Winter barley	2282	206	294	-	2782
Maize (Irrigated)	1922	310	856	1485	4573
Maize (Rainfed)	1922	248	856	-	3026
Rapeseed	2382	289	323	-	2994
Sunflower	1922	-	596	-	2518
Soyabean (Irrigated)	1922	-	980	605	3507
Soyabean (Rainfed)	1922	-	980	-	2902
Peas (Irrigated)	2433	-	488	220	3140
Peas (Rainfed)	2433	-	488	-	2920

3.3. Results and discussion

3.3.1. Overall scenario analysis

Table 3.10 presents the increase in pea's area for each alternative scenario and farm type. It shows that the implementation of the alternative scenarios affect differently the behavior (in term of adoption of legume crops) of the three farm types. Thus, those alternative scenarios are divided into non-significant alternative scenarios (i.e. which did not change the pea area and indicator values) and significant alternative scenarios (i.e. which changed the pea area as well as indicator values).

3.3.1.1. Non significant alternative scenarios ($S_{tec.innov}$, $S_{price.var}$ and $S_{yield.var}$)

The implementation of these alternative scenarios ($S_{tec.innov}$, $S_{price.var}$ and $S_{yield.var}$) did not change the pea area (Table 3.10), as well as the values of the assessment indicators (data not shown), for none of the farm types. In $S_{tec.innov}$, the new grain legumes-based cereals activities, proposed to the FSSIM model were not sufficiently attractive on an economic point of view to be selected by the model. This is contrasting with Von Richthofen et al. (2006) findings, who reported that grain legume-based cereals rotation generally have slightly higher gross margin than intensive cereal-based rotations. They found that in Saxony-Anhalt (Germany), inclusion of peas in five-year cereals based-rotations increased the gross margin by 11%.

Even if grain legumes become less risky than other crops in scenarios $S_{price.var}$ and $S_{yield.var}$, this did not led to adoption of grain legumes by the farmer simulated with FSSIM, even with a 50% reduction of price and yield variability. This is again an invalidation of the common hypothesis that price and yield variability of grain legumes are two of the major limitations for grain legumes production (Von Richthofen et al., 2006).

In both case, our study indicate that technological innovations leading to new rotations with legumes and reduction of prices and yield instability would not be sufficient for the three types of farmers in the region to increase the grain legume share in their cropping systems. It is well known that bio-economic models have some bias to simulate farmer's decisions not driven by income (Janssen et al., 2007), but this economic rationality is generally the argument given in the legume literature (e.g. Von Richthofen et al., 2006) and by our experts, to promote such scenarios..

Table 3.10 : Difference in pea's area for reference and alternative scenarios for the three farm types.

Alternative scenarios		Measure	FT1			FT2			FT3		
			Reference scenario	Alternative scenario	Difference in reference and alternative scenario	Reference scenario	Alternative scenario	Difference in reference and alternative scenario	Reference scenario	Alternative scenario	Difference in reference and alternative scenario
			Area (ha)	Area (ha)	Area (ha)	Area (ha)	Area (ha)	Area (ha)	Area (ha)	Area (ha)	Area (ha)
Non-significant	$S_{tec.innov}$	Nine new rotations	8	7	-1	0	0	0	0	0	0
	$S_{price.var}$	50 % decrease than current one		8	0		0	0		0	0
	$S_{yied.var}$	50 % decrease than current one		8	0		0	0		0	0
Significant	$S_{premium}$	400 €/ha		12	4		18	18		21	21
	S_{price}	50 % increase than current one		10	2		9	9		8	8
	S_{yield}	50% increase than current one		10	2		10	10		8	8
	S_{comb}	$S_{tec.innov}$ + $S_{premium}$ + S_{price} + S_{yield}		15	7		34	34		32	32

3.3.1.2. Significant alternative scenarios

$S_{premium}$ Scenario

The most significant impact in term of change in pea area and indicator values was observed in the $S_{premium}$ scenario. For example, for a supposed premium amount of 400 euros/ha, pea area has been increased by 4 ha, 18 ha and 21 ha (Table 3.10) and farm income by 4%, 3% and 1 % (data not shown) for FT1, FT2 and FT3 respectively. This is consistent with the finding of UNIP (2009) that provision of more premiums to legumes is one of the main driving forces for increasing their areas in EU and in France. Sensitivity analysis show that the three farm types react differently. FT1 requires a higher premium (4500 €/ ha) than FT2 and FT3 to reach the maximum pea area of 45 ha per farm (Figure 3.1a).

This is mainly due to the difference in initial cropping pattern and the characteristics of each farm type, especially the initial area of winter cereals and irrigated land.

The initial area of winter cereal crops was higher in FT1 (cereal farm type) than FT2 (cereal/fallow farm type) and FT3 (mixed farm type). FT1 initially cultivated 37% of its UAA with cereals (winter durum wheat, winter soft wheat, winter barley and oats), 21% with oilseeds and 14% with maize. Grain legumes were already significant in this farm type, with 8% of the UAA, which is above the regional average. The results show that with gradual increase in premium level for grain legumes, the irrigated pea which was rotated with cereal started first to replace irrigated maize grown as a monocrop, which became progressively less profitable than the winter cereal-pea rotation. In a second step, the cereal-pea rotation substituted progressively the maize-soyabean rotation, which was more profitable than the irrigated monocrop maize. The maximum pea area was reached with premium level of 4500 euros/ha. In this case, FT1 grew only winter cereal, pea and oilseeds. This situation is not realistic regarding the level of premium and it is not sustainable because pea was cultivated only in bi-annual rotations which would induce a high disease pressure for pea.

The same explanation can be given for FT2 and FT3. However, for these farm types with gradual increase in premium level, the increase in pea area was quicker than FT1 due to different cropping pattren, especially in term of most profitable rotation maize-soyabean. In fact, on these farm types, pea mainly replaced successively fallow, maize monocrop rotation and then oilseeds. In these both farm types and contrary to the FT1 no maize was cultivated in rotation with soyabean which was more profitable than maize monocrop rotation or oilseeds.

The share of irrigated area in the farm UAA seems to affect negatively the adoption of grain legumes. In fact, farmers prefer first the cultivation of more profitable irrigated maize and soyabean and than irrigated pea. By increasing the premiums for legume crops, the irrigated pea first replaced the rainfed crops than the irrigated crops such as maize. This may also explain why FT1, which had the highest irrigated area (40 ha), reacted more slowly to the premium increase than the two others farm types.

S_{price} and S_{yield} Scenarios

Increasing pea price (S_{price}) or pea average yield (S_{yield}) has led to an increase of 2 ha, 10 ha and 8 ha in pea area (Table 3.10) and of farm income of 2%, 1% and 0 % (data not shown) for FT1, FT2 and FT3 respectively. A more detailed analysis showed that the impact of these scenarios on farm behavior was similar to the $S_{premium}$ scenario. Overall, similar tendencies in term of change in pea area as well as for assessed indicators were observed for these both scenarios (Table 3.10).

The sensitivity analysis shows that pea area on FT2 and FT3 can be increased more rapidly than FT1 (Figure 3.1b and 3.1c). However, for both farm types (FT2 and FT3); even for very high levels of increase in price and yield (100%), the increase of pea area is very small and does not exceed 15 ha (Figure 3.1 b and 3.1c). On the other hand, FT1 seems insensitive to these scenarios. This is despite a high level of pea yield increase (up to 100%) compared to the current one, for which the actual tendency is rather to a reduction during the past two decades (Schneider, 2008).

S_{comb} Scenario

As shown by the previous scenarios, none of the individual drivers would be sufficient to increase pea yield in the MP region, if we remain in a realistic range of technological changes (influencing yield) or economical changes (influencing prices or premiums). The originality of the modelling chain we used is that it allows combining in a single scenario several of these drivers to identify possible synergies between minor variations of these drivers. The simulation of S_{comb} scenario shows (Table 3.10) that combining a premium of 400 euros/ha with a 50% increase of price and yield would induce a significant increase of the pea area (7 ha, 34 ha and 32 ha for FT1, FT2 and FT3 respectively) and of the farm income (11%, 26% and 20% respectively) . On the other hand for getting the same increase in pea area, it would require a premium of 750 €/ha for FT1, of 850 €/ha for FT2 or of 600 €/ha for FT3 (figure 3.1 a), or an unrealistic level of increase in price (figure 3.1 b), or yield (figure 3.1 c).

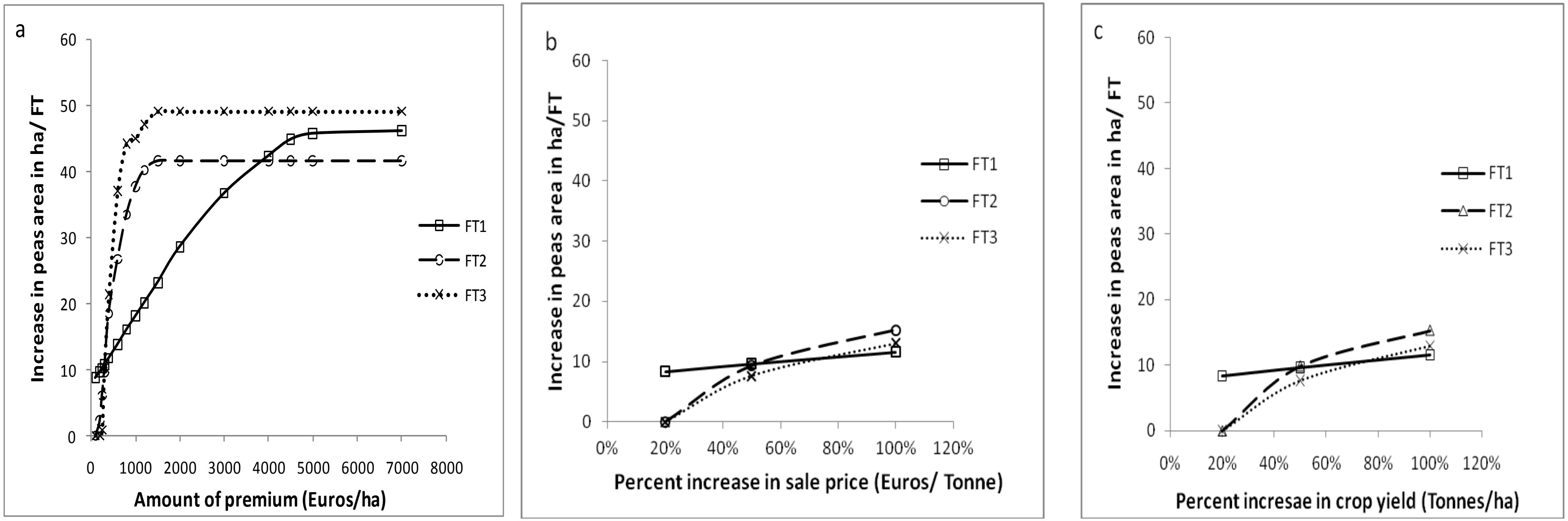

Figure 3.1: Figure 1 (a), (b) and (c): Sensitivity of pea area to the premium amounts (a), sale price (b) and pea yield (c) for the three farm types (FT1, FT2 and FT3).

