DIVERFARMING

Crop diversification and low-input farming across Europe: from practitioners' engagement and ecosystems services to increased revenues and value chain organisation

DEVELOPMENT OF ROUTINES TO SIMULATE C SEQUESTRATION OF DIVERSIFIED CROPPING SYSTEMS

Deliverable D7.2

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Executive summary

The implementation of diversification strategies under low-input management in place of traditional farming systems is gaining attention in agriculture not only to meet up the demand of food for over growing populations but also with respect to environmental resilience and sustainability. The aim of Diverfarming is to increase the long-term resilience, sustainability and economic revenues of agriculture across the EU. The Diverfarming project is assessing the real benefits, while minimising limitations, barriers and drawbacks, of diversified cropping systems using low-input agricultural practices that are tailor-made to fit the unique characteristics of six European pedoclimatic regions (Mediterranean South and North, Atlantic Central, Continental, Pannonian and Boreal) and by adapting and optimising the downstream value chains organization through 13 short term (3 years) and 7 long-term (7-21 years) field case studies. An important part of the Diverfarming project involves the simulation of soil organic carbon (SOC) sequestration in the European agroecosystems addressed above. The process-based model ECOSSE (Estimate Carbon in Organic Soils-Sequestration and Emissions) has been chosen as a starting point to develop a new modelling tool able to account for all six pedoclimatic regions' conditions and simulate all new low input agricultural practices. ECOSSE has been widely used to simulate SOC dynamics both in mineral and organic soils from field to regional scale. However, the use of ECOSSE under diversified cropping systems and farming managements in very diverse climatic regions is limited. This report presents how new algorithms were developed and existing ones modified to make ECOSSE suitable to estimate SOC content for all Diverfarming diversified agroecosystems. The main modifications made to ECOSSE concern the modelling of 1. different soil types (moisture categories: normal, dry, semiarid); 2. the possibility of multiple cropping in arable land; 3. SOC dynamics under woody cropland (olive/almond, citrus and grapevine); 4. intercropping with woody and herbaceous crops; and 5. irrigation.

The model was parameterised against 7 long term experimental plots and evaluated against the case studies across all European agroecosystems considered in Diverfarming (four are presented here). A reasonable agreement between modelled and measured SOC under different cropping systems and farming managements suggests that the modified version of ECOSSE is suitable to represent all diversifications considered in Diverfarming, both at field and regional scale.

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1. Introduction

Agriculture has developed towards increasing intensification but simplified production with lower diversity of cropping systems, higher genetic uniformity, and a higher uniformity of agricultural landscapes. These practises have shown detrimental effects on environment and biodiversity, and the adaptability of these cropping systems to climate change has been a growing concern (Hufnagel et al., 2020). It has been observed that according to various outcomes (e.g., productivity, profitability, biodiversity) different diversification strategies such as rotations, cover crops, and agroforestry (among others) can be a possible solution strategy, as they can help reducing the negative environmental impacts and loss of biodiversity, while stabilising the productivity of the cropping systems (Beillouin et al., 2019). Therefore, innovation based on crop diversification can represent an important step towards the development of more sustainable agriculture systems in Europe (Iocola et al., 2020).

1.1. Diversified cropping systems in Europe

Research in agriculture is important to achieve the sustainable development goals of ending poverty and hunger, and addressing climate change, but also of sustaining natural resources (Nhemachena et al., 2018). To meet the demand of a growing population and as consequence to climate change, intensive agricultural systems, e.g., extensive use of fertilizers, pesticides, intense mechanization, and monocultures, have been practised to increase crop productivity. However, such simplified farming systems had detrimental effects not only on the cropping systems themselves, but also on the environment with respect to resilience, adaptation to climate change, groundwater pollution, biodiversity loss, reduction of ecosystem function, soil erosion (Francaviglia et al., 2020; Lichtenberg et al., 2017), and loss in economy (Pretty, 2018). Consequently, in the last few years greater attention has been given to sustainability and use of resources that would minimise the costs and maximise the benefits while enhancing resilience and increasing productivity. Sustainable agriculture has been identified as an important strategy to achieve the 2030 Agenda for Sustainable Development. As addressed by Nhemachena et al. (2018), the sustainability challenge faced by the agriculture sector is to be able to provide enough food for the growing population without increasing the use of primary resources such as water and farmland, and by reducing biodiversity.

The European Union is committed to support the development of a sustainable agriculture in Europe. Agricultural land in Europe occupies about 460 Mha which is 10% of the world agricultural land covering 20% of the total land in Europe (FAOSTAT, 2020). As a consequence, the H2020 Diverfarming project (2017-2022) has been designed to empower farmers and agro-industries by implementing low-input innovative practices of crop diversification and improving the related value chains, and by removing the barriers that limit their adoption. One of the main objectives of Diverfarming is to develop experiments to test multiple diversified cropping systems under low-input practices, in order to reach a resilient and sustainable agriculture. The aim is to increase land productivity and crops quality while reducing the use of machinery, fertilisers, pesticides, energy and the water demands. This approach can provide: i) increased overall land productivity; ii) more rational use of farm land and farming inputs (water, energy, machinery, fertilisers, pesticides); ii) improved delivery of ecosystem services by increments in biodiversity and soil quality; iii) proper organization of downstream value chains adapted to the new diversified cropping systems with decreased use of energy; and iv) access to new markets and reduced economy risks by adoption of new products in time and space (Diverfarming project; Figure 1).

In order to gain insights into the effectiveness of the different diversification practises, a comparison between conventional and diversified cropping systems, which utilises data and results from all partners and working packages WP3 - WP5, is needed. The analysis of the experimental data is crucial and allows to measure the immediate benefits in considering diversified cropping systems. On the other hand, the aid of a process-based model gives the possibility to extend the information obtained experimentally to future scenarios, adding a new level of relevance to the whole study and providing key information to farmers and stakeholders when they consider diversified cropping systems as a potential improvement to their own agroecosystems.

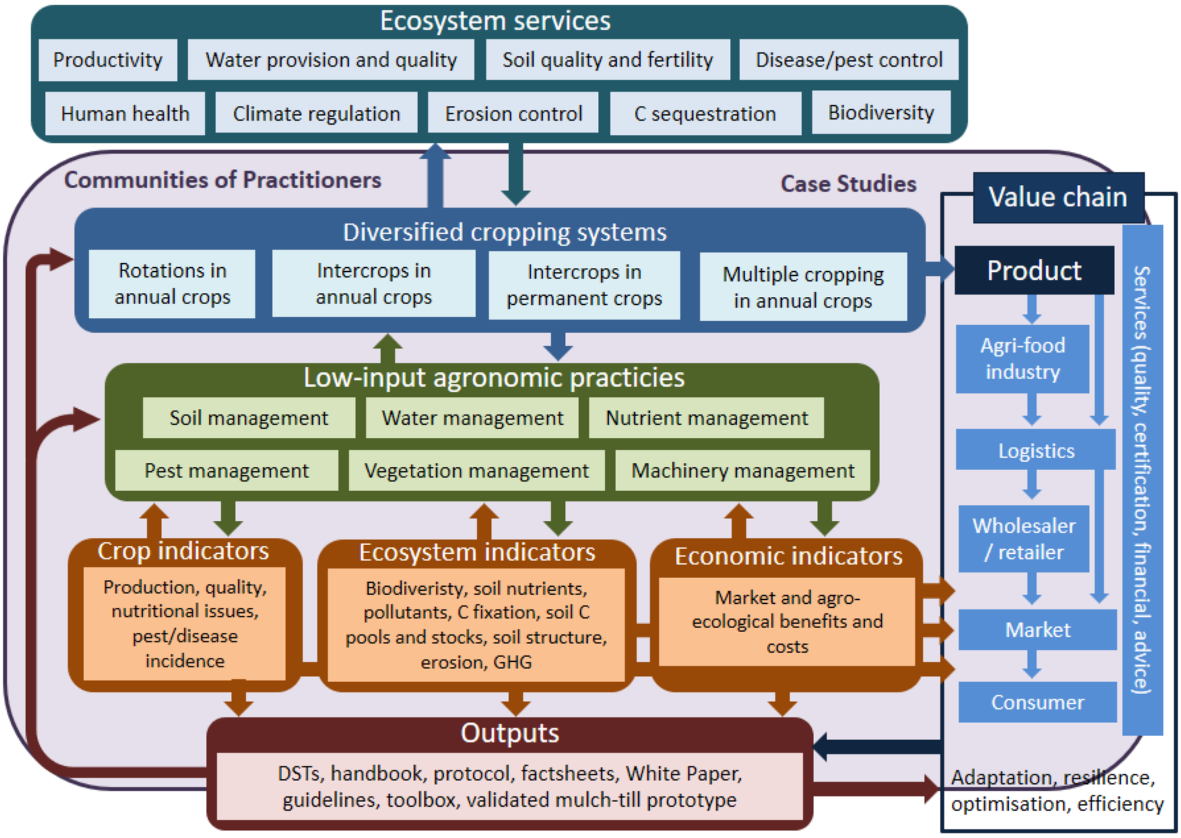

Figure 1*. Diverfarming conceptual framework (Diverfarming project)*

1.2. Process-based model for SOC dynamics

One of the aims of Diverfarming is to support the analysis and comparison between conventional (monocrop) and diversified cropping systems by implementing a new modelling tool. For this purpose, the existing model ECOSSE (Model to Estimate Carbon in Organic Soils-Sequestration and Emissions; Smith et al., 2010) was modified and used to simulate carbon (C) sequestration in soils under conventional and diversified cropping systems. New algorithms were developed to simulate crop associations and agricultural practices that were not yet included in the model, and existing algorithms were modified to include additional soils and land use types. The enriched model, which was parameterised using seven long-term experimental plots provided by the partners (UPCT, CSIC, CREA, UT, UP, Luke), will allow to gain insights into the effect of diversification on soil C dynamics. The final objective is to estimate how the different managements affect soil organic carbon (SOC) stocks, and to identify the most suitable diversified cropping systems and low-input agricultural practices for each of the studied pedoclimatic region.

1.2.1. Soil process-based models

Soil organic carbon is considered as one of the most important indicators of soil quality and agronomic sustainability because of its impact on other physical, chemical and biological properties of the soil (Reeves, 1997). An increase in SOC improves soil health by maintaining (if not increasing) soil fertility, and it can help to mitigate the effects of climate change (Begum et al., 2017). To investigate SOC dynamics and observe changes in different management practises in contrast to the traditional one requires long time (>10 years). Further it is costly to measure SOC stocks. For these reasons, SOC sequestration is often estimated using numerical soil/ecosystem models. Several process-base models have been developed to simulate the dynamics of soil C. Process-based soil models describe biogeochemical processes that are formulated according to mathematical-ecological theory. They are able to simulate SOC turnover based on site-specific conditions and the adopted management practices, can represent different temporal and spatial scales, as defined by the user, and simulate different environmental scenarios (Morais et al., 2019). Process based models have been developed based on the understanding of how SOC is affected by soil properties, land management and weather fluctuations. The incorporation of these different levels of understanding and the detailed processes make the process-based models important, and often successful, at predicting the dynamics of quantities such as soil C and greenhouse gas (GHG) emissions at site level (Bell et al., 2012; Dondini et al., 2015). However, one of the limitations in model testing is the lack of field data against which the simulations can be compared (Desjardins et al., 2010).

1.2.2. ECOSSE and its limitations

The model ECOSSE was developed to simulate both C and N cycles using minimal input data on both mineral and organic soils (Dondini et al., 2015; Jo et al., 2010). ECOSSE has already been validated and applied spatially to simulate land-use change impacts on SOC at field and regional scale (Bell et al., 2012). During the last few years ECOSSE was extensively used to assess GHG emissions from different soils and cropping systems in Europe (Dondini et al., 2015), and has gone through further changes in which new land uses such as those for the production of bioenergy-woody crops were introduced (Dondini et al., 2015, 2016). However, the use of ECOSSE for diversified cropping systems under arable land use e.g., crop rotation and multiple cropping has been limited, and although the impact of rotation has been performed by ECOSSE in European arable soils, such study did only estimate changes in N flux (Bell et al., 2012). Finally, there is no literature on the use of ECOSSE for woody crops or to understand the effect of cover crops and/or intercropping on SOC dynamics, nor to simulate dry or semiarid climatic regions.