3.3.1.3. Analysis of intermediate variables

To understand the overall results of the S_{comb} scenario, a more detailed analysis of the intermediate variables (crop pattern and crop rotations) is needed.

Cropping pattern

Figure 3.2 shows the difference in cropping pattern for the reference and S_{comb} scenario for the three farm types. The simulated results for FT1 show that in the S_{comb} scenario small modifications are observed in term of cropping pattern. The area of cereals increased by 2 ha and grain legumes by 7 ha at the expense of the maize area (- 4 ha) and of other minor crops (Figure 3.2a). The same trend is observed for FT2 (Figure 3.2b) and FT3 (Figure 3.2c) with a more pronounced effect on maize (suppression) and on pea area (+ 34 ha and 32 ha respectively for FT2 and FT3).

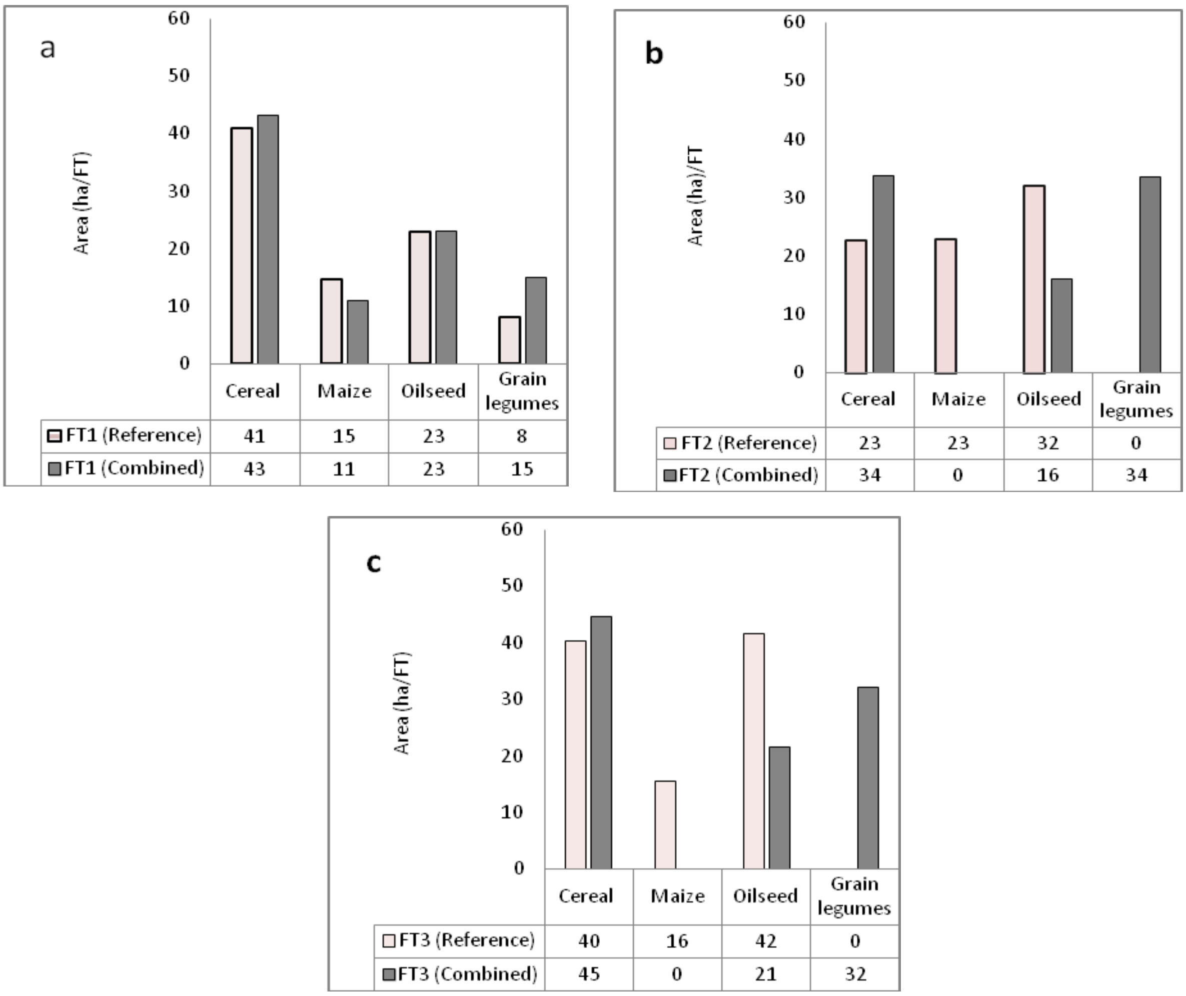

Figure 3.2 : Cropping pattern for reference and S_{comb} scenarios for FT1 (a), FT2 (b) and FT3 (c).

Crop rotations

The S_{comb} scenario induced significant modifications of crop rotations in the three farm types (data not shown). For FT1, the area of the maize–soyabean rotation (cultivated on loamy soil) was reduced by 12 ha to the benefit of the winter soft wheat–pea (+16 ha). The winter soft wheat–rapeseed rotation disappeared and new rotations appeared (oats–oats, winter barley–winter durum and winter soft wheat–winter barley–winter durum wheat).

These types of modifications in crop rotations were also observed in FT2 and FT3 but with higher amplitude. For example, in FT3, strong reductions of some rotations (-15 ha for maize–maize), -33 ha for winter barley–rapeseed) and -10 ha for winter durum wheat–sunflower) were compensated by an increase in area of others rotations (+11 ha for winter soft wheat – rapeseed, +27 ha for winter barley–pea, + 27 ha for winter durum wheat–pea and +10 ha for winter soft wheat–pea).

3.3.1.4. Analysis of the assessment indicators

The modeling chain allows assessing the impact of the scenario on a set of indicators reflecting the farming systems sustainability, which is analyzed below for the S_{comb} scenario. They are covering the socio-economic domain for the farmer (Farm income, total costs, labour use), the policy domain (Share of premium in farm income) or the environmental domain (Water use, Nitrogen fertilizer use, Nitrate leaching, Soil erosion, Energy use).

Farm income

Farm income increased in the S_{comb} scenario for all farm types (Table 3.11), with the increase in legume crop area (11%, 26% and 20% for FT1, FT2 and FT3 respectively). This is consistent with the results of Von Richthofen et al. (2006) and Rao et al., (1999) who reported that inclusion of more grain legumes into cereals based cropping system can increase the farm income.

For FT1, this was obtained (data not shown) by the replacement of rotations with lower gross margin (i.e. on average 677 €/ha/year for maize–soyabean) by rotations with higher gross margin (i.e. winter soft wheat-pea with an average 751 €/ha/year). The same type of results was also observed in FT2 and FT3. For example, the 20% increase in farm income of FT3 in S_{comb} (Table 3.11) can be explained by the replacement of the barley–rapeseed rotation (on average 665 €/ha/year) with winter soft wheat–rapeseed (on average 759 €/ha/year), winter barley–pea (averagely 836 €/ha), winter durum wheat–pea (on average 1021 €/ha/year) and winter soft wheat–pea (on average 830 €/ha) rotations.

Total costs

The S_{comb} scenario has increased the total costs of farming for FT1 (+18%) and reduced them for FT2 (-26%) and FT3 (-18%) (Table 3.11). The increase in total cost in FT1 is a result of the replacement of some maize area (-4 ha) by pea (+7 ha), although the former is more costly (624 €/ha of variable costs compared to 373 €/ha for peas), but the decrease in area of maize by 4 (total cost due to 4 ha 2496 €) and incresae in area of peas by 7 ha (total cost due to 7 ha 2611 €) slightly increases the total cost (+ 3%) in FT1. The decrease in total cost in FT2 and FT3 is also linked to decrease in area of maize at the benifit of peas (data not shown).

Labour use

The labour used in S_{comb} scenario increased slightly in FT1 (+3%) and strongly decreased for FT2 (-67%) and for FT3 (-65%) (Table 3.11). Rao et al. (1999) reported the requirement of same labour hours for cereals monocrop rotation and legumes based-cereal rotation, while Wery and Ahlawat (2007) gave the contrary statement, which was also confirmed by the study of Nemecek and GL-Pro partners (2006). In our case the reduction of labour requirement is clearly linked to the reduction of maize area, a crop requiring more labour, especially for irrigation (50 hours/ha for irrigated and 4.3 hours/ha for rainfed) than grain legumes (12 hours/ha for irrigated and 2.5 hours/ha for rainfed) but also than winter cereals (3 hours/ha for rainfed) which are rotated with pea.

Share of premium in farm income.

Table 3.11 shows that S_{comb} has increased the share of premium in income by 6%, 13% and 11% respectively for FT1, FT2 and FT3. This can be explained by the reduction in area of rotations with lower subsidies (e.g. in FT1 the maize–soyabean rotation with a premium of 423 €/ha) at the benefit of rotations with a higher premium (e.g. 640 €/ha for winter soft wheat–pea in FT1). The similar explanation also applies for FT2 and FT3.

Water use

S_{comb} strongly reduced (between 54 % and 93%) water consumption for all farm types (Table 3.11). Again the major driver is the reduction of maize area, this crop being mostly cultivated under irrigated conditions on the three farm types. Even when the crop substituted to maize was irrigated, at least on some soil types, the amount of water required by this crop was lower. For example pea crop receives in average 40 mm in the region compared to 250 mm for maize (table 3.1).

Nitrogen fertilizer use

As expected, when grain legumes (without any N fertilization) replace cereals (systematically fertilized), the amount of fertilizer used by the farm was significantly reduced (38% and 28% respectively for FT2 and FT3) (Table 3.11). For FT1, the reduction was not significant (-1%) because the development of pea-based rotation (+17ha for winter soft wheat–pea, fertilized with 120 kgN/ha on wheat crop) was done at the expense of the soyabean-based rotation (-12 ha for the maize–soyabean rotation, fertilized with 150 kg N/ha on the maize crop).

Nitrate leaching.

The impact of the S_{comb} scenario on the average amount of nitrate leached on the farm also differed between farm types. It increased by 6% for FT1 and decreased by 7% on FT2 and 17% on FT3 (Table 3.11). Nemecek et al. (2008) and Von Richthofen et al. (2006) reported a higher risk of N leaching by including more legumes in cereal based rotations, while Drinkwater et al. (1998) reported the opposite results, with a 7% reduction of N leaching with legumes based systems, compared to cereal monocrops. The analysis of our results require a more in depth analysis of changes in crop rotations, their allocation to soil types and nitrate leaching of each crop depending on the preceding crop and on crop management (Belhouchette et al, 2011). For example, the increase in N leaching for FT1 can be explained by the replacement of the maize–soyabean rotation area (- 12 ha for a yearly average N leaching of 30.4 kg N ha^{-1}) by crop rotations inducing more N leaching : winter soft wheat–pea (+ 17 ha with 79.5 kg N ha^{-1} leached per year) and a four year rotation of winter soft wheat–rapeseed–winter durum wheat–sunflower (+ 9 ha with 52.1 kg N ha^{-1} leached per year).

Similarly the 17% decrease of N leaching for FT3 can be explained by the replacement of high N leaching rotations (winter barley–rapeseed with 70.2 kg N ha^{-1} leached per year) with lower N leaching rotations (winter barley–pea and winter durum wheat–pea with 41.2 and 35.8 kg N ha^{-1} per year respectively). Similar explanation can be found for FT2 (not shown).

Soil erosion

Soil erosion increased with S_{comb} for FT1 (+6%) and FT2 (+13%) and was reduced for FT3 (-18%) (Table 3.11). Again this complex behavior emerges from the evolution of crop rotations selected by the farmer simulated with FSSIM and their biophysical functioning simulated by the APES model. For example, in FT1, 12 ha of the maize–soyabean rotation (1 t ha^{-1} of average soil erosion per year) were replaced by 16 ha of winter soft wheat–pea rotation (2 t ha^{-1} of average soil erosion per year)

Energy use

As expected with an increase of legume area (Wery and Alhawat, 2007), the S_{comb} scenario led to a reduction of energy use: 4%, 9% and 8% respectively for FT1, FT2 and FT3 (Table 3.11). This energy reduction was mainly due to the reduction of maize, which needs more N fertilizer (on average 150 Kg N/ha) with a high energy consumption for N fertilization (on average 278 MJ/ha) to the benefit of peas receiving no N fertilization. Moreover, maize uses more water (on average 250 mm/ha) with high energy consumption (1485 MJ/ha) than peas, which needs less irrigation water (40 mm/ha) with lower energy consumption (220 MJ/ha) (Table 3.9). These results are similar to those of Carrouée et al. (2007) who reported in a five years (1994-1998) experiments conducted in bassin parisien (France) that, as compared to wheat monocrop, the legumes based-cereal rotation of peas-wheat can reduce N fertilizer use by 22%, which ultimately can save 24% of the energy. A 14% reduction of energy used through fertilizers was also obtained by Nemecek et al. (2008) for peas-wheat rotation compared to wheat monocrop. But in our case this effect through N fertilizer reduction is analyzed in the context of a farm with an amplification through the reduction of energy consumption for irrigation of maize and a counter-effect of reduction of another legume (soyabean) suppressed with the plan it is rotated with (maize).

Table 3.11 : Simulated results of economic and environmental indicators at farm scale using the APES-FSSIM modelling chain for three farm types.

Selected indicators	Farm type 1 (FT1)			Farm type 2 (FT2)			Farm type 3 (FT3)		
Economic	Reference	Alternative	Difference (%)	Reference	Alternative	Difference (%)	Reference	Alternative	Difference (%)
Farm income (Euros)	109488	121765	11	73785	92828	26	78539	94075	20
Share of premium in income (%)	36	38	6	45	50	13	51	56	11
Total cost (Euros)	31657	37343	18	75025	55338	-26	76741	62935	-18
Labour use (Hours)	466	482	3	1075	350	-67	942	328	-65
Environmental									
Nitrate leaching (kg $N\text{-}NO_3$ ha^{-1})	45	48	6	54	50	-7	64	53	-17
Soil erosion (t ha^{-1} per year)	1.6	1.7	6	1.6	1.8	13	1.7	1.4	-18
Water use (m^3 ha^{-1})	26	12	-54	60	5	-91	39	3	-93
Nitrogen fertilizer use (kg N ha^{-1})	109	108	-1	113	71	-38	130	94	-28
Total Energy use (MJ)	283485	273556	-4	269405	246229	-9	304539	281576	-8

3.4. Conclusion

The scenario simulated in this study for the MP region provide quantitative evidence of the major role of economic constraints, frequently raised in the literature to explain the poor development of grain legumes (UNIP, 2009; Von Richthofen et al., 2006). Premium paid specifically to legumes ($S_{premium}$ scenario) or specific increase of market price for these crops (S_{price} scenario) are required to “force” the simulated farmer (with FSSIM) to adopt grain legumes. Nevertheless the amounts required appear too high to be applied in the real conditions. Technological innovations leading to higher yields (S_{yield} scenario) could also be a significant driver of legume development of grain legumes, provided it reaches a doubling of the current level of pea yield in the region, which is also out of expectations with the current technologies. The reduction of inter-annual variability in pea prices ($S_{price.var}$ scenario) or yield ($S_{yield.var}$ scenario) did not change the simulated farmer’s behaviour, even for 50% reduction of this variability which would require very efficient market regulations (for price) or crop management (for yield).

It’s only when several of these measures where combined (S_{comb} scenario) that the simulated farmer replaced some of its cereal crops (mainly maize) by a grain legume (pea), sometimes to the expense of another grain legume (soyabean) tightly linked to maize through the rotation process. In that case the economic performances of the farm (assessed with the farm income indicator) were increased for all farm types, in comparison with the business as usual scenario. But at the same time the share of premium in total farm income has ben increased making the farming systems more dependent on the public policies and finances. The potential environmental impacts of the farms were reduced for all farms through water use, N fertilizer use and total energy use.

But the impact was also depending on farm types for the other sustainability indicators: total cost, labour use and N leaching increased in the S_{comb} scenario for FT1, while they decreased for FT2 and FT3. Detailed analysis of the intermediate variables of the simulations showed the importance of the initial situation of the farm and of the rotations selected in each farm type.

The modelling chain APES-FSSIM-Indicators used in this study appeared as a powerful tool to analyse the current constraints and propose some levers to the development of grain legumes in the main farm types of a region. By combining simulation of the biophysical behaviours of crops in a rotation (with the APES model) and of the farmer’s decisions of crop allocation and management (with the FSSIM model) it allowed to analyse the reaction of complex scenarios combining economic changes and technological changes, with economic and environmental indicators. These models cannot reproduce all aspects of the complex agricultural systems under study (e.g. disease impact on nitrogen uptake and nitrate leaching or farmer's decision driven than other aspects than resource management) (Belhouchette et al., 2011). But when used, as in our study, in interaction with experts for the elaboration of crop databases (e.g. with yield depending on soil and previous crop) and for strategic thinking with farmers, the modelling chain is likely to bring significant improvement in impact assessment and policy analysis.

CHAPTER 4

GENERAL DISCUSSION AND PERSPECTIVES

4.1. Major results

Grain legumes can play a pivotal role in modern agriculture by reducing the threat of depleted non-renewable energy resources and by lessening the negative environmental effects (Jezierny et al., 2010; Nemecek et al., 2008). However, in France and for example in Midi-Pyrénées region (MP), grain legumes area is very low as compared to other world region (UNIP, 2009; Schneider, 2008). Therefore, it was important to identify the factors affecting their cultivation and the main strategies to develop this agricultural sector. Thereby, the general objective of the thesis was to analyse the main conditions for the development of grain legumes in the Midi-Pyrénées farming systems. To achieve this objective three main steps have been identified and followed, to identify, simulate and analyse scenarios allowing the promotion of legume crops. First, these scenarios were identified and defined in interaction with local experts, based on pre-diagnosis of the main grain legumes biophysical and socio-economic constraints. In a second step, the impacts of these scenarios in comparison to the baseline one (business as usual) were assessed by using the modeling chain APES-FSSIM-Indicators. In a third step, the impacts of these scenarios have been assessed, in comparison with the reference scenario, using environmental and socio-economic indicators at farm level.

In term of increase in grain legumes area, most of the results of the alternative scenarios were in accordance to our expectations. For example, we were expecting a positive effect on grain legumes area on the MP farming systems (UNIP, 2009; Von Richthofen and GL-Pro partners, 2006) by increasing the price (S_{price}), yield (S_{yield}) and premiums ($S_{premium}$) for grain legumes. It was observed both scenarios of S_{price} and S_{yield} have almost similar effect on grain legumes area and 50% increase in price and/or yield, compared to the current level, has increased the grain legumes area by 2%, 7 % and 9% respectively for cereal, cereal/follow and mixed farm types. Similarly, provision of high premium to grain legumes, compared to other arable crops, was found, as expected, an efficient strategy for the promotion of grain legumes in the MP region: a premium of 400 €/ha has increased the grain legumes area by 4 % 16% and 18% respectively for cereals, cereals/follow and mixed farm types. However, the level of premium required, depends on the current level of EU and regional economic incitation, the current price, the yield of grain legumes (rainfed and irrigated) and the characteristics of the farm types in which these crops are cultivated. For example, it is observed that it is more profitable to grow grain legumes under irrigated conditions in cereal/fallow or mixed farm types than in cereal ones. In all cases, in the biophysical context of the study area, characterized by a low temperature and a rainy weather in winter and often a hot and dry spring and summer (Nolot and Debaecke, 2003), rainfed grain legumes seems to be economically not competitive unless a very high, and unrealistic, level of premium is given to the farmers.