In the present deliverable D7.2, it is shown how the model ECOSSE has been modified, evaluated and its suitability to model the dynamics of SOC in the diversified cropping systems implemented within Diverfarming, assessed. In the following section, the long-term and short-term Diverfarming case studies are described underlining all those features that needed to be considered to modify ECOSSE.

1.3. Diverfarming case studies

In the Diverfarming project the implementation of crop diversification for cereals, horticulture, fodder, floriculture, fruit trees, olive groves and vineyards is performed under both conventional and organic systems. For Pan-European relevance of the research outcomes, 13 field case studies (Figure 2) were set up in the following six pedoclimatic regions:

i. Mediterranean South
ii. Mediterranean North
iii. Atlantic Central
iv. Continental
v. Pannonian and
vi. Boreal

Figure 2. Multi-actor approach consortium with the selected diversified cropping systems in each pedoclimatic region. (Diverfarming project)

The case studies have been designed to integrate the socioeconomic, environmental, cultural and technical features of each region. Within the Diverfarming project, different strategies and diversification options have been adopted (Vanino et al., 2019). For example, diversification through intercropping in monocrop woody and/or arable croplands has been achieved by sowing different types of plant/grass in-between tree rows, or with the main crop as an intercrop, or as rotation crop, or as a cover crop in the time period between two main crop cycles. The list of crop diversification (intercropping, crop in rotation, multiple cropping) and different crops selected as main crop (woody or cereal monocrop) under short term case studies are described in the Deliverable D2.1 (Gómez-López et al., 2019). Here, the different management practices and cropping systems are described for both the long-term and the short-term case studies emphasizing those characteristics that would have an impact on SOC and that therefore were accounted for in the modelling analysis.

1.4. Long term case studies

Eight long-term experimental plots (7-21 years) were initially planned to assess the long-term effects and efficiency of some associations and practices. However, it was possible to have access to the historical data of only seven of the eight long-term experiments (UPCT, CSIC, CREA, UT, UP, Luke). A brief description of each long-term sites with the agronomic practises under diversified and conventional management is presented in Table 1 and Table 2.

***Table 1**. Results of farming practices selected by crop and country in each long-term case study (LT)*

LT	Country	Crop	Farming practice1	Farming practice 2	Farming practice 3
1	Spain	Horticultures	Addition of organic matter (manure, compost etc)	Drip fertigation	Maintenance of vegetation cover (natural or cover crops)
2	Italy	Arable	No tillage	Residues incorporated	Crop rotations
3	Spain	Rainfed almonds	Green manure	Minimum tillage	
4	Spain	Rainfed barley	No tillage	Residues incorporated	
5	Germany	Vineyards	Addition of organic matter (manure, compost etc)	Maintenance of vegetation cover (natural or cover crops)	
7	Finland	Fodder crops	Addition of organic matter (manure, compost etc)	Maintenance of natural vegetation on the edges	Minimum tillage, no tillage
8	The Netherlands	Fodder crops	Addition of organic matter (manure, compost etc)	Maintenance of natural vegetation on the edges	Minimum tillage
9	Hungary	Vineyards	Addition of organic matter (manure, compost etc)	Maintenance of natural vegetation on the edges	No tillage

- **LT1 Diversified horticulture in Spain**

  In the Region of Murcia (SE Spain), three diversified cropping systems with different soil management (conventional vs organic) were considered. The experimental period is 2010-2018 with melon in summer and cabbage in winter. Pesticides, inorganic fertilizer, manure, and irrigations are practised on this site. The following details are the data used in the model simulations:

  i) Conventional: 12 t ha^{-1} sheep manure + irrigation 0.0024 Hm^3 ha^{-1} yr^{-1}
  ii) Diversification 1 (organic): 15 t ha^{-1} sheep manure + irrigation 0.0025 Hm^3 ha^{-1} yr^{-1}
  iii) Diversification 2 (organic): 10 t ha^{-1} sheep compost + irrigation 0.0022 Hm^3 ha^{-1} yr^{-1} + cover crop (*Avena sativa* and *Vicia sativa*)

Table 2. *Results of diversification and crop options by crop and country in each long-term case study (LT)*

LT	Country	Crop	Diversification	Crop option 1	Crop option 2
1	Spain	Horticultures	Crop rotations and multiple cropping	Melon	Cabbage
2	Italy	Arable	Crop rotations	Wheat	Tick bean
3	Spain	Rainfed almonds	Intercropping	Oats and vetch as cover crop	
4	Spain	Rainfed barley	Monocrop	Barley	
5	Germany	Vineyards	Permanent vegetation cover		
7	Finland	Fodder crops	Crops in rotations	Legumes and cereals	Legumes and grass
8	The Netherlands	Fodder crops	Intercropping	Wheat, clover, broad bean, vetch, flax, phacelia, oat, pea	Corn, phacelia, buckwheat
9	Hungary	Vineyards	Intercropping	Cover crop with natural herbaceous	

- **LT2 Durum wheat in Italy**

  The impact of crop rotation and tillage on the soil physicochemical properties of the Italian site in Foggia has been analysed. The dynamics of SOC under wheat monocropping systems with conventional tillage (CT) and no tillage (NT) established in 1997 and 2008 respectively, and the impact of tillage on wheat - tick bean rotations has been assessed. The four management practises for this site are the following:

  i) Conventional: Durum wheat monocrop with CT
  ii) Diversification 1: Durum wheat monocrop NT
  iii) Diversification 2: Rotation tick bean-durum wheat with CT
  iv) Diversification 3: Rotation tick bean-durum wheat with NT

Tick bean grown on this site was used as green manure and incorporated in the field.

- **LT3 Almond orchard in Spain**

To observe the impact of tillage and intercropping on woody monocrop almond, an experimental field started in the Region of Murcia, SE Spain, in 2010. Along with biodiversity, erosion, and GHG emission, SOC was measured under three management practises to compare the changes of SOC between conventional tillage monocrop and the Diversification managements:

i) Conventional: Almond monocrop with conventional tillage
ii) Diversification 1: Almond monocrop with reduced tillage (RT)
iii) Diversification 2: Almond intercropped with *Avena sativa* and *Vicia sativa* with RT

- **LT4 Tillage in rainfed systems in Spain**

The impact of tillage was studied in rainfed barley monocrops for 10 years. The two management practices in Huesca, Spain are the following:

i) Conventional: Barley monocrop under conventional tillage
ii) Diversification: Barley monocrop under no-till

- **LT5 Low-input vineyard management in Germany**

The main aim of this experiment was to assess the impact of erosion in different slopes in Germany under two management systems including:

i) Organic monoculture: Organic vineyard management
ii) Diversification: Organic vineyard management with different manure application and cover crops

- **LT7 Fodder crops in Finland**

Four-year crop rotation has been practised from 1997 till 2018 to observe changes in SOC, biodiversity, yield etc. in the city of Toholampi, Finland. The rotation includes cereal, grass, and legumes. Tillage and different types of manure are practised on this site. The managements organised in four-year crop rotations are the following:

i) Conventional: Conventional cereal (barely, barley, rye, oats)
ii) Diversification 1: Organic cereal (barely, ley, rye, oats)
iii) Diversification 2: Conventional grass (barley, ley, ley, barley)
iv) Diversification 3: Organic grass (barley, ley, ley, oats/vetch)

- **LT9 Vineyards in Hungary**

Three management practises with vineyard have been experimented in Hungary for more than 10 years. 80 t ha^{-1} of cattle manure was applied at the planting time. The managements include:

i) Conventional: Vineyard monocrop, CT
ii) Diversification 1: Vineyard with natural cover crops (grass), S exposition, CT
iii) Diversification 2: Vineyard with natural cover crops (grass), W exposition and NT

1.5. Short term Diverfarming case studies

Field experiments have been set up as case studies in the six different pedoclimatic regions to test benefits and drawbacks of the tailored Diversification cropping systems in comparison with the conventional systems and management practices of each region. Each of the 13 case studies was designed to have a three-year crop cycle (2018-2020). ECOSSE was modified to model all cropping systems and management practises as described below.

- **CS1 Almond trees in Spain**

  Two types of diversifications in almond orchards have been applied. Diversification consists of alley intercropping along with traditional monocrop almond:

  i) Conventional: Almond monocrop
  ii) Diversification 1: Almond intercropped with *Capparis spinosa*
  iii) Diversification 2: Almond intercropped with *Thymus hyemalis*

- **CS2 Citrus in Spain**

  Two types of diversifications in almond orchards have been applied. Diversification consists of intercropping as alley cropping; two to three crops are grown in between citrus tree rows.

  i) Conventional: Mandarin monocrop
  ii) Diversification 1: Mandarin with reduced tillage intercropped with vetch/barley and fava bean
  iii) Diversification 2: Mandarin with reduced tillage intercropped with vetch/barley and fava bean (2018), vetch/barley and purslane (2019), and vetch/barley and cowpea (2020)

- **CS3 Irrigated and rainfed crops in Spain**

  Different diversifications are tested in Aragon, Spain, to analyse the impact of crop diversification (rotations and multiple cropping) and soil management managements (tillage, fertilization) on soil health in contrast to the conventional management practise. Two case studies are included:

  a) CS3a: Rainfed barley

  i) Conventional: Barley monocropping with CT
  ii) Diversification 1: Barley monocropping with NT
  iii) Diversification 2: Barley-wheat-pea rotation (phase 1, wheat)
  iv) Diversification 3: Barley-wheat-pea rotation (phase 1, barley)
  v) Diversification 4: Barley-wheat-pea rotation (phase 1, pea)

  b) CS3b: Irrigated maize

  i) Conventional: Maize monocrop
  ii) Diversification 1: Pea-maize multiple cropping at 3 different fertilization rates
  iii) Diversification 2: Barley-maize multiple cropping at 3 different fertilization rates

- **CS4 Olive in Spain**

  Different types of annual and perennial crops grown as alley crops in olive yards in Andalusia, Spain, to observe the effect of intercropping in contrast to monocrop. The three diversifications are as follows:

  i) Conventional: Olive monocrop
  ii) Diversification 1: Olive intercropped with *Avena sativa* and *Vicia sativa* for feed
  iii) Diversification 2: Olive intercropped with *Crocus sativus* for food
  iv) Diversification 3: Olive intercropped with *Lavandula spp* for aromatic oil

- **CS5,6,7 and 7bis Annual crop rotations in Italy**

  The case studies CS5,6,7 and 7bis are in different provinces in Italy. In the four-year cycle, the crop selected for 2018-2021 are corn (C), wheat (W), and Tomato (T). The impact of rotation is studied in contrast to monocropping. The management practises included in the study are: irrigation (with irrigation IR1, without irrigation, IR0) and application of digested slurry (with digested slurry, D1 and without digested slurry, D0).