Overall, it is concluded that the promotion of grain legumes (irrigated or non-irrigated) in a context like the MP region cannot be achieved in a realistic way by implementing individual incentive measures such as increasing price and yield or provision of specific premium for these crops. This result can explain the current low share of grain legume crops in the EU agricultural regions (UNIP, 2009). It also explains why in some regions the implementation of only specific premium to promote grain legumes is insufficient (Schneider, 208). Overall, this study shows that the most effective and realistic way to promote grain legumes on MP farming systems, and possibly in other EU regions, is to implement combined agronomic and socio-economic measures like the ones used in the S_{comb} scenario ($S_{tec.innov}$ + $S_{premium}$ + S_{price} + S_{yield}). It has increased the grain legumes area significantly by 6% (of the total area of 111 ha), 32% (of the total of 107 ha) and 29% (of the total area of 110) respectively for cereal, cereals/follow and mixed farm types.

Some unexpected results in term of change in grain legumes area have also been obtained. The main ones are related to measures such as introducing new grain legumes-based cereals rotations ($S_{tec.innov}$) and decreasing the price and yield variability ($S_{price.var}$ and $S_{yied.var}$). These measures, although frequently cited in our interviews, were found insufficient for increasing grain legumes area on the MP farming systems. Two reasons can be advanced to explain such results:

- In an environment like the MP region, where the biophysical (soil, weather) and the socio-economic (cereal market price, specific premium EU premium for cereal) conditions are more suitable to the dominant crops (cereals), such measures cannot increase the competitiveness of grain legume crops and hence their area (Schneider, 2008). These types of results may also be valid in other EU regions, and especially in the Mediterranean ones, where grain legumes are rarely economically competitive with cereal or oleaginous crops (Chambre d'Agriculture de l'Ariege, 2009).

- In both irrigated and rainfed conditions, the existing grain legume crops are characterized by low yields and market prices (Von Richthofen et al., 2006). Therefore, even by reducing the price and the yield variability, their incentive effect on adoption of grain legumes will be negligible.

Regarding socio-economic and environmental indicators, no difference was observed for the alternative scenarios of $S_{tec.innov}$, $S_{price.var}$ and $S_{yied.var}$ compared to the baseline one. However, the scenarios of S_{price}, S_{yield}, $S_{premium}$ and S_{comb} showed the expected results characterized by: an increase in farm income (Von Richthofen et al., 2006; Rao et al., 1999), a reduction in N fertilizer use (Nemecek and Erzinger, 2005) and in water use, mainly due to the decrease in area of more fertilizer and water demanding maize, to the benefit of non-fertilized and less irrigated pea. The total energy was also decreased, as expected by increasing the non fertilized grain legume crops instead of cereals, especially maize (UNIP, 2008).

Similarly the results of indicators of total cost, labour use, N leaching and soil erosion were also reduced with the introduction of grain legumes, as reported in literature (Rao et al., 1999; Drinkwater et al., 1998), at least for cereal/fallow and mixed farm types (FT2 and FT3). However, the reverse trend was observed for cereal farm type (FT1), with an increase (3 to 18%) of these indicators, which is also consistent with the findings of some authors (Nemecek and GL-Pro partners 2006; Von Richthofen et al., 2006; Fillery, 2001). This specific behavior of FT1 may be the consequence of an initial situation with 8% of the UAA in grain legumes, which is above the regional average of 3% (UNIP, 2009). Moreover, the initial area of winter cereals crops was higher in FT1 than FT2 and FT3, and mostly grain legumes (peas) were rotated with winter cereals. This did not allow to significantly increase the pea area in FT1 (+ 7 ha), compared to FT2 (+34 ha) and FT3 (+32 ha) due to the land constraints implemented in the model. This increase in 7 ha of peas in FT1 was not sufficient to decrease the values of the above mentioned indicators. The higher share of irrigated area in FT1 (40 ha) compared to FT2 (28 ha) and FT3 (15 ha) was another reason. Our virtual FT1 farmer, simulated with FSSIM, preferred to grow the more profitable irrigated summer crops (maize and soybean), instead of the irrigated spring pea.

4.2. The limits of our work

Some limitations of this work were identified both in conceptual and modeling levels:

- **The simplification regarding the representation of cropping systems**. For this type of study, where the target was to analyse grain legume developement by considering regional diversity, it was difficult to represent all the current agricultural systems observed in the study area. For example, in the MP region a large diversity concerning the crops, crops varieties, soil types, climates and management practices can be found (Nolot and Debaecke, 2003). In this study, only the main crops (without considering varieties), two soil types and two types of crop management (irrigated vs rainfed) have been considered. Practically, it would have been very expensive in terms of money and time to fulfill the large heterogeneous data sets required by this type of analysis (Biarnes et al., 2004).

- **For the representation of farming systems variability**, this study considered only three average and representative farm types over the 5412 real farms in the region (Belhouchette et al, 2011; Andersen et al., 2007). Simulating the behaviour of average farm types using a calibrated FSSIM model ensures that all important crop products that are produced by farms of specific farm type will be part of the simulated production plan. This is very important for upscaling purposes for further analysis at regional scale. Currently we did not consider it due to complexity of aggregation procedure and shortage of time, but in future may be someone would take it into account. Nevertheless, as expressed by Kanellopoulos et al. (2010), using the individual farms (instead of the average ones) for representing the farm types make it more difficult to ensure adequate representation of all observed activities of farms of a specific farm type in the simulated production plans. However, simulating the average farm has also important drawbacks (Louhichi et al., 2010). In reality an average farm does not exist, and consequently, an average activity pattern also does not exist. It is clear that usually the activity pattern of the average farm is much more diversified than that of individual farms. As a consequence, calibrating the FSSIM model by using average farms cropping pattern would require a large number of binding constraints. In many cases, it is possible that such constraints do not even exist in reality and consequently they are difficult to define (Kanellopoulos et al., 2010). It would also be interesting to conduct the same type of scenario approach on individual farm types (real ones) instead of average ones. However, this would require a collection of large biophysical, socio-economic and institutional farm data, which is often impossible. In fact, in many cases (such as the FADN data used in this study) individual farm data are usually treated as confidential information and are not available for research (Zander et al., 2009).

- **The exclusion of the simulation of weeds and diseases effects on crop yield**. This common strategy in most crop simulation studies can be an important source of error. Indeed, several studies suggest that the variability and low yields of grain legumes is due to their sensitivity to diseases and the presence of weeds (Beaver et al., 2003; Coyne et al., 2003). In this study, the effects of diseases and weeds on crop yield were not simulated by the APES model. The main reason is that no specific modules in APES enable for such simulations. In addition, simulating the impacts of weeds and diseases on the current cropping systems in the

Midi-Pyrenees region would require the collection of large data base for model calibration, which is often not available. Therefore, the decision was taken to consider the various effects of weeds and diseases on crop production by expertise. In fact, the performance of each activity has been specified in the survey by expertise (chapter 3, section 3.2.2.1) by considering not only the rotational, the soil, the management and climate effects on crop yield, but also the potential negative impacts of diseases and weeds. For example it was specified, to consider the weeds and diseases effects, that the yield of a pea in a bi-annual rotation is 15% lower than in a 5 years rotation with only one pea. However, by following this methodology, the risk of over-estimating the externalities, such as nitrate leaching, is not negligible is for example growth, and therefore nitrogen uptake is limited by disease damage on legumes crops. As it was impossible to estimate by expertise the impacts of the presence of weeds and diseases on externalities, therefore we assumed that the error generated by their non-simulation would be the same in all scenarios.

- **At the farm level, all constraints are considered on an annual basis** (including labour). However, we know that in many cases it would be more appropriate to specify these constraints on a monthly period basis. Wery and Ahlawat (2007) and Nemecek and GL-Pro partners (2006) found that some agricultural operations generally required more labour than the others. For example, sowing event often requires higher labour, especially in winter when the sowing of cereals and grain legumes take place at the same period. This type of constraint can be introduced in the FSSIM model, but for this purpose two challenges must be fulfilled: i) change the code in FSSIM-MP, which require huge hard coding work, and ii) collection of additional data on monthly or period basis to characterize the input requirement of each cropping system which is usually not an easy task for a large region such as Midi-Pyrenees.

- As reported by (Kanellopoulos et al., 2010), the farmer’s decision making is a dynamic process of resources allocation. In general, with the passage of time more information becomes available and helps farmers in decisions adapted to maximize utility (Belhouchette et al., 2011). This is how the farmers deal with investments, risk and uncertainty. A number of different approaches have been proposed to deal with dynamics and inter-temporal decisions involved in farming (Kanellopoulos et al., 2010; Belhouchette et al., 2011). In many situations and contexts, a multi-years dynamic farm model is more complex and requires information which is often not available at a very large regional scale. The FSSIM model used in this study attempts to capture some of these interactions (e.g. specifying activities as crop rotations instead of single crop). In a static way to match the data requirements with the data availability in EU level databases (e.g. FADN database) a survey on agricultural management has been realized by interviewing experts in the Midi-Pyrenees region. In addition, investment decisions have not been taken into account and for that reason it is important to notice that the model can only be used for relatively short term forecasts where major investment decisions or changes to the fixed costs are not expected.

4.3. APES-FSSIM modeling chain genericity and re-usability

The APES-FSSIM-Indicators modeling chain implemented for this study in the MP region, has been developed for a broader use across european regions in the SEAMLESS project (Van Ittersum et al., 2008), with data currently available in EU databases. However, this modeling chain (as all models) cannot include all factors that influence biophysical, socio-economic and institutional processes acting on farmers decisions.

As mentioned in the above section, a number of limitations and critical choices have been made during this thesis, to take into account data availability for several methodological aspects: integrating the effects of diseases and weeds in post-cropping system modeling, simulating average farms instead the individual ones…. This raises the question of whether our approach can be extended to other EU regions and at which conditions. It is clear that the re-usability of this modeling chain in EU regions to answer policy questions will depend on the target of the study to be adjusted to the available data. Globally, three situations, with different degree of modeling chain complexity, can be identified:

- **Use the modeling chain as an analytical tool** to study the effect of different policy decisions on the behavior of representative farming systems. In this case, the largest efforts must be devoted to: i) collect very detailed data from experiments, surveys and experts to characterize the current agricultural diversities and to calibrate the modeling chain: APES-FSSIM-Indicators; ii) develop/improve existing cropping system models (such as APES or a another one if already calibrated and assessed in the region) in order to simulate all the key variables of crop yields and externalities in the study area; iii) develop/improve the bio-economic model to include, as possible, all the specific constraints of each farming system. In that case the modeling chain can be applied inspecific and very small region with few biophysical and socio-economic diversities and constraints.

- **Use the modeling chain as a tool to help policy maker to take strategic decisions**. In that situation, the overall target is to assess scenarios at regional level with existing databases and the modeling chain results will be often less accurate for each farm type than in the first situation because only common constraints will be considered. However, the main results will be often used in a relative way for comparing scenarios. Overall, the modeling chain APES-FSSIM-Indicators will be less flexible to be implemented without additional development for all EU regions.

- Use the modeling chain APES-FSSIM-indicators in **a model-assisted participatory approach at regional level to help local actors in making a shared decision**. Delmotte (2011) mentioned that combined use of Bio-economic (BEM) approach and agent based approach (ABM) should allow overtaking the main limits of each individual method. BEM will improve ABM because it allows delimiting the "window of opportunities" for agricultural development and identifying the limits of the systems'. On the other hand, in the ABM approach, the key parameters for making farmer decision, such as partnership, networks, neighborhood effects or negotiation, can be considered. In this type of approach, the modeling chain APES-FSSIM-Indicators could be used but by considering only real farm types and by activating limited constraints for a better interaction with farmers. In this case, participation of farmers and regional stakeholders in the simulation process generally allows easier access to detailed data on farms and crop activities (Delmotte, 2011).

Overall, future users of the current modeling chain to assess the impacts of policiesand technological innovations allowing the promotion of legume crops in other EU regions will likely be confronted with the same issues as ones we have faced in this study and they have to, collect data and probably redefine/include new modules in the existing models. In any cases, a tradeoff should be considered between the expected results from the study (which should be specified in interaction with users) and the data availability for the needed spatial scale and the degree of flexibility of the modeling chain APES-FSSIM-Indicators.

4.4. Perspectives for application of the approach

Despite these weaknesses/limitations, this research opens up many opportunities to extend and enrich the analysis for the promotion of grain legumes in MP region in particular and in other EU regions. In fact, the particular novelty of this modeling chain approach is that it i) goes beyond earlier impact assessment models focusing on specific issues and scales, by combining disciplines and scales in a flexible and generic way depending on the policy issue to be addressed (Therond et al., 2009; Ewert et al., 2009) and ii) set up assessments of grain legumes in front of a wide range of biophysical conditions (soil, weather), type of land use system (grassland, cereal, legumes, perennial crops, agro-forestry), and type of socio-economic contexts (CAP reform, nitrate directive).

However, many of the modeling decisions for developing the APES-FSSIM-indicators have been made because of data limitations. This might have implications for the quality of the results of the model. Several modules could be added in the current version of the FSSIM model, e.g. dynamics, structural change, investment, and perennial modules should give more flexibility to the current modeling chain to be used for other EU regions, for large policy questions and for the short and the long terms assessment.

This type of development will be even more recommended if this modeling chain should be applied to other areas outside Europe, such as in my home land. In Pakistan grain legumes are grown only for human food (i.e. called pulses) and on an area ranging from 2 to 5% of the total cultivated area (NARC, 2010; Aslam et al., 2000). However, even that, pulses are one of the major food crops in Pakistan and their demand is increasing day by day with the increasing population. Pakistan's per annum pulse requirement is around one million tons and local production is about 0.7 to 0.8 million tones, which shows a shortfall of about 0.2 million tones (NARC, 2010). Every year, this shortage is fulfilled by importing the pulses from other countries. Pulses production in the country has been on the decline due to lack of government support and many biotic, abiotic stresses of cold, drought, diseases, weeds, insect pest and low yield and price and yield fluctuations etc. (Zahid et al., 2004; Aslam et al., 2000). As compared to Midi-Pyrénées region, in Pakistan a large diversity can be found in term of types of pulses. Major pulse crops grown in the country are chickpea (*Cicer arietinum L.*), lentil (*Lens culinaris Medic*.), mungbean (*Vigna radiata (L.)* Wilczek), black gram or mash *(Vigna mungo L. Hepper).* There are also other summer pulses such as pigeonpea *(Cajanus cajan L. Millsp.),* cowpea *(Vigna unguiculata (L.) Walp.),* moth bean *(Vigna aconitifolia (Jack) Merechal),* common beans *(Phaseolus vulgaris L.)* and winter pulses such as fababean *(Vicia faba L.),* which are considered as minor pulses and are grown on small areas. Most of these crops are cultivated on marginal lands under rainfed conditions (Aslam et al., 2000). Moreover they are also facing almost same climatic, agronomic, socio-economic and environmental production problems as in Mediterranean regions (NARC, 2010; Zahid et al., 2004; Ramakrishna et al., 2000). Therefore, it would be of great importance to consider the same approach to address similar questions on legumes production in Pakistan. In this context the main challenges would be:

- To adapt/develop the APES model in order to simulate all the current legume crops. The main challenge here will be to collect experimental data that could serve to develop and parameterize the new modules. Various experiments on legume crops are conducted by the NARC (National Agricultural Research Centre) and UAF (University of Agriculture Faisalabad), but, as everywhere in the world, they appear difficult to collect and with key variables for model calibration (e.g. LAI dynamic) missing.

- At farm scale, the current version of the FSSIM model simulates only the rented labour (Louhichi et al., 2007). In Pakistan for farming system production, generally there are three types of labour i.e. family, daily wages and labour exchanged between farmers. Moreover, the availability of rent labour on high period of requirement is also questionable. Therefore, to include this kind of constraints, some modifications would have to be made in the FSSIM model code.

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Annexe 1: Questionnaire : quelle perspective pour les légumineuses en France

A1. Introduction :

L'objectif ultime de ce questionnaire est d'identifier des scénarios crédibles permettant d'encourager les agriculteurs à cultiver plus les légumineuses dans les systèmes de culture actuels : les solutions proposées doivent tenir compte les enjeux socio-économiques (revenu agricole, main-œuvre…), environnementaux (érosion, lessivage de l'azote…) et techniques (innovation technique…) de la région étudiée.

Ce document (questionnaire) est subdivisé en deux parties :

A1.1. La première partie vise à identifier les principales contraintes et limites quand au développement des légumineuses dans la région Midi Pyrénées.

A1.2. La deuxième partie de ce questionnaire visera à identifier des solutions, techniques et politiques, (qui seront testée plus tard avec la chaine de modèle APES-FSSIM-Indicateurs) permettant une meilleure intégration de système de culture à base de légumineuse.

A1.1. Identification des principales contraintes et limites du développement des légumineuses dans la région Midi Pyrénées

A1.1.1. Quelles sont les principales rotations dans votre région ? …………………………… ………………………………..

A1.1.2. Quelles sont les légumineuses couramment cultivées ?

………………………………. ………………………………

A1.1.3. Pourquoi pas d'autres?

………………………………………………………………………………………………

A1.1.4. Dans quels types de rotations les agriculteurs préfèrent introduire les légumineuses à grain?

…………………………….. ……………………………….

A1.1.6. Dans quels types de sol vous cultivez les légumineuses à grains ?

…………………………………. ………………………………

A1.1.7. Pourquoi ?

……………………………………………………………………………………………

A1.1.8. Quelles sont les différences entre les rotations avec des légumineuses à grains et les rotations sans légumineuses à grains ? Si vous n'avez pas des chiffres, utilisez une des symboles suivantes (+ ou -)

	Rotations avec des légumineuses	Rotations sans des légumineuses
Utilisation des machines (Hours/ha)		
Quantité d'engrais N P K	 …………………………… ………………………….. ……………………………	 ………………………….. …………………………. ……………………………
quantité des pesticides	.	.
Main d'œuvre (h/ha)		
Cout de production (€/ha)		
Rendement (T/ha)		
Marge brute (€/ha)		

A1.1.9. Quelles sont les principales contraintes pour la production de légumineuses à grains dans la région Midi-Pyrénées ?

A1.1.9.1 : Contraintes/avantages agronomiques : Tableau : principales contraintes biophysiques des légumineuses

	Légumineuse d'hiver			Légumineuses de printemps		
	Pois	Fèverole	lupin	Pois	Fèverole	lupin
Sol						
Maladie						
Sensibilité au gel						
Sensibilité à l'excès d'eau						
Stress hydrique						
Stress thermique						
Problème de la récolte						
Autres						

A1.1.9.2 : Contraintes/avantages agro-environnementaux : comparaison d'une rotation céréale/légumineuse et une rotation céréale/céréale.

Ce tableau vise à identifier les principaux impacts (problèmes/avantages) d'une rotation de type céréale-légumineuse par rapport à la rotation céréale-céréale. Pour indiquer cette différence, il faut utiliser une des symboles suivantes (➚ ou➘).