  CS5: Rotation tomato-wheat pea/tomato intercropping

  i) Conventional: Control (2018 C, 2019 C, 2020 W, 2021 T)
  ii) Diversification 1: Rotation tomato-wheat pea/tomato intercropping (2018T, 2019P/T, 2020W) D0
  iii) Diversification 2: Rotation tomato-wheat pea/tomato intercropping (2018T, 2019P/T, 2020W) D1
  iv) Diversification 3: Rotation tomato-wheat pea/tomato intercropping (2018P/T, 2019W, 2020T) D0
  v) Diversification 4: Rotation tomato-wheat pea/tomato intercropping (2018P/T, 2019W, 2020T) D1
  vi) Diversification 5: Rotation tomato-wheat pea/tomato intercropping (2018W, 2019T, 2020P/T) D0
  vii) Diversification 6: Rotation tomato-wheat pea/tomato intercropping (2018W, 2019T, 2020P/T) D0

  CS6: Rotation tomato-wheat-barley

  viii) Conventional: Control, Rotation tomato-wheat-barley (2018 W 2019 B, 2020 W, 2021 T) D0
  ix) Diversification 1: Control, Rotation tomato-wheat-barley (2018 W 2019 B, 2020 W, 2021 T) D0
  x) Diversification 2: Rotation tomato-wheat pea/tomato intercropping (2018W, 2019T, 2020P/T) D0
  xi) Diversification 3: Rotation tomato-wheat pea/tomato intercropping (2018W, 2019T, 2020P/T) D1
  xii) Diversification 4: Rotation tomato-wheat pea/tomato intercropping (2018P/T, 2019W, 2020T) D0

xiii) Diversification 5: Rotation tomato-wheat pea/tomato intercropping (2018P/T, 2019W, 2020T) D1
xiv) Diversification 6: Rotation tomato-wheat pea/tomato intercropping (2018T, 2019P/T, 2020W) D0
xv) Diversification 7: Rotation tomato-wheat pea/tomato intercropping (2018T, 2019P/T, 2020W) D1

CS7: Rotation tomato-wheat-tomato

i. Conventional: Control Rotation tomato-wheat-tomato (2018 T 2019 T, 2020 W, 2021 T) D0
ii. Diversification 1: Control Rotation tomato-wheat-tomato (2018 T 2019 T, 2020 W, 2021 T) D1
iii. Diversification 2: Rotation tomato-wheat pea/tomato intercropping (2018T, 2019P/T, 2020W) D0
iv. Diversification 3: Rotation tomato-wheat pea/tomato intercropping (2018T, 2019P/T, 2020W) D1
v. Diversification 4: Rotation tomato-wheat pea/tomato intercropping (2018P/T, 2019W, 2020T) D0
vi. Diversification 5: Rotation tomato-wheat pea/tomato intercropping (2018P/T, 2019W, 2020T) D1
vii. Diversification 6: Rotation tomato-wheat pea/tomato intercropping (2018W, 2019T, 2020P/T) D0
viii. Diversification 7: Rotation tomato-wheat pea/tomato intercropping (2018W, 2019T, 2020P/T) D1

CS7bis: Rotation tomato-wheat-tomato

ix. Conventional: Control Rotation tomato-wheat-tomato (2018T, 2019W, 2020T) IR1
x. Diversification 1: Rotation tomato-wheat-tick bean (2018T, 2019W, 2020TB) IR1
xi. Diversification 2: Rotation tomato-wheat-tick bean (2018T, 2019W, 2020TB) IR0
xii. Diversification 3: Rotation wheat-tomato-wheat (2018W, 2019T, 2020W) IR1
xiii. Diversification 4: Rotation wheat-tomato-wheat (2018W, 2019T, 2020W) IR0
xiv. Diversification 5: Rotation tomato-wheat-tick bean (2018TB, 2019W, 2020T) IR1
xv. Diversification 6: Rotation tomato-wheat-tick bean (2018TB, 2019W, 2020T) IR0

- **CS9 Vineyard in Germany**

Oregano and thymes are planted in between the interrow of vineyards in Germany for food, feed and industrial products. The three treatments are:

i) Conventional: Vine monocrop
ii) Diversification 1: Vine intercropped with *Origanum vulgare*
iii) Diversification 2: Vine intercropped with *Thymus vulgaris*

- **CS10 Horticulture in Hungary**

  This case study is located in Bács-Kiskun, Hungary, based on the growth of asparagus in sandy soils. The treatments are:

  i) Conventional: Asparagus monocrop
  ii) Diversification 1: Asparagus intercropped with *Pisum sativum*
  iii) Diversification 2: Asparagus intercropped with *Avena sativa*

- **CS11: Vineyard in Hungary**

  The benefits of intercropping in vineyards is also observed in Baranya, Hungary, for three years. The treatments are:

  i) Conventional: Vine monocrop
  ii) Diversification 1: Vine intercropped with yarrow (*Achillea millefolium*) for commercialisation
  iii) Diversification 2: Vine intercropped with native grass mix for fodder

- **CS12 and CS13: Cheese production in Finland**

  Two experiments are conducted in the Boreal region, southeast Finland. The conventional cropping system for CS12, which has been used for cheese productions for the past 10 years, includes rainfed conventional cereal mono-cropping with intense tillage, mineral fertilizer, and pesticides. In contrast to this traditional management, three diversifications are considered:

  i) Conventional: Barley amended with rye grass crop under CT
  ii) Diversification 1: Barley monoculture under NT
  iii) Diversification 2: Barley-rapeseed-barley under CT
  iv) Diversification 3: Barley-rapeseed-barley under NT

  For CS13, the diversification in contrast to simple rotations are:

  i) Conventional: Simple rotations barley-ley-ley-barley and barley-barley-rye-oats
  ii) Diversification 1: Legume in feed rotation (barley - clover grass - ley – vetch + oat)
  iii) Diversification 2: Legume in cereal rotation (barley - clover grass - rye - oats)

- **CS16: Intercropped vegetables in Spain**

  CS16 is in Mediterranean south Spain (Murcia Region). The management practises include monocrop (horticultural and legume crops), and intercropping between horticultural and legume crops with 30% decrease in fertilizer rates compared to conventional management:

  i) Conventional: Monoculture (melon, cowpea, broccoli, fava bean) with 100% fertilizer rate
  ii) Diversification 1: Row intercropping 1:1 (melon/broccoli: cowpea/fava bean) with 70% fertilizer rate
  iii) Diversification 2: Row intercropping 2:1 (melon/broccoli: cowpea/fava bean) with 70% fertilizer rate
  iv) Diversification 3: Mixed intercropping with 70% fertilizer rate

2. ECOSSE for Diverfarming

2.1. The model

ECOSSE was developed in 2007 to examine the impacts of changes in land-use and climate on thin organo-mineral soils with <50 cm surface organic horizon (Smith et al., 2007), which tend to undergo more land-use changes than the deeper peat soils and are more accessible for agriculture (Smith et al., 2010). By implementing ECOSSE Smith et al. (2010) aimed to simulate the impacts of land-use and climate change on GHG emissions from organo-mineral, mineral and peat soils.

ECOSSE simulates the major below-ground C and N turnover in mineral and highly organic soils using concepts derived from two well established models, ROTHC (Colman and Jenkinson, 1996) and SUNDIAL (Bradbury et al., 1993). In ECOSSE soil organic matter (SOM) is described as five pools: active pools of humus (HUM), biomass (BIO), resistant plant material (RPM) and decomposable plant material (DPM), and an inert organic matter (IOM) pool. The DPM/RPM ratio determines the decay of plant material added to the soil, this ratio being derived from standard values for each land use type or modified for new land-uses (Figure 3).

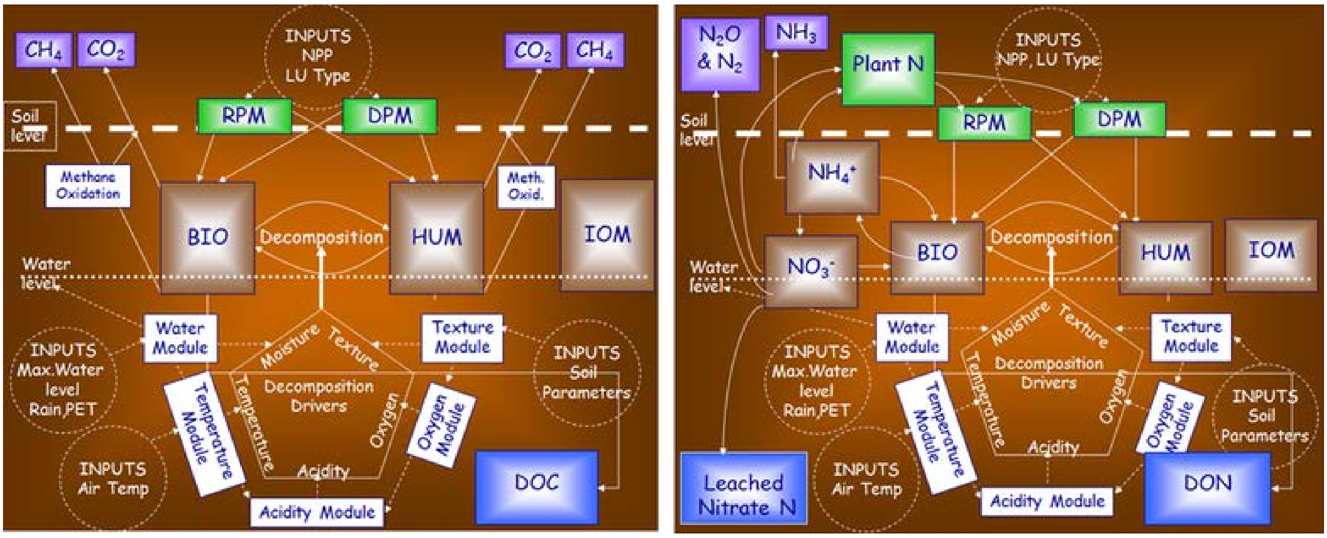

***Figure 3**. Structure of the carbon (left) and nitrogen (b) components of ECOSSE (figure from Smith et al., 2010)*

The main differences in the simulation of soil C dynamics in ECOSSE compared to RothC and SUNDIAL are in:

1. the response of aerobic decomposition to soil pH, which is included in ECOSSE;
2. the anaerobic decomposition (depending on temperature, soil water and pH);
3. the change of C:N ratio with the soil pH following the model:

$$(C:N)_{stable} = (p_{bac} \times (C:N)_{bac}) + \left(p_{fun} \times \ (C:N)_{fun}\right)$$

where p_{bac} and p_{fun} are the proportions of bacteria and fungi in the soil respectively, and are functions of the soil pH;

4. the layer structure, with 5 cm layers throughout the soil profile for solute movement;
5. the leaching of dissolved organic C and N; and finally

6. the implementation of land-use change, with protected SOM release from HUM to DPM and RPM and a linear equation to model the establishment phase for new land use (Smith et al., 2010).

The amount of information input required by the model depends on the specific simulation mode chosen by the model user. In fact, it is possible to run simulations in two different modes: 1. a low-input requirement mode, called **limited data mode**; and 2. a **site-specific mode**.

In the *limited data mode,* the only inputs are the commonly available meteorological data, such as monthly air temperature and precipitation, and potential evapotranspiration; soil data such as soil pH, soil clay content, initial total SOC content, inert organic C content, and soil texture class; and land-use (or management data) such as vegetation type, cultivation/planting schedules, and amount and timing of nutrient amendments. With these drivers the model is able to simulate daily N-gas flux (N_2O, N_2 and NH_3), C-gas flux (CH_4 and CO_2), dissolved organic C, dissolved organic N, and leached nitrate N, and therefore to predict how land-use and climate change impact C and N dynamics in organic and mineral soils. The limited data mode is well suited for simulations at both national and field scales, thus allowing results to be used to directly inform policy decisions. In *site-specific mode*, along with the above-mentioned input, the user needs to provide detailed management data describing planting times, cultivation, fertiliser applications and crop type. Also, the user can decide to either provide detailed soil parameters, such as soil carbon and soil water parameters, or to have them calculated by the program as in limited mode. Simulations in site specific mode allow to get a better approximation of the share of factors that determine the activity of the SOM, and of the plant inputs needed to calculate the soil C.

2.2. ECOSSE and the Diverfarming case studies

Modifications to ECOSSE have been included to simulate the different pedoclimatic regions and agricultural practices considered within the project (e.g. Mediterranean semiarid regions, different cropping systems, etc.). All changes to the code, parameterization of the new (and old) routines and the validation of the model are based on the data provided by the Diverfarming partners. For the model calibration, since only one (in most cases) or two measured data points are currently available from the short-term case studies, the long-term datasets were used instead. The most suitable version of ECOSSE, either site specific or limited mode, for each long-term experiment and case study was selected based on the information available on the one drive, and on the type of crop and/or intercropping planned in each experiment (Table 3).

Table 3. ECOSSE version used to simulate SOC dynamics for Diverfarming case studies

CS	Description of CS	ECOSSE version
LT1	Diversified horticulture in spain	SS
LT2	Durum wheat in Italy	SS
LT3	Almond orchard in Spain	LIM
LT4	Tillage in rainfed systems in Spain	SS
LT5	Low-input vineyard management in Germany	LIM
LT7	Fodder crops in Finland	SS
LT9	Vineyards in Hungary	LIM
CS1	Almond trees in Spain	LIM
CS2	Citrus in Spain	LIM
CS3a	Rainfed barley in Spain	SS
CS3b	Irrigated maiz in Spain	SS
CS4	Olive in Spain	LIM
CS5, 6,7,7bis	Annual crop rotations in Italy	SS
CS9	Vineyard in Germany	LIM
CS10	Horticulture in Hungary	SS
CS11	Vineyard in Hungary	LIM
CS12, 13	Cheese production in Finland	LIM

CS: Case studies, SS: Site mode, LIM: Limited mode

2.3. SOC stock data from case studies

The main aim of all modifications made in ECOSSE was to improve (or allow) SOC simulations for all Diverfarming long-term and short-term case studies, based on the experimental data supplied by the project partners. For the long-term case studies, 0-30 cm depth SOC measurements were provided. For the short-term case studies, the SOC was measured both at 0-10 and 10-30 cm depth at the beginning of each experiment. In the following years, further measurements of SOC were (and will be) taken at 0-10 cm depth. SOC simulations were run considering 0-30 cm depth. In the case of short-term case studies, the 2019 SOC value at 10-20 cm depth was assumed to be the same as the one measured in 2018. The supplied SOC data values are expressed in g kg^{-1}, this is converted to percentages and then multiplied with bulk density and soil depth to obtain SOC stock in t ha^{-1} (Farina et al., 2017):

$$t\ C\ ha^{-1} = C\ (\%) \times BD \times depth(cm)$$

2.4. Intercropping and multiple cropping

Different types of intercropping have been designed for the different Diverfarming case studies. The intercropping was intended as the simultaneous cultivation of two or more crops on the same field. In other cases, multiple cropping has been performed as the cultivation of two crops in the same year but in different seasons (winter and summer crops). In tree crops, herbaceous crops were sown with the main woody crop in-between rows (e.g., LT3). In the case of herbaceous crops, the intercrops were either grown in the same rotation year (e.g., LT2), or in the time period between two main crop cycles (e.g., LT1). Generally, in intercropping practises with tree crops (citrus, mandarin, almond, olive, vine) all residues of alley crops were incorporated in the soil. Oat (*Avena sativa*) and vetch (*Vicia sativa*) are among the most common cover crops used in Diverfarming (e.g., LT1, LT3). These species have also been used as a rotation crop in LT7, but they were then harvested and used as fodder for animals. Other alley crops (*Capparis spinosa, Thymus hyemalis, Crocus sativus, Lavandula spp*) and grass (timothy, meadow fescue ley) were used in several case studies. A preliminary analysis of correlation was performed to gain insights into the relationship between the presence of cover crops on the one hand, and the yield of the main crop and SOC on the other hand. Most case studies showed a significant positive correlation between SOC and N. However, the data available on cover crop were not enough yet to get satisfactory conclusions about their impact on crop yield and soil quality.

2.5. Statistical analysis

For each case studies, simulated and measured SOC were compared. The model performance was evaluated with MODEVAL (Smith and Smith, 2007), which allows to determine coincidence and association between measured and modelled SOC by calculating the root mean square error (RMSE) that indicates the total difference between observed and predicted values. The degree of association between modelled and measured values was determined using the correlation coefficient r. r values range from -1 to +1. Values close to -1 indicate a negative correlation between simulations and measured values, 0 indicates no correlation, and values close to +1 indicate a positive correlation (Smith et al., 1996). The significance of the association between simulations and measurements was assigned using a Student’s t-test as outlined in (Smith and Smith, 2007). The mean difference between observation and simulation (M) was calculated to assess bias in the modelled values and is expressed in the same unit as the analysed data (Dondini et al., 2015). The bias is expressed as a percentage of the relative error, E.

3. Routines to simulate C sequestration of diversified cropping systems

As previously emphasized, the main aim of task 7.1 is to use an existing model ECOSSE (Smith et al., 2010) to simulate C sequestration in soils under different diversified cropping systems and, when needed to develop new algorithms, or modify existing ones, to simulate crop associations and agricultural practices not included in the model, and to include additional soils and land use types. Woody crops, such as almond, olives, citrus and grapevine have been developed in limited mode, and introduced in the model as “new land use types”. The intercropping has been modelled with the same kind of reasoning, by considering a specific annual carbon distribution for each of the cover crops used in this study. On the other hand, herbaceous crops, their different management practices, and their intercropping with other crops and cover crops (multiple sequential crops in the same year) have been developed in site specific mode.

3.1. Limited Mode

In ECOSSE, one of the methods to calculate the size of the SOM pools at the beginning of the simulations is based on an equilibrium run of the model RothC (Colman and Jenkinson, 1996). In this equilibrium run, an average plant input is determined by the attainment of the steady state of the system, where no more variation in SOC is observed. The equilibrium run consists of several iterations, and the steady state, or equilibrium, is reached when the estimated (initial value for the) carbon, calculated by using the weather 30-year monthly averages, differs less than 0.0001 kg C ha^{-1} layer^{-1} from the observed values. Once the SOM pools size is obtained, the proportions of these pools will define the activity of the SOM turnover (J Smith et al., 2016). When the carbon input is not specified in the input file, but it is entered as zero, ECOSSE calculates it from the net primary production (NPP), which is estimated using the MIAMI model (Lieth, 1975). At each time step of the simulations, the total annual plant input is calculated according to the distribution of leaf fall and debris inputs for each land use type. Such distribution is also used when the total plant input is provided by the user. ECOSSE has been originally parameterised for six land use types. Default values for the distribution of the plant input can be found in ECOSSE's User Manual (Smith et al., 2010).

3.2. New Land use for woody crops

The distribution of total annual plant input for almond/olives, citrus and grapevines (Figure 4) has been obtained from the literature (Aguilera et al., 2018; Farina et al., 2017; Iglesias et al., 2013; Pardo et al., 2017).

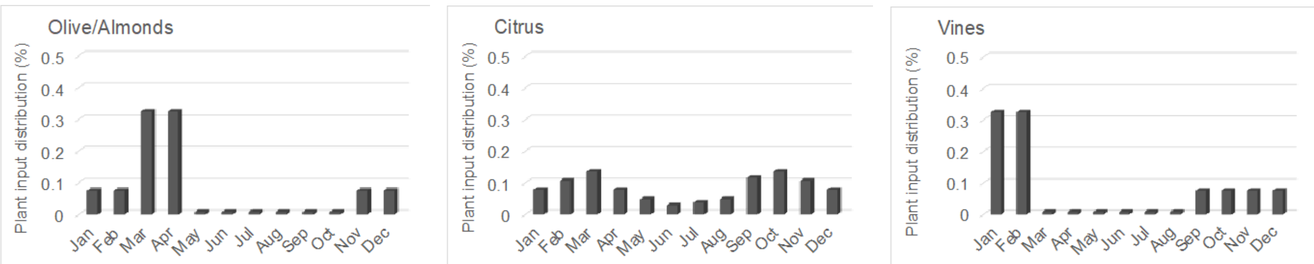

***Figure 4**. Plant input distributions for olive/almonds, citrus and grapevines.*

Depending on the type of crop it was assumed that two thirds of the plant input would be found in the soil within the first 30 cm of the soil profile, with almost all the remaining being allocated to the second 70 cm layer, and only a small amount (between 3% and 9%) reaching over the 100 cm depth (Table 4). In agreement with the standard way in which ECOSSE distributes all inputs along the soil profile, default values for plant inputs were calculated assuming an average total input (in 0 to 3m) of 3787 t ha^{-1} for almond/olive, 10 295 t ha^{-1} for Citrus, and 8400 t ha^{-1} for grapevine (Table 4) (Farina et al., 2017; Iglesias et al., 2013; Pardo et al., 2017). The subroutine *GET_PLANT_DIST(),* which is called in limited mode to get the plant input distribution across the months and down the soil profile, and the plant input default values, was modified accordingly and the modification can be found in ANNEX 2.

***Table 4**. Standard values (t C ha^{-1}) per layer and monthly distribution (%) of total annual plant input for almond/olives, citrus and grapevine*

Month	1	2	3	4	5	6	7	8	9	10	11	12
Olive/Almonds												
0-30cm	0.199	0.199	0.860	0.860	0.022	0.022	0.022	0.022	0.022	0.022	0.199	0.199
30-100cm	0.060	0.060	0.258	0.258	0.007	0.007	0.007	0.007	0.007	0.007	0.060	0.060
>100cm	0.026	0.026	0.111	0.111	0.003	0.003	0.003	0.003	0.003	0.003	0.026	0.026
Distribution	0.076	0.076	0.324	0.324	0.008	0.008	0.008	0.008	0.008	0.008	0.076	0.076
Citrus												
0-30cm	0.534	0.734	0.934	0.534	0.334	0.200	0.260	0.334	0.800	0.930	0.734	0.534
30-100cm	0.240	0.330	0.420	0.240	0.150	0.090	0.117	0.150	0.360	0.420	0.330	0.240
>100cm	0.027	0.037	0.047	0.027	0.017	0.010	0.013	0.017	0.040	0.047	0.037	0.027
Distribution	0.078	0.107	0.136	0.078	0.049	0.029	0.038	0.049	0.117	0.136	0.107	0.078
Vines												
0-30cm	1.820	1.820	0.050	0.050	0.050	0.050	0.050	0.050	0.420	0.420	0.420	0.420
30-100cm	0.820	0.820	0.020	0.020	0.020	0.020	0.020	0.020	0.190	0.190	0.190	0.190
>100cm	0.090	0.090	0.000	0.000	0.000	0.000	0.000	0.000	0.020	0.020	0.020	0.020
Distribution	0.325	0.325	0.008	0.008	0.008	0.008	0.008	0.008	0.075	0.075	0.075	0.075

The *MIAMI* model, which is implemented in ECOSSE in the *MIAMI-DYCE* subroutine, calculates the plant input (PI) as a fraction of the net primary production (NPP), which is considered to be the corrected rescaled minimum between the temperature limited NPP (NPPT, T is for temperature):

$$NPPT = \frac{3000}{1+EXP(1.315-0.119*T)},$$

and the precipitation limited NPP (NPPP, P is for precipitation):

$$NPPP = 3000 \times \left(1 - EXP(-0.000664 * P)\right).$$

That is,

$$PI = frac \times NPP = frac \times (0.5 \times 10 \times resc \times \min(NPPT, NPPP)).$$

The fitting of the NPP rescaling factor for each of the three new land cover types, and of the factors used to express the soil input as fraction of NPP for each land cover type was done using the average SOC and the weather data provided by the partners (Table 5). Parameter ranges were suggested by the parameter values used in ECOSSE for the other land use types and from the literature (Aguilera et al., 2018).

Table 5. *Parameter values for MIAMI-DYCE for each new land use type: olive/almond, citrus and grapevine.*

	olive/almond	citrus	grapevine
resc	2.5	2.4	2.1
frac	0.62	0.77	0.76

3.3. New Carbon input from Intercropping in limited mode

In limited mode the contribution of cover crops to SOC is modelled following the same structure as for the main crops. The default total annual plant inputs and distributions of the cover crops, which are used in the Diverfarming case studies (single crop or combinations of crops), are based on the measurements provided by the partners and on the literature (Aguilera et al., 2018). The C input was calculated using the harvest index for each cover crop (Salmoral and Garrido, 2015). A new file named COV_CROP.DAT was added to ECOSSE to simulate all Diverfarming cover crops (ANNEX 1).