	Légumineuse d'hiver-céréale*/céréale-céréale				Légumineuse de printemps-céréale/céréale-céréale			
Description	Sec		irriguée		sec		Irriguée	
	Argilo-calcaire	Argilo-limoneux	Argilo-calcaire	Argilo-limoneux	Argilo-calcaire	Argilo-limoneux	Argilo-calcaire	Argilo-limoneux
Fertilité du sol : Résidu d'azote M.O	………….. ……………	………….. ……………	………….. ……………	………….. ……………	………….. ……………	………….. ……………	………….. ……………	………….. ……………
Var du rendement de la céréale après : Pois Féverole Lupin	………. ……… ……….	………. ……… ……….	………. ……… ……….	………. ……… ……….	………. ……… ……….	………. ……… ……….	………. ……… ……….	………. ……… ……….
Problème phytosanitaire								
Erosion								
Lessivage								
Consommation d'énergie								
Autres								

* variation des paramètres agro-environnementaux d'une rotation céréale-légumineuse par rapport rotation céréale-céréale.

A1.1.9.3. Contraintes/avantages socio-économique : comparaison d'une rotation céréale/légumineuse et une rotation céréale/céréale.

Ce tableau vise à présenter les conséquences socio-économiques (problèmes/avantages) d'une rotation de type céréale-légumineuses par rapport à la rotation céréale-céréale. Si vous n'avez pas des chiffres, utilisez une des symboles suivantes (+ ou -).

	Légumineuse d'hiver-céréale*/céréale-céréale				Légumineuse de printemps-céréale*/céréale-céréale			
Description	Sec		irriguée		sec		irriguée	
	Argilo-calcaire	Argilo-limoneux	Argilo-calcaire	Argilo-limoneux	Argilo-calcaire	Argilo-limoneux	Argilo-calcaire	Argilo-limoneux
Charge opérationnel:								
Travail du sol	……… …	……… …	……… …	……… …	……… …	……… …	……… …	……… …
Semis	……… …	……… …	……… …	……… …	……… …	……… …	……… …	……… …
Fertilisation	……… …	……… …	……… …	……… …	……… …	……… …	……… …	……… …
Traitement phytosanitaire	……… ..	………..	………..	………..	………..	………..	………..	………..
Désherbage	……… …	……… …	……… …	……… …	……… …	……… …	……… …	……… …
Irrigation	……… …	……… …	……… …	……… …	……… …	……… …	……… …	……… …
Main d'œuvre	……… …	……… …	……… …	……… …	……… …	……… …	……… …	……… …
Autres	……… …	……… …	……… …	……… …	……… …	……… …	……… …	……… …
Primes								
Marge brute								
Autres								

***** variation des paramètres socio-économique d'une rotation céréale-légumineuse par rapport rotation céréale-céréale.

A1.2. Questionnaire pour l'identification des scénarios alternatifs

A1.2.1. Scénario politique

A1.2.1.1. Est ce que l'augmentation de la prime consacrée aux légumineuses peut promouvoir cette culture en Midi Pyrénées ?

Conditions d'augmentation de la prime	Description
Quelles légumineuses	
Dans quelle rotation	
Avec quelles techniques	
Dans quel type de sol	
Autres	

A1.2.1.2. Est ce que le recours à la taxation (azote, eau…) peut modifié le plan d'assolement en faveur les légumineuses ?

Produit à taxer	Niveau de taxation	Impacts		
		Agronomique	Economique	environnemental
Exemple : azote	20%	*Réduit l'utilisation d'azote de 10% dans une rotation de type céréale-céréale *réduit le rendement de 15%	*réduit la marge brute de 5%	* réduit le lessivage de 2%

A1.2.2. Scénario d'innovation technologique

A1.2.2.1. Quel type d'innovation technologique (nouvelle rotation, nouvelle technique de production…) peut-il proposer dans la Midi Pyrénées pour encourager les légumineuses ?

Innovation technologique	Description	Impacts
Exemple : nouvelle rotation (pois d'hiver-tournesol)	Sol : argilo-calcaire Technique : en irriguée Semis de pois : entre 5 et 20 novembre Profondeur de semis : 5 cm	*amélioration de la fertilité du sol *réduit les maladies *augmente le rendement du tournesol

Annexe 2: General equations for indicator calculation in FSSIM model (Louichi at al., 2009)

A2.1. Production

The general equation for production can be written as:

$$MO_j = \sum_{i,t} Y_{i,j,t} \frac{x_i}{\eta_i} / \sum_i x_i \tag{1}$$

Where:

- J is the indexes for set of economic outputs
- Y is a vector of economic outputs (i.e. yield) produced by each agricultural activity
- MO is a vector of model outputs at farm level

A2.2. Farm income

The general equation for farm income in FSSIM model is formulated as:

$Z = Z_c + Z_a + \text{Pr}em + PMPterm$ (for both crops and livestock) (2)

Where:

- Z is the expected income (in euros)
- Zc is the crop income without premiums (in euros)
- Za is the livestock income without premiums (in euros)
- Prem is the received EU premium (in euros)
- PMPterm is the PMP terms (in euros)

However specifically the indicator of farm income is calculated as an expected farm income (**Z**) which is considered as a non-linear profit function. Using mathematical notation it can be written as:

$$Z = \sum_J p_J q_J + \sum_{J,l} p^a_{J,l} q^a_{J,l} + \sum_{i,t} \frac{s_{i,t}}{\eta_i} x_i (1 - \alpha b) - \sum_{i,t} \frac{c_{i,t}}{\eta_i} x_i + \sum_{i,t} \left(\frac{d_{i,t}}{\eta_i} + \frac{\psi_{i,t} x_i}{2\eta_i} \right) x_i - \varpi L \tag{3}$$

Where:

- i indexes agricultural activities,
- j indexes crop products,
- l indexes quota types (e.g. for sugar beet these are A and B),
- t indexes the number of years in a rotation,
- p is a vector of average product prices,
- q is a vector of sold production,
- p^a is a vector of additional price that the farmer gets when selling within quota l,
- q^a is a vector of sold production within quota l,
- s is a vector of subsidies per crop within agricultural activity i (depending on the Common Market Organisations (CMOs)),
- c is a vector of variable cost per crop within an agricultural activity i,
- d is a vector representing the linear term used to calibrate the model (depending on the calibration approaches),
- ψ is a symmetric, positive (semi) definite matrix of a quadratic term used to calibrate the model (depending on the calibration approaches),
- η is a vector representing the length of a rotation within each agricultural activity,
- $\acute{\omega}$ is a scalar for the labor cost
- L is the number of hours of rented labor

A2.3. Total cost

Total cost for crop production in FSSIM can be written as:

$$\text{Total cost} = \left[\sum_{r,s,t,p,sys} \text{Costs}_{r,s,t,p,sys} \cdot \frac{X_{r,s,t,sys}}{N_r} + \sum_{r,ggrs,gprds,t,p,sys} \text{Harv\_Costs}_{r,ggrs,gprds,t,p,sys} \cdot Bv_{r,ggrs,gprd,s,t,p,sys} \cdot \frac{X_{r,s,t,sys}}{N_r} \right] \quad (4)$$

(Variable costs for crops without mineral fertilizer costs) + (Harvesting costs of grass)

$$+ \quad [\text{ Nfertilizer} * \text{pfertilizer}] \quad (5)$$

(Costs of purchased for N and P fertilizers)

$$+ \sum \text{twage.Tlabour} \quad (6)$$

(Average labour cost)

Where:

Index

- i is the index for agricultural activities, r, s, t, p, sys represents crop rotations, soil types, production techniques, period (i.e. yeras) and systems (i.e. production orientation) respectively
- ggrs represents the grass groups (lye, temporary and permanent grassland) and gprd is the grass product types (silage, hay, fresh…)
- Nr: number of years within each crop rotation, i.e. the length of crop rotation (2 years, 3 years, 4 years …)

Parameters

- $Harv\_costs_{i,gprd}$ represents the harvesting cost per grass and product types gprd within activity i
- $Bv_{i,ggrs,gprd,p}$ represents the the grass product decision
- Nfertilizer and Pfertilizer are Mineral fertilizer prices (Euros/kg)
- Twage is the labour cost (Euro/hour) and Tlabour is the average number of hours borrowed labour (in hours)

Variables

- $X_{c,s,t,sys}$ is the level of selected crop per soil type, production technique and system.

A2.4. N fertilizer use

The indicator of "N fertilizer use" in FSSIM model refers to the amount of N fertilizer that is required to satisfy the N requirements of crops and grassland grown on the farm. It is represented as:

$$N_{requirement} = \sum Nuse_{r,s,t,sys,p} X_{r,s,t,sys} / N_r \qquad (7)$$

Where:

- $N_{requirement}$ is the N requirement of all crops and grassland needed to produce them (kg N per farm),

- Nuse represents the N requirement of each crop within each agricultural activity (kg N per ha),
- r, s, t, sys, p are the indices of crop rotations, agri-environmental zones, production techniques and number of years in a rotation
- $X_{r,s,t,sys}$ and N_r represent the agricultural activities (in ha) and length of a rotation (in number of year) respectively

A2.5. Externalities (N leaching, Soil erosion...)

For calculation of externalities at farm scale, firstly, for each activity the environmental indicators can be simulated at field scale by using APES model. Then for each selected scenario, the FSSIM model was run in order to select most profitable activities. At the end the average value of each environmental indicator simulated by APES model is calculated at farm scale by aggregating values of FSSIM selected most profitable activities (Belhouchette et al., 2011). The general equation for aggregation is given as:

$$MO_o = \sum_{i,t} E_{i,o,t} \frac{x_i}{\eta_i} \Big/ \sum_i x_i \qquad (8)$$

Where:

- O is the indexes the set of environmental externalities
- E is a vector of environmental outputs linked to each agricultural activity (most of these data are generated by APES model)
- MO is the vector of model outputs at farm level

A2.6. Total Energy use

The indicator of total energy use was calculated outside the modeling chain APES-FSSIM-Indicators. For this purpose, the INDIGO method of energy calculation was considered (Bockstaller and Girardin, 2003 and Pervanchon et al., 2002). Pervanchon et al. (2002) separated the energy use by crops into two parts, direct energy use and indirect energy use. Direct energy use includes the fuel and electricity which are directly used at farm and on fields. The indirect energy use includes the fertilization, seeds, machinery, irrigation and pesticides. Among these five items due to deficiency of data, only four major (fertilization, machinery, irrigation and pesticides) items of indicator total energy use were considered in this study. Pervanchon et al. (2002) reported the method and the corresponding equations for energy indicator that can be used for the arable cropping systems. The same method and equations for the indicator of total energy use are also considered for this study.