A new subroutine was developed to account for changes in SOC dynamics due to cover crops. Such subroutine reads the cover crop plant input distribution and its default values ($PIcover$), and after correcting them, it adds this (corrected) input to the one attributed to the main crop ($PImain$). The distribution of the cover crops does also affect the soil cover. To perform the correction of the default values of the cover crop plant input, ECOSSE calls another newly developed subroutine (NCEAS(), ANNEX 2) that takes into account the difference between the NPP produced by the cover crop in the current year (c) and the NPP value produced with the average weather conditions (a) provided by the user. In NCEAS() the NPP is calculated following the NCEAS model developed by Del Grosso et al. (2010),

$$NPP_i \ = \ 6166 \times \left(1 - EXP(-6.05 \times 0.00001 \times P_i)\right), \ \ i = a, c.$$

After calculating the current and average NPP, the subroutine NCEAS() computes the ratio between the two NPP_i, i=a,c, values ($COVRatio$). The total plant input ($totPI$) is then assumed to be:

$$totPI = PImain + PIcover \times COVRatio.$$

3.4. Dry soils

The routine that calculates the soil moisture modifier has been modified to account for dry soil conditions. When no crop is present (bare fallow) the modification allows the soil to dry out more than it can do in the original version so reducing the soil decomposition rate. The user can now choose between three types of dryness categories: normal, dry, and semiarid. The minimum water level expressed as fraction of the maximum one is set to be 0.2 for normal soils, 0.15 for dry soils and 0.1

for semiarid soils like those in south Italy and Spain. This modelling approach follows the one suggested by Farina et al. (2013) and the implementation works both in limited and site-specific mode. Details of the subroutine and its modifications can be found in ANNEX 2.

3.5. Site Specific Mode

In site specific mode no new subroutine was introduced in the code, but the existing subroutines were modified to adapt the program to all Diverfarming management strategies.

- **Multiple cropping**

  ECOSSE was modified to allow simulations of multiple crops in the same year. The management file provided as input by the user was changed accordingly (ANNEX 3).

- **Different types of manure**

  In site specific mode, the C input from manure is estimated from the C and N content in kg t^{-1} fresh manure. The following manures used within Diverfarming and not included in the original ECOSSE were added to the model: sheep manure (%C 22.5 and %N 9.8); sheep compost (%C 22 and %N 15.3); fox manure (%C 12.7 and %N 9.86); farmyard manure (%C 5.25 and %N 0.60); cow slurry (%C 0.45 and %N 0.23).

- **Water accumulation through irrigation**

  One of the limitations of ECOSSE's previous version was the fact that irrigation was not implemented in the model. This feature has now been added and if there is irrigation, the user needs to provide the total number of days during which irrigation occurs and the water quantity in hm^3 ha^{-1} $year^{-1}$ (ANNEX 2, 3). In this way it is possible to simulate all case studies that consider irrigation among their management strategies (e.g. LT1, CS7bis).

- **Asparagus**

  The original ECOSSE had already been modified to simulate SOC dynamics under miscanthus. This information was used as starting point to add the new horticultural crop (asparagus) to the input data file CROP_SUN.dat (ANNEX 3).

4. Parameterization and evaluation of ECOSSE

ECOSSE was parameterised using data from seven long-term experiments: LT1, LT2, LT3, LT4, LT5, LT7, and LT9. A highly significant positive agreement between SOC simulations and observations was found when ECOSSE was used to simulate two multiple cropping systems in Spain (LT1). Simulations of dry arid regions in Italy (LT2) and Spain (LT3) were run setting the level of soil dryness to 3 (semiarid soils), which improved the overall model performance compared to using different levels. The modified version of ECOSSE was also tested under different tillage and manure management, to assess the impact they have on SOC under cereal and legume rotations. These simulations showed a good agreement with the observations (LT7). Finally, the modified ECOSSE was used to simulate SOC dynamics in perennial woody crops with and without cover crops as intercropping. The SOC was predicted well compared to the measured data over 10 years of simulations in almond woody crops, Spain (LT3). However, some discrepancies can be observed between the simulated and measured SOC in Germany (LT5) under vine, while a reasonable agreement between simulations and observations was found in Hungary both under vine monocrop and vine intercropped with cover crops (LT9).

***Table 6**. Statistics for the evaluation of the performance of the modified ECOSSE model on SOC simulations in different European agroecosystems at 0-30 cm soil depth*

LT	Land use	Management	RMSE (%)	r	M (t ha^{-1} yr^{-1})	E (%)
LT1	Arable	Conventional (n = 8)	9.35	0.88^{***}	0.96^{ns}	-3.23
		DV1 (n = 8)	8.52	0.92^{***}	1.70^{ns}	-4.67
		DV2 (n = 8)	6.74	0.97^{***}	1.25^{ns}	2.86
LT2	Arable	Conventional (n = 5)	6.07	0.77^{ns}	1.91^{ns}	3.20
		DV1 (n = 4)	3.98	0.89^{ns}	1.10^{ns}	1.77
		DV2 (n = 5)	5.75	0.90^{*}	1.56^{ns}	2.67
		DV3 (n = 4)	9.51	0.71^{ns}	4.38^{ns}	6.80
LT7	Arable + grass	Conventional (n = 4)	9.86	0.69^{ns}	11.30^{ns}	7.62
		DV1 (n = 4)	4.99	0.81^{ns}	6.60^{ns}	3.96
		DV2 (n = 4)	3.97	0.77^{ns}	0.01^{ns}	0.01
		DV3 (n = 4)	7.74	0.02^{ns}	8.98^{ns}	5.67
LT5	Woody crops	Conventional (n = 5)	11.10	0.92*	-5.21^{ns}	-4.57
LT9	Woody crops	Conventional (n = 3)	2.68	0.78^{ns}	1.41^{ns}	1.87
		DV1 (n = 3)	11.31	0.42^{ns}	-2.44	-4.45
		DV2 (n = 3)	11.00	0.26^{ns}	-2.87^{ns}	-3.77

*** Significant correlation between modelled and measured SOC at $p < 0.001$.

* Significant correlation between modelled and measured SOC at $p < 0.05$, or significance mean error (M) at p=0.025.

ns =Non-significant between modelled and measured values at $p < 0.05$, or no significance mean error (M) at p=0.025.

n = number of samples.

NB. Due to lower number of data points (only 2) for LT3 and LT4 and LT5 Diversification 1, the statistical analysis has not been performed.

4.1. SOC simulations under long term arable cropping systems

- **LT1 Diversified horticulture in Spain**

ECOSSE was applied to assess the effects of agricultural management in melon-cabbage multiple cropping systems under organic management in contrast to traditional management on SOC content in the Mediterranean region of Spain. Both modelled and observed results for the three management systems of this site revealed that SOC increased over time (Figure 5). There is a highly significant ($p<0.001$) positive relationship between modelled and measured SOC and a good agreement (RMSE = <10%) between observed and simulated SOC trends at this site under all three managements (Table 6). Although SOC was slightly underestimated by the model in conventional and Diversification 1 management, no significant bias was found in the simulations.

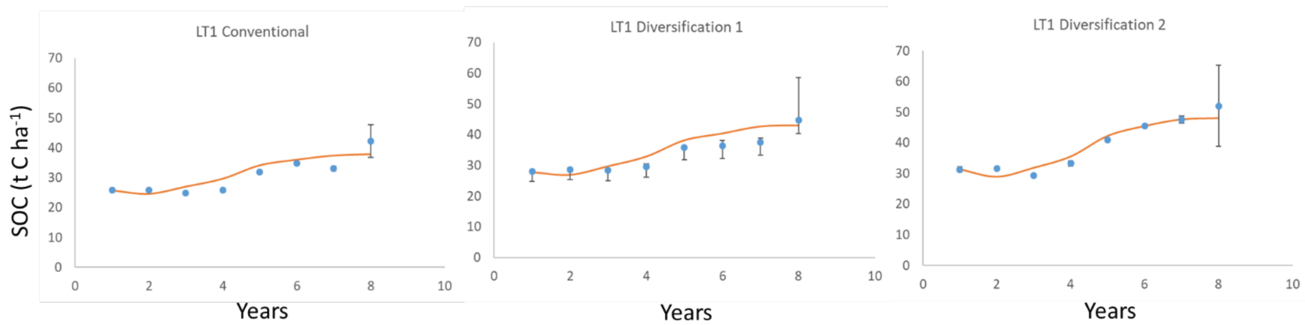

Figure 5. *Measured (point) and modelled (line) SOC in LT1 under conventional and diversified management*

- **LT2 Durum wheat in Italy**

The effect of tillage on SOC stock under rotations and monocropping systems was tested in Italy. Although the model shows a positive impact on SOC when no tillage (NT) (Diversification 1 and 3) is practised instead of conventional tillage (CT), the measured data show a slight decline in SOC under NT when the rotation is implemented (Figure 6). A good agreement between observed and predicted values (RMSE < 10%) was observed for all of these sites under the four different treatments. A significant positive association between measured and modelled SOC was attained under the Diversification 2 management with CT. A non-significant positive association between modelled and measured SOC was observed in the other managements, with a non-significant bias (Table 6).

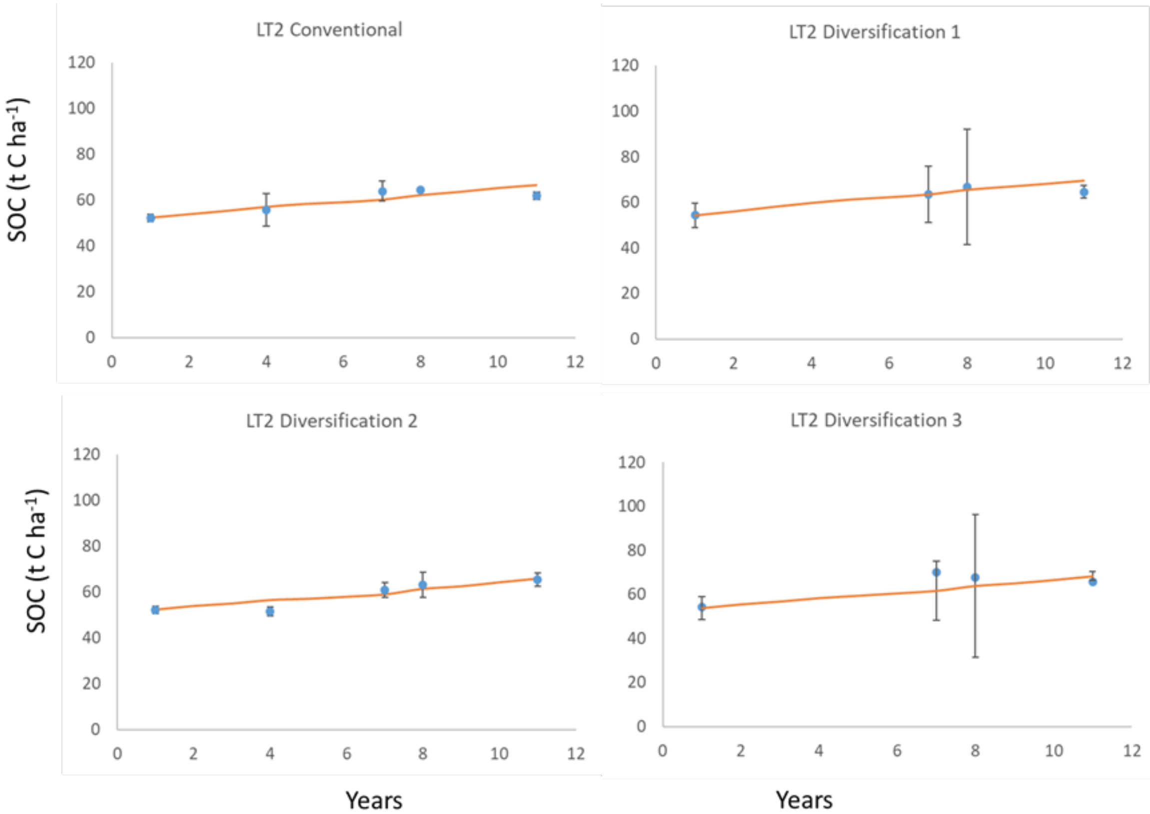

***Figure 6**. Measured (point) and modelled (line) SOC in LT2 under conventional and diversified management*

- **LT4 Tillage in rainfed systems in Spain**

In LT4 experimental data showed no differences between SOC values under barley monocropping with and without tillage. The model however predicted around 15% more SOC under NT compared to CT (Figure 7).

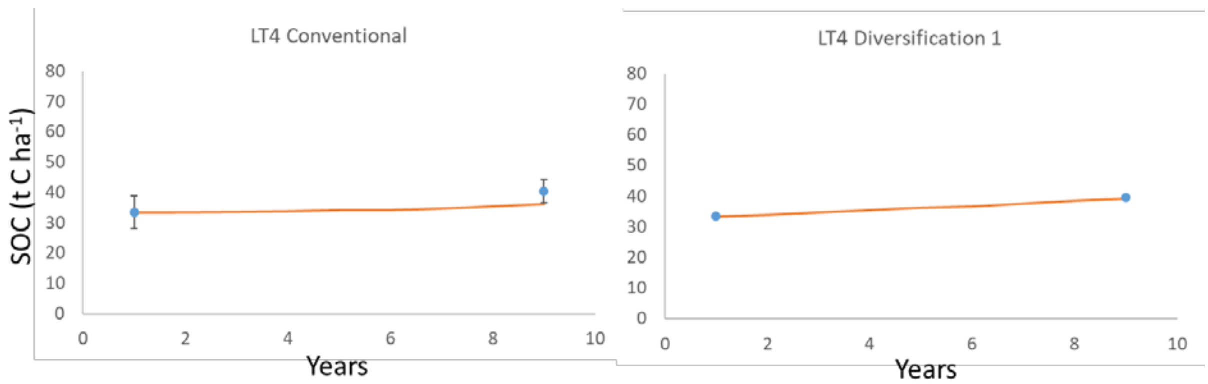

***Figure 7.** Measured (point) and modelled (line) SOC in LT4 under conventional and diversified management*

4.2. SOC simulations under long term arable cropping systems associated with grass

- **LT7 Fodder crops in Finland:**

In the Finnish case studies, diversification was introduced in cereal monocropping to improve soil quality. The study quantifies the long-term effects of organic farming - with more diversified crop rotations and lower nutrient intensity - on soil properties, runoff quality and crop yield compared to conventional farming. The diversifications consider different proportions of legumes and grass in the crop rotations. SOC was observed over 20 years from 1997 to 2018. SOC declines in the conventional rotations which is also caught by the model simulations (Figure 8). The diversifications reduce the SOC loss, which is showed both in measured data and simulations. Statistical analysis using 4 measured data points at 0-30 cm depth showed a non-significant but positive relationship between model and data under all treatments (Table 2). A good agreement (RMSE <10%) and a non-significant bias were observed between modelled and measured SOC on this site (LT7).

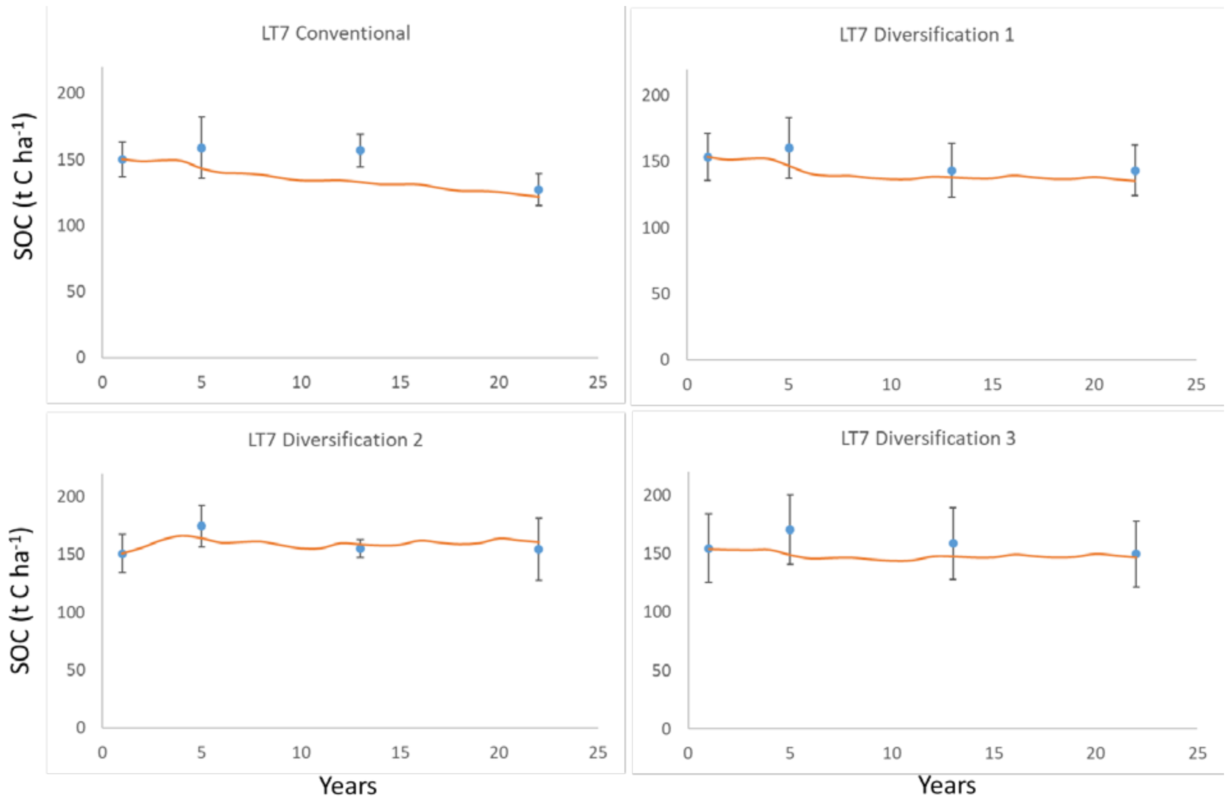

***Figure 8**. Measured (point) and modelled (line) SOC in LT7 under conventional and diversified management*

4.3. SOC simulations under long term woody crops

In order to keep the limited mode as a “minimum”-input mode, C input from exogenous source, e.g. from manure or tillage, has not been implemented in the code. However, it is possible to simulate exogenous sources by adding the carbon calculated from the manure (as used in the specific site mode) to the plant C input values provided in the input file. The impact of tillage can be calculated as an additional 15-30% SOC, this value is based on previous literature (Omara et al., 2019; Senapati et al., 2014; Smith et al., 2008)

- **LT3 Almond orchards in Spain**

The simulations of SOC content in conventional and diversified management systems (Diversification 1 and Diversification 2) for almond orchards are shown in Figure 9. Almond monocropping under CT leads to a decrease in SOC, this declining trend is compensated when converting CT to RT (Diversification 1) or to RT+CC (Diversification 2). The trend found in the observations is caught by the simulations.

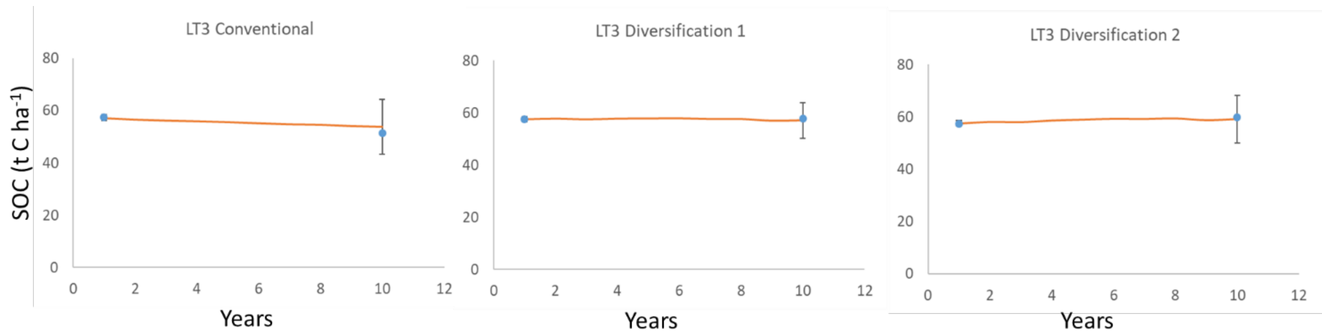

Figure 9. *Measured (point) and modelled (line) SOC in LT3 under conventional and diversified management*

- **LT5 vineyards in Germany**

One of the features in the new version of ECOSSE is the possibility to simulate C dynamics under vineyards. The comparison between SOC measurements from the German sites and the simulated values are shown in Figure 10. The simulations of the conventional organic site start in 2007, when the land use was changed from conventional management to organic. Compared to the observations it is possible to see that under the conventional management there is a slight overestimation of the estimated SOC (still within the error bar). Diversification 1 on the other hand consists of the same farming system but with manure amendments. These changes in management seem to reduce SOC loss which is observed both in the measured and modelled results. Finally, a significant positive correlation was observed for both German sites, and without any bias (Table 6).

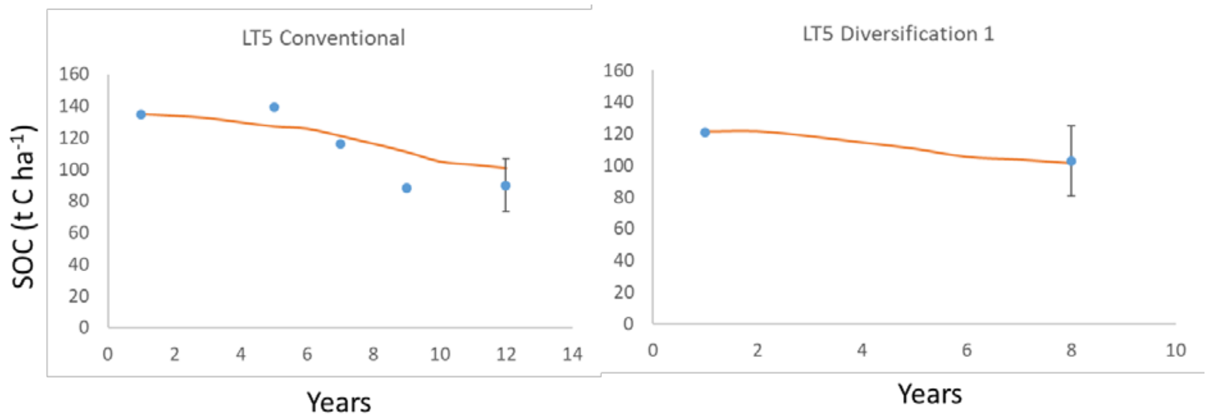

__Figure 10.__ Measured (point) and modelled (line) SOC in LT5 under conventional and diversified management

- **LT9 vineyards in Hungary**

  As for Germany, the impact of sustainable farming systems under vineyard was observed in a long-term site in Hungary (Figure 11). At the beginning of the experiment 80 t ha^{-1} of cattle manure (contain 8400 kg C ha^{-1}) was added to the soil. The simulations show that the manure produced an initial increase in SOC of 5 t ha^{-1} which then declined in the years, therefore no SOC changes were observed from 2005 to 2018 under this conventional management. The trend was well reflected by the model. The use of the cover crop (grass - Diversification 1) shows an increase in SOC, which was observed both in simulations and observations. The data show an increase in SOC of 12 t ha^{-1} whereas the model predicts an increase of about 10 t ha^{-1} under this management. The experiment for Diversification 2 started in 2002. Manure was applied in 2003. In this site no tillage, instead of CT, was practised. The use of a cover crop (grass) and the implementation of no tillage leads to a gain in SOC of 14 t ha^{-1} whereas model predicted about 9 t ha^{-1}. A positive association with no bias was shown by each management on these sites (Table 6).