A2.6.1. Energy used by machinery

It is difficult to estimate the energy used by machinery at farm due to missing the necessary information required from the farmers (Pervanchon et al., 2002). However, it can be estimated indirectly for each pass of the equipments, by following equation (9) given by Donaldson et al. (1994).

$$E_m = (36P_n) / (VLF) \qquad (9)$$

Where:

- E_m is the energy used by machinery (MJ/ha)
- P_n is the power required by tractor for specific equipment (kW)
- L is the width of the machine (m)
- V is the forward speed of the tractor (km/h)
- F is the field efficiency (%)

Donaldson et al. (1994) defined the field efficiency as the percentage of time, in which machine remains actually in work and not turning on headlands or refilling.

Pervanchon et al. (2002) adapted the equation (9) by replacing P_n by the factor P_a/η and did the addition of some correction factors for F, as given in equation (10).

$$E_m = [(36P_a/\eta) / (VLC)] + D/S \qquad (10)$$

Where:

- P_a is the absorbed power by tractor used in carrying the machine for its functioning (kW)
- C is a correction coefficient, which take into account the risk of over-consumption,
- D is a correction factor, which take into account the distance between the farm and the field
- S is the field area (ha)

- η is the engine efficiency estimated at 35% (CEMAGREF, 1991a)

All of above data given in equations (9) and (10) are difficult to fulfill at farm level. The SEAMLESS database (Zander et al., 2009) is lacking the information of all machinery factors and coefficient given in both equations. However, in this database, the data on type of machine and number of hours used for a specific operation are available. Bockstaller and Girardin, (2003) have already calculated the amount of energy used by machinery by following the factors and coefficient given in equations (9) and (10). Table A2.1 shows that amounts of energy used for a specific machine and specific operation calculated by (Bockstaller and Girardin, (2003). This table shows that if only the data on type of machine and number of hours used by the machine for a specific operation are available then one can calculate the energy used by machinery for a specific operation. As mentioned above that data on type of machine and number of hours used by machinery for a specific operation are available in the SEAMLESS database (Zander et al., 2009). Therefore in this study, the same amounts of energy used for specific machinery and operation given in table A2.1 were used.

Table A2.1 : Amount of energy used (MJ/h) for a specific machinery and specific agricultural operations (Bockstaller and Girardin, 2003)

Kind of operation	Type of machine	Efficiency (h/ha)	P_a (kW)	C	V (km/h)	L (m)	Puisabs (intermediate)	Energy consumption (MJ/h)
Soil tillage	Cover crop 28 -32 disques (100-120 ch)	1	0.736	1	3.33	3	52	391.4
	Plough with 5 ploughshares (130 ch)	1	0.736	1	3.33	3	65	490.6
	Rotative harrow 3 m (100 ch)	1	0.736	1	3.33	3	65	490.6
Sowing	Seed drill 3 m (110 ch)	1	0.736	1	3.33	3	22	166.2
Fertilization	Fertilizer distributer (120 ch)	1	0.736	1	8	15	10	6.4
Pesticides application	Pesticide sprayer 15 to 18 m rampe (90 ch)	1	0.736	1	11	15	56	25.6
Harvesting	Combine harvester 6 m (300 ch)	1						1127

A2.6.2. Energy used by irrigation system

Pervanchon et al. (2002) reported that energy used by irrigation system is based on the same method as energy used by machinery. For this purpose, they used the general equation (11) given by Duke (1989):

$$E_i = (36P_uI/ (QG)) + A/S \qquad (11)$$

Where:

- E_i is the energy used by an irrigation system (MJ/ha)
- P_u is the absorbed power by the pump (kW)

- I is the irrigation amount (mm)
- Q is the water flow (m3/h)
- G is a correction coefficient, which takes into account the risk of over-consumption
- A is a correction coefficient, it takes into account the cost of energy used for implementation of the irrigation system (reservoir or drilling)
- S is the area of the irrigated field (ha)

Pervanchon et al. (2002) stated that P_u must be estimated, but due to non-availability of data at farms, they considered the data provided by experts. In addition they also considered some hypothesis on parameters and expressed the P_u as a function of available variables on farm as follow.

$$P_u = [2.72Q\ [B+z_2-z_1+0.0826(0.065L/D^5+0.20)\ (Q^2/3600^2)]]/1000 \qquad (12)$$

Where:

- L is the pipe length (m),
- D is the average pipe diameter (m),
- Z_2-Z_1 is the height of pumped water (m),
- B is one of the members of the total manometric height formula; as a function of the pressure difference of water between entry and exit of the irrigation system and it depends on the type of irrigation system. After discussion with experts, Pervanchon et al. (2002) proposed the value of "B" as 51.8 for localized irrigation and 31.1 for integral cover irrigation.

The correction factor G in equation (11) can be further described by three factors:

$$G = G_1 G_2 G_3 \qquad (13)$$

Where:

- G_1 is a correction coefficient for the application efficiency
- G_2 considers the water transport efficiency
- G_3 varies with the maintenance and accessories of the irrigation systems

The explanation of these correction factors were given by Pervanchon et al. (2002).

The correction coefficient A given in equation (11) takes into account the estimation of energy cost for drilling or irrigation reservoir and can be presented as:

$$A_{drilling} = [(\text{drilling height}).\ ((4000 + 120 + 130)]/30 \qquad (14)$$

The detail of $A_{drilling}$ correction coefficient is given in Pervanchon et al. (2002). The SEAMLESS database (Zander et al., 2009) is lacking the information's required for calculation of energy used by irrigation system as given in equations (11), (12), (13) and (14). However, Bockstaller and Girardin, (2003) has already calculated the amount of energy used by irrigation system by using above method of energy used and proposed a 5.5 MJ of energy required to irrigate an area of 1 m^3/ha for a sprinkler or pivot irrigation system. Therefore, if one has data on amount of irrigation water for a specific area, then the amount of energy used by irrigation can be calculated. In SEAMLESS database (Zander et al., 2009), the data on quantity of irrigation water (m^3/ha) for each crop is available. Thus we calculated the amount of energy used for irrigation of all crops by using the value (5.5 MJ for an area of m^3/ha) given by Bockstaller and Girardin, (2003).

A2.6.3. Energy used by fertilization

Pervanchon et al. (2002) reported that energy used by fertilization can be calculated by multiplying the amounts of fertilizers by a specific energetic coefficient. They proposed the following relation for calculating the energy used for fertilization.

If quantity of fertilizer given in kg then:

E_{fert} = (Quantity of fertilizer (kg) *fertilizer coefficient) +FPT (15)

If quantity of N, P_2O_5, K_2O contents given in kg rather than quantity of fertilizer then:

E_{fert} = [(Quantity of N, P_2O_5, K_2O contents (kg) /percent of N, P_2O_5, K_2O content in respective fertilizer) * fertilizer energy coefficient] +FPT (16)

Where:

- E_{fert} is the energy used by fertilization,
- FPT is the energy cost of Formulation, Packaging and Transport of the fertilizers. On an average the FPT cost is estimated to be 1.5 MJ/kg of N fertilizers, 9.8 MJ/kg of P fertilizers and 7.3 MJ/kg of K fertilizers. For NP fertilizers, Pervanchon et al. (2002) used the mean value between N and P fertilizers: 5.7 MJ/kg. They also used the mean value of 6.0 MJ/kg for all other type of fertilizers. In this study, we considered only the N fertilizer with FPT value as 1.5 MJ/kg.

For percentage (from 0 to 100%) of N, P_2O_5, and K_2O content in respective fertilizers they used the values given in table (A2.2). In SEAMLESS database (Zander et al., 2009) the information on quantity of fertilizer used as N content is available. Therefore in this study we calculated the amount of energy used for each crop by using formula given in equation 16.

Table A2.2 : Energy values of coefficients for different fertilizers (given by Pervanchon et al., 2002)

Fertilizer name	Energy coefficient
Ammonia)	32,8
Ammonium nitrate 27%	13,4
Ammonium nitrate 33,5%	16,6
Urea	26,0
Solution	19,2
Ammonium sulphate	9,6
Super triple 45	8,5
Slag (scories)	*2,3*
KCl	7,2
Sulfate K	*6,8*
0-15-30	*4,5*
0-17-27	*4,5*
0-18-28	*4,7*
0-20-30	*5,1*
0-24-24	*5,1*
0-25-25	*5,4*
12-52-0	*11,5*
13-13-13	*8,0*
13-13-21	*8,6*
14-20-20	*9,9*
15-15-15	*9,2*
14-20-20	*9,9*
18-46-0	12,0
24-6-12	*11,3*
9-23-30	*9,1*

A2.6.4. Energy used due to pesticides application

Pervanchon et al. (2002) suggested the calculation of energy used due to pesticides by the relation given in equation (17).

$\mathbf{E_{pesticides}}$ = Amount of pesticides used (kg/ha)* coefficient value for each pesticide active ingredients (17)

They extrapolated the existing data provided by Green, (1987) and Lambert, (1996) for energy coefficient of some active ingredient of same family (Table A2.3). The energy used by pesticides, using above method has also been described and validated by Gaillard et al., (1997). Pervanchon et al. (2002) reported that in the absence of data for the same family, the average energy used of all products of the same type (insecticide, herbicide...) can be taken as: insecticides = 310 MJ/kg, herbicides = 272 MJ/kg, fungicides = 214 MJ/kg. In the SEALLESS database (Zander et al., 2009); total amount of pesticides used is available, while the data on separate use of herbicides, fungicide, or insecticide are not available. Therefore, in this study we considered the average of insecticides, herbicides and fungicides as 265 MJ/kg.

Table A2.3 : Energy coefficients for different active materials in pesticides **(**Green, 1987 and Lambert, 1996).