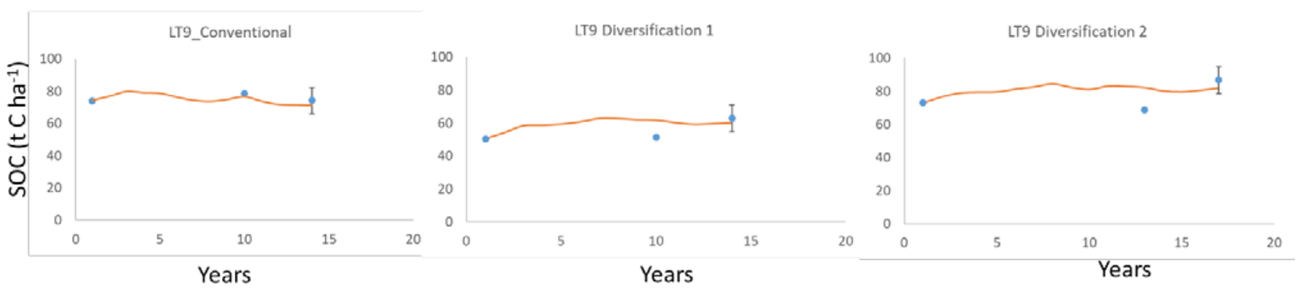

__Figure 11__. Measured (point) and modelled (line) SOC in LT9 under conventional and diversified management

4.4. Model Evaluation: SOC simulations under short case studies

In this section the simulations of SOC for the short-term case studies of CS2, CS9, CS10 and CS11 are shown. Due to lack of data, the results for the other case studies are not presented in this report.

DIVERFARMING

- **CS2 Citrus in Spain**

Using two-year data points, the modified ECOSSE model was tested for citrus in Spain under three different managements. The simulations from 2017 to 2020 predicted an increase in SOC values under the diversified managements as compared to the conventional one (Figure 12).

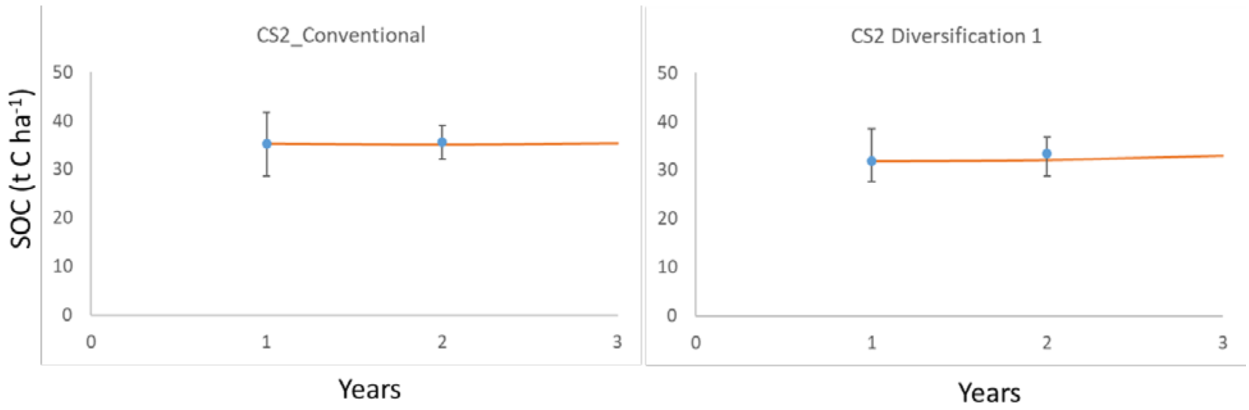

Figure 12. *Measured (point) and modelled (line) SOC in CS2 under conventional and diversified management*

- **CS9 Vineyard in Germany**

The model well predicts the measured values of SOC for all different managements (Figure 13). However, the simulations show that SOC stays at equilibrium in all three managements over five years simulations while the measured data present a slight declining trend. In principle, this could be due to the dry weather conditions occurred in 2018.

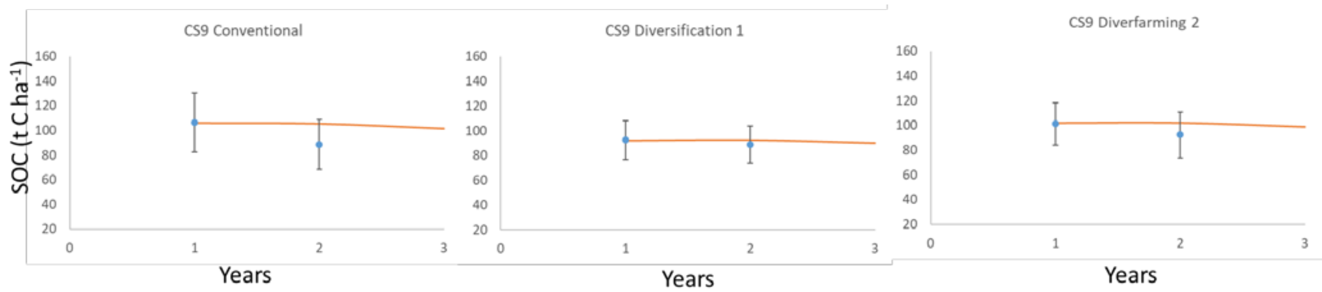

Figure 13. *Measured (point) and modelled (line) SOC in CS9 under conventional and diversified management*

- **CS10 Asparagus in Hungary**

The new version of ECOSSE was used to predict SOC dynamics under asparagus. The model was run in site-specific mode. The model was calibrated using the monocropping sites and validated against the two diversified management systems. The trend of simulated SOC is well associated with the measured SOC at 0-30 cm depth under all managements (Figure 14).

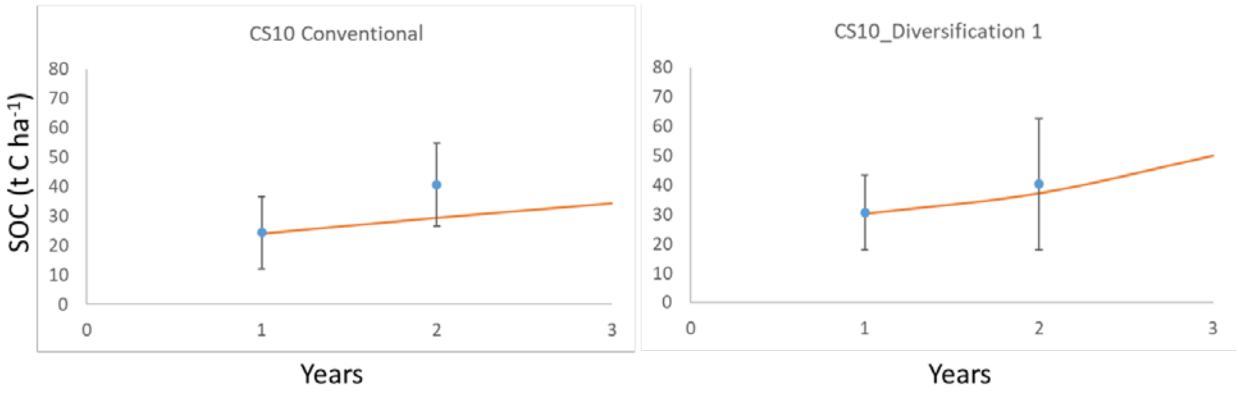

Figure 14. *Measured (point) and modelled (line) SOC in CS10 under conventional and diversified management*

- **CS11 Vineyard in Hungary**

  The experimental results revealed that Intercropping with yarrow (*Achillea millefolium*) (Diversification 2) in vine monocrop does not have any impact on SOC changes whereas grass mixture (Diversification 2) in the interrow gained an increase of 20 t ha^{-1} in SOC in one year from 2018 to 2019. Such a sharp increase in SOC after one year of diversification was not caught by the model, nor was the increase of 8 t ha^{-1} in SOC in the conventional management system (Figure 15).

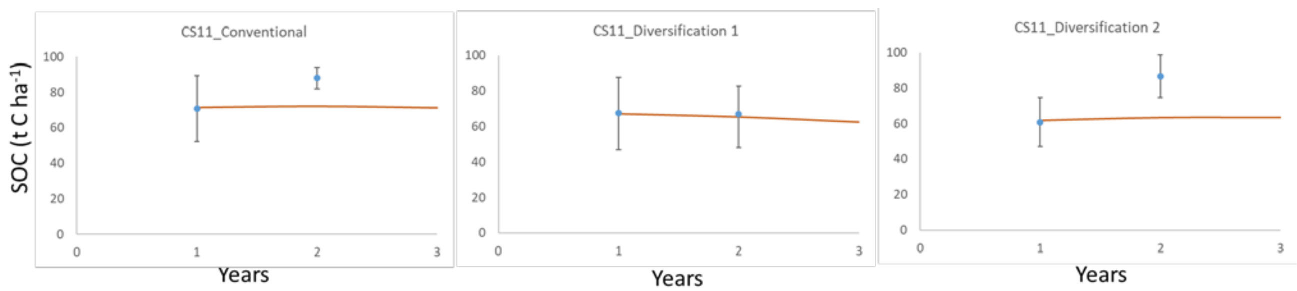

Figure 15. *Measured (point) and modelled (line) SOC in CS11 under conventional and diversified management*

5 Conclusion

New subroutines have been developed and existing ones modified in ECOSSE to allow the prediction of soil organic carbon (SOC) dynamics in various European diversified agroecosystems. The implementation of different moisture modification factors improved the performance of ECOSSE in dry and semiarid soil. To represent the impact of all diversifications considered within the Diverfarming project on soil quality, it was crucial to be able to simulate SOC dynamics under crop rotation, intercropping, and multiple cropping, which was not possible in the previous version of ECOSSE. A new subroutine to calculate net primary production for cover crops and intercropping was a significant step forward towards such a goal. The new version of ECOSSE is now able to simulate SOC dynamics for all considered (in Diverfarming) land use, climate and soil type, soil properties, irrigation and different farming management e.g., tillage, manuring, crop rotations, intercropping, multiple cropping, etc. The modified version was parameterised using data from long term experiments and evaluated against data from short-term case studies. In all cases, a good agreement was found between modelled and measured SOC. A positive but non-significant relationship was observed in case studies where the number of measured data points was less than five. A good agreement between modelled and measured SOC, indicates that the model is suitable to be applied to diversified agroecosystems.

The executable file of the modified ECOSSE and a folder with examples of input files for both limited and site-specific mode will be made available for download from the Diverfarming project website, Diverfarming Community on Zenodo repository and GitHub (software sharing platform). A simulation guide with the new features and the link to the original ECOSSE manual will also be provided, together with details of whom to contact if users wish to modify the FORTRAN code.