Family	Action mode	Active material	Coefficient
Dérivés aryloxy acétiques	Herbicide	2,4-D*	85
Diphényléthers	Herbicide	Aclonifen	267
Dérivés des amides	Herbicide	Alachlore	278
Triazines	Herbicide	Atrazine	190
Strobilurines	Fongicide	Azoxystrobine	214
Non classé	Herbicide	Bentazone	434
Diphényléthers	Herbicide	Bifenox*	268
Benzonitriles	Herbicide	Bromoxynil octanoate	268
Carbamates	Fongicide	Carbendazime*	400
Carbamates	Insecticide	Carbofuran*	454
Choline	Raccourcisseur	Chlormequat*	246
Non classé	Fongicide	Chlorothalonil	118
Acide propionique	Herbicide	Clodinafop-propargyl	518
Quinoline	Herbicide	Cloquintocet-mexyl	272
Pyréthrinoïdes de synthèse	Insecticide	Cyperméthrine	580
Pyrimidines (anilino-)	Fongicide	Cyprodinil*	190
Pyréthrinoïdes de synthèse	Insecticide	Deltaméthrine	580
Acide benzoïque	Herbicide	Dicamba*	295
Amides (thiophén-)	Herbicide	Dimethenamid	265
Organophosphorés systémiques	Insecticide	Diméthoate	184
Urées (substituées)	Herbicide	Diuron	270

Azoles (tri-)	Fongicide	Epoxiconazole	250
Acide propionique	Herbicide	Fénoxaprop-P-ethyl	518
Morpholines	Fongicide	Fenpropimorphe*	190
Acide pyridyloxyacétique	Herbicide	Fluroxypyr*	268
Phosphinates (méthyl-)	Herbicide	Glufosinate (sel d'ammonium)	272
Benzonitriles	Herbicide	Ioxynil*	268
Urées substituées	Herbicide	Isoproturon*	309
Organochlorés	Insecticide, nématicides	Lindane*	58
Aryloxy-propioniques	Herbicide	Mecoprop (ou MCPP)*	130
Non classé	Molluscicide	Métaldéhyde	241
Amides	Herbicide	Metazachlore*	284
Acétanilides	Herbicide	Métolachlore	276
Urées (sulfonyl-)	Herbicide	Metsulfuron méthyle*	309
Urées (sulfonyl-)	Herbicide	Nicosulfuron	315
Toluidines	Herbicide	Pendiméthaline*	154
Pyridazine (phényl-)	Herbicide	Pyridate	268
Carbamates	Insecticide	Pyrimicarbe*	306
Acides quinolénine carboxaliques	Herbicide	Quinmérac	272
Cétones (tri-)	Herbicide	Sulcotrione	272
Azoles (tri-)	Fongicide	Tébuconazole	250
Morpholines	Fongicide	Tridémorphe	190
Toluidines	Herbicide	Trifluraline*	150
Non classé	Raccourcisseur	Trinexapac-ethyl	248

A2.6.5. Indication of total energy used

Pervanchon et al. (2002) calculated the indicator of total energy use by the aggregation of all above given items as given in equation 18.

$$E_t = E_{machinery} + E_{irrigation} + E_{fertilizers} + E_{pesticides} \quad (18)$$

Where:

- E_t is the total energy used at the field scale (expressed in MJ/ha),
- $E_{machinery}$ is the sum of the energy consumed by machinery
- $E_{irrigation}$ is the sum of the energy consumed by irrigation system
- $E_{fertilizers}$ is the sum of the energy consumed by fertilizer application
- $E_{pesticide}$ is the sum of the energy consumed by pesticides application

Annexe 3: Constraints in FSSIM model

The FSSIM includes a set of explicit resource (arable land, grass and irrigable land per agri-environmental zone, labour, water…), policy (minimum and maximum set-asides, production quotes, cross compliance…) and animal (feed requirement vs feed availability, Feed restrictions, maximum share of concentrates in animal diets, maximum feed availability from grazing…) constrains (Louhichi et al., 2007)**.** The aim of including these constrains, is to make model more realistic for operating in real conditions for different farms in EU (Louhichi et al., 2007). Moreover it is important to introduce constraints in optimization model to characterize the different production systems and understanding the evolution of each farm type subjected to a specific constraint (Mallouli, 2010). Indeed, the choice of production system depends largely on biophysical constraints and economic policies that result in:

- Competition between several activities or variables for the use of a scarce resource (water, labor ...)**.**
- Influence of an exogenous economic or political situation on the production system.

The productive constraints occur in most of farm optimization model and they related to farm resources endowers. The principal productive capacity constraints currently implemented in FSSIM model are the land, labour and water constraints (Louhichi et al., 2007). Although FSSIM included many other constrains, but here we have listed only productive and set-aside constraints.

A3.1. Land constrains

A3.1.1. Arable land

The availability of land per farm type is specified by soil type. The purpose of this constraint is to limit the availability of land i.e. the amount of land devoted to different crops must be less than or equal to the total useable agricultural area (UAA) per farm (Louhichi et al., 2007). Mathematically it is written as:

$$\Sigma X_{c,\,t,\,s} \leq SAUS \qquad (19)$$

Where:

- $X_{c,\,t,\,s}$ represents the area under each type of soil
- SAUS is the available area by soil type

A3.1.2. Permanent cropland

Louhichi et al. (2007) stated that all permanent (perennial) crops (citrus, apples, olives, tobacco, grapes, olives…) are related to long term investment decisions and it assumes that the levels of perennial crops should be equal as observed in the base year. It is written as follow:

$$\sum_{t,sys} X_{percrops,s,t,sys} = X^{0}_{percrop,s} \tag{20}$$

Where:

- percrops is the index for perennial crops
- $X_{percrops,s,t,sys,}$ is the level of perennial crops with soil type, production technique and cropping syetm (ha)
- $X^{0}_{percrops,s\ ,}$ is the area of perennial crops observed in base year per soil type (ha)

A3.1.3. Grassland

Louhichi et al. (2007) stated the grassland constrains as more complicated due to quality and variation in grassland from one farm to another. Initially, they separated the grasslands as temporary grassland and permanent grassland. For modeling grassland activities, they selected ley grass (like annual crop), temporary grassland (mono-crops rotations of 4 years) and permanent grass (monocrop rotations for several years). Then they differentiate the temporary and permanent grass in term of technical coefficients. In the current version of FSSIM, they fixed that temporary and permanent grassland activities in each farm cannot exceed the initial grassland endowment. It is represented as:

$$\sum_{t,sys} X_{'grss',s,t,sys} \sum \le PERGRLAND_{s} \tag{21}$$

$$\sum_{t,sys} X_{'grst',s,t,sys} \sum \le TEMGRLAND_{s} \tag{22}$$

Where:

- $X_{'grss',s,t,sys}$ represents the level of permanent grass per soil type, production technique and cropping system (in ha)

- $PERGRLAN_s$ and $TEMGRLAN_s$ are the permanent and temporary grassland endowment respectively per soil type (in ha)

A3.1.4. Irrigable land

It is explained as, total area dedicated to different irrigated activities should not exceed the available irrigable land (Louhichi et al., 2007). It can be expressed as:

$$\sum_{r,s,ti,sys} X_{r,s,ti,sys} \leq Irland \qquad (23)$$

Where:

- t_i is the index for the irrigated technique
- $X_{r,s,ti,sys}$ is the area of the selected activity *i* (ha)
- Irland is the initial available irrigable land (ha)

A3.2. Labour constraint

Louhichi et al. (2007) reported that on the farm for conducting different operations, there are several types of labour with different costs and available working days under the limitations of weather. It is stated that generally for each type of labour, in addition to temporary labour, total labour required for each selected activity should be less than available family and permanent labour. However, in current version of FSSIM due to data deficiency, the authors did not included the specification of labour availability and requirement per type of labour as well as the division between permanent and family labour availability. It is assumed that there is only one labour type and all the available labour is of family labour. It is expressed as:

$$\sum_{r,s,t,sys,p} X_{r,s,t,sys} * Lr_{r,s,t,sys,p}/N_r = Lreq \leq Flabour + Tlabour \qquad (24)$$

Where:

- $X_{r,s,t,sys}$ is the level of the selected activity i (i.e. $i = r,s,t,sys$) (ha)
- $Lr_{r,s,t,sys,,p}$ is the type of labour required per year (P) for each activity $_i$ (hours/year)
- N_r is the number of years within each crop rotation

- Lreq is the sum of labour required for each selected activity (hours/year)
- Flabour is the available family working day related to limitations of weather conditions (per labour type (k))
- Tlabour is temporary labour available (hours/year)

A3.3. Water requirement constraints

According to Louhichi et al. (2007) water requirement constrains are linked to irrigated agricultural region. It is explained that sum of water required for each selected activity should not exceed the availability of total volume of water. It can be expressed as:

$$\sum_{r,s,ti,sys,p} X_{r,s,t,sys} . Wr_{r,s,ti,sys,p} / N_r = Wused \leq Towater \qquad (25)$$

Where:

- t_i represents the index for the irrigated technique
- Xr,s,t,sys, is the level of the selected activity *i* (i.e. *i* = *r,s,t,sys*) (ha)
- $Wr_{r,s,t,sys,p}$ is the irrigation water requirement for each irrigated crop within agricultural activity *i* (m3/year)
- Wused is the sum of water required for each selected activity (m3/year)
- N_r is the number of years within each crop rotation
- Towater is the total available water per year (m3/year)

A3.4. Set-aside constraint

With reference to the agreement of the common agricultural policy, a set-aside rate of 10% of the area allocated to cereals, oilseeds and protein (SCOP) is mandatory. This minimum percentage is required to qualify for European subsidies. However, a maximum rate of 30% of SCOP is not exceeded. Fallow is introduced into the model and expressed as 'FALL':

$$\Sigma X_{FALL,\, t,\, s} \geq 0.1\, \Sigma X_{scop,\, t,\, s} \qquad (26)$$

$$\Sigma X_{FALL,\, t,\, s} < 0.3\, \Sigma X_{scop,\, t,\, s} \qquad (27)$$

Where**:**

- X_{FALL} represent the fallow area (in ha).

- X_{scop} is the area of SCOP in different techniques and types of soil.

Louhichi et al. (2007) also reported the constraints related to livestock (herd demography, feeding requirements and restrictions, livestook building), investment, cash flow, Equipment requirement, risk etc. For detail see Louhichi et al. (2007).