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ANNEX 1: SOC estimate in ECOSSE

***Table 7**. Default pattern of cover crops plant carbon inputs (t C ha^{-1}) to the soil. Monthly plant input distribution is expressed in percentage.*

Month	1	2	3	4	5	6	7	8	9	10	11	12
						Caper						
0-30cm	0.013	0.013	0.013	0.013	0.100	0.100	0.201	0.625	0.013	0.013	0.013	0.013
30-100cm	0.005	0.005	0.005	0.005	0.043	0.043	0.086	0.268	0.005	0.005	0.005	0.005
>100cm	0	0	0	0	0	0	0	0	0	0	0	0
Distribution	0.011	0.011	0.011	0.011	0.089	0.089	0.178	0.555	0.011	0.011	0.011	0.011
						Thyme						
0-30cm	0	0	0	0	0.056	0.056	0.056	0.112	0.350	0	0	0
30-100cm	0	0	0	0	0.024	0.024	0.024	0.048	0.150	0	0	0
>100cm	0	0	0	0	0	0	0	0	0	0	0	0
Distribution	0	0	0	0	0.089	0.089	0.089	0.178	0.555	0	0	0
						Faba_bean_S						
0-30cm	0.253	0	0	0	0	0	0	0	0.041	0.041	0.041	0.081
30-100cm	0.108	0	0	0	0	0	0	0	0.017	0.017	0.017	0.035
>100cm	0	0	0	0	0	0	0	0	0	0	0	0
Distribution	0.555	0	0	0	0	0	0	0	0.089	0.089	0.089	0.178
						Faba_bean_L						
0-30cm	0	0	0	0	0	0	0	0	0.015	0.015	0.030	0.109
30-100cm	0	0	0	0	0	0	0	0	0.006	0.006	0.013	0.047
>100cm	0	0	0	0	0	0	0	0	0	0	0	0
Distribution	0	0	0	0	0	0	0	0	0.089	0.089	0.178	0.644
						Cowpea						
0-30cm	0	0	0	0	0.030	0.030	0.030	0.061	0.190	0	0	0
30-100cm	0	0	0	0	0.013	0.013	0.013	0.026	0.081	0	0	0
>100cm	0	0	0	0	0	0	0	0	0	0	0	0
Distribution	0	0	0	0	0.089	0.089	0.089	0.178	0.555	0	0	0
						Pea						
0-30cm	0.009	0.036	0.036	0.071	0.222	0	0	0	0	0.009	0.009	0.009
30-100cm	0.004	0.015	0.015	0.031	0.095	0	0	0	0	0.004	0.004	0.004
>100cm	0	0	0	0	0	0	0	0	0	0	0	0
Distribution	0.022	0.089	0.089	0.178	0.555	0	0	0	0	0.022	0.022	0.022
						Vetch barley						
0-30cm	0.062	0.062	0.062	0.187	0.187	0.374	1.166	0	0	0	0	0
30-100cm	0.027	0.027	0.027	0.080	0.080	0.160	0.500	0	0	0	0	0
>100cm	0	0	0	0	0	0	0	0	0	0	0	0

Month	1	2	3	4	5	6	7	8	9	10	11	12
Distribution	0.030	0.030	0.030	0.089	0.089	0.178	0.555	0	0	0	0	0
Purslane												
0-30cm	0	0	0	0	0.271	0.438	1.041	0	0	0	0	0
30-100cm	0	0	0	0	0.116	0.188	0.446	0	0	0	0	0
>100cm	0	0	0	0	0	0	0	0	0	0	0	0
Distribution	0	0	0	0	0.155	0.250	0.595	0	0	0	0	0
Cardoon												
0-30cm	0.331	0.391	0.536	0.933	1.072	2.354	0	0	0	0.134	0.134	0.134
30-100cm	0.142	0.168	0.230	0.400	0.459	1.009	0	0	0	0.058	0.058	0.058
>100cm	0	0	0	0	0	0	0	0	0	0	0	0
Distribution	0.055	0.065	0.089	0.155	0.178	0.391	0	0	0	0.022	0.022	0.022
Campion												
0-30cm	0.385	0.385	0.385	0.385	0.385	0.385	0.385	1.369	0.385	0.385	0.385	0.385
30-100cm	0.165	0.165	0.165	0.165	0.165	0.165	0.165	0.587	0.165	0.165	0.165	0.165
>100cm	0	0	0	0	0	0	0	0	0	0	0	0
Distribution	0.069	0.069	0.069	0.069	0.069	0.069	0.069	0.245	0.069	0.069	0.069	0.069
Rocket												
0-30cm	0.036	0.036	0.071	0.221	0	0	0	0	0	0	0.018	0.018
30-100cm	0.015	0.015	0.030	0.095	0	0	0	0	0	0	0.008	0.008
>100cm	0	0	0	0	0	0	0	0	0	0	0	0
Distribution	0.089	0.089	0.178	0.555	0	0	0	0	0	0	0.045	0.045
Avena sativa and Vicia sativa												
0-30cm	0	0.003	0.003	0.005	0.019	0	0	0	0	0	0	0
30-100cm	0	0.001	0.001	0.002	0.008	0	0	0	0	0	0	0
>100cm	0	0	0	0	0	0	0	0	0	0	0	0
Distribution	0	0.089	0.089	0.177	0.646	0	0	0	0	0	0	0
Avena sativa												
0-30cm	0.016	0.016	0.016	0.048	0.048	0.095	0.297	0	0	0	0	0
30-100cm	0.007	0.007	0.007	0.020	0.020	0.041	0.127	0	0	0	0	0
>100cm	0	0	0	0	0	0	0	0	0	0	0	0
Distribution	0.030	0.030	0.030	0.089	0.089	0.178	0.555	0	0	0	0	0
Vicia sativa												
0-30cm	0.052	0.052	0.052	0.156	0.156	0.312	0.972	0	0	0	0	0
30-100cm	0.022	0.022	0.022	0.067	0.067	0.134	0.416	0	0	0	0	0
>100cm	0	0	0	0	0	0	0	0	0	0	0	0
Distribution	0.030	0.030	0.030	0.089	0.089	0.178	0.555	0	0	0	0	0

Month	1	2	3	4	5	6	7	8	9	10	11	12
						Saffron						
0-30cm	0	0	0	0	0	0	0.0001	0.0001	0.0001	0.0002	0.0006	0
30-100cm	0	0	0	0	0	0	0	0	0	0.0001	0.0002	0
>100cm	0	0	0	0	0	0	0	0	0	0	0	0
Distribution	0	0	0	0	0	0	0.071	0.071	0.071	0.214	0.571	0
						Lavandel						
0-30cm	0.096	0.096	0.096	0.096	0.096	0.096	0.096	0.342	0.096	0.096	0.096	0.096
30-100cm	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.147	0.041	0.041	0.041	0.041
>100cm	0	0	0	0	0	0	0	0	0	0	0	0
Distribution	0.069	0.069	0.069	0.069	0.069	0.069	0.069	0.244	0.069	0.069	0.069	0.069
						Oregano						
0-30cm	0.020	0.020	0.041	0.126	0	0	0	0	0	0	0.010	0.010
30-100cm	0.009	0.009	0.017	0.054	0	0	0	0	0	0	0.004	0.004
>100cm	0	0	0	0	0	0	0	0	0	0	0	0
Distribution	0.089	0.089	0.178	0.555	0	0	0	0	0	0	0.044	0.044
						Yarrow						
0-30cm	0.008	0.009	0.012	0.021	0.024	0.053	0	0	0	0.003	0.003	0.003
30-100cm	0.003	0.004	0.005	0.009	0.010	0.023	0	0	0	0.001	0.001	0.001
>100cm	0	0	0	0	0	0	0	0	0	0	0	0
Distribution	0.055	0.065	0.089	0.155	0.178	0.391	0	0	0	0.022	0.022	0.022
						Grass_mix						
0-30cm	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.035	0.010	0.010	0.010	0.010
30-100cm	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.015	0.004	0.004	0.004	0.004
>100cm	0	0	0	0	0	0	0	0	0	0	0	0
Distribution	0.069	0.069	0.069	0.069	0.069	0.069	0.069	0.243	0.069	0.069	0.069	0.069

ANNEX 2: Fortran code for new routines and modifications to existing ones

```
C---------------------------------------------------
      SUBROUTINE GET_PLANT_DIST(PI_ANN,PI_CEQ_MON,LUCODE,COVERC,NXCOVER)
C
C Subroutine to get plant input distribution
C
…
C (7) Olives/Almonds crops
C (7.1) 0-30cm
C
      DATA (PLADD(M,7,1),M=1,12)/0.199,0.199,0.86,0.86,0.022,0.022,
     and                           0.022,0.022,0.022,0.022,0.199,0.199/
C
C (7.2) 30-100cm
C
      DATA (PLADD(M,7,2),M=1,12)/0.0602,0.0602,0.25844,0.25844,
     and                           0.00658,0.00658,0.00658,0.00658,
     and                           0.00658,0.00658,0.0602,0.0602/
C
C (7.3) >100cm
C
      DATA (PLADD(M,7,3),M=1,12)/0.0258,0.0258,0.11076,0.11076,0.00282,
     and                           0.00282,0.00282,0.00282,0.00282,0.00282,
     and                           0.0258,0.0258/
C (8) Citrus crops
C (8.1) 0-30cm
C
      DATA (PLADD(M,8,1),M=1,12)/0.534,0.734,0.934,0.534,0.334,0.2,
     and                           0.26,0.334,0.8,0.93,0.734,0.534/
C
C (8.2) 30-100cm
C
      DATA (PLADD(M,8,2),M=1,12)/0.2403,0.3303,0.4203,0.2403,
     and                           0.1503,0.09,0.117,0.1503,0.36,
     and                           0.4203,0.3303,0.2403/
C
C (8.3) >100cm
C
      DATA (PLADD(M,8,3),M=1,12)/0.0267,0.0367,0.0467,0.0267,
     and                           0.0167,0.01,0.013,0.0167,0.04,
     and                           0.0467,0.0367,0.0267/
C
C Grapevines
C (9.1) 0-30cm
C
      DATA (PLADD(M,9,1),M=1,12)/1.92,1.92,0.049,0.049,0.049,
     and          0.049,0.049,0.049,0.445,0.445,
```

```
     and        0.445,0.445/
C
C (9.2) 30-100cm
C
      DATA (PLADD(M,9,2),M=1,12)/0.865,0.865,0.022,0.022,0.022,
     and        0.022,0.022,0.022,0.2,0.2,0.2,0.2/
C
C (9.3) >100cm
C
      DATA (PLADD(M,9,3),M=1,12)/0.096,0.096,0.0024,0.0024,0.0024,
     and             0.0024,0.0024,0.0024,0.022,0.022,
     and             0.022,0.022/
C
C The total plant input distribution is calculated by summing up values for each layer down the profile,
both from main and cover crop.
C
      PLADD1=PLADD
      IF(NXCOVER.NE.0)THEN
      DO 130 I=1,NXCOVER
           CALL GET_COVER_CROP_DIST(COVERC(I),COVERD)
           DO 150 ILAY=1,MAXPILAY
             DO 250 IMON=1,12
           PLADD1(IMON,LUCODE,ILAY)=COVERD(IMON,ILAY)+PLADD(IMON,LUCODE,ILAY)
250       CONTINUE
150        CONTINUE
130   CONTINUE
      ENDIF
...
...
c----------------------------------------------------
```

```
C----------------------------------------------------
C Routine for adjusting cover crops carbon input. Based on the paper by Del Grosso et al. 2008
C
      SUBROUTINE NCEAS(AveRain,Rain,Si)
! Routine to adjust cover crops carbon input.
      IMPLICIT NONE
      REAL :: AveRain   ! mean annual precipitation
      REAL :: Rain     ! mean total annual precipitation
      REAL :: npp1      ! precipitation-limited npp at average
      REAL :: npp2      ! precipitation-limited npp currently
      REAL :: Si        ! ratio between NPP with average rain and current rain

     ! Calculation of net primary production with average  and current precipitation
       npp1 = 6166*(1-EXP(-6.05*0.00001*AveRain))
       npp2 = 6166*(1-EXP(-6.05*0.00001*Rain))

       !Ratio between average and current npp
       Si = npp2/npp1

      END SUBROUTINE NCEAS
C----------------------------------------------------
```

```
C
C-------------------------------------------------------------
C
        SUBROUTINE GET_COVER_CROP_DIST(COVERC,COVERD)
C
C Subroutine to get the plant input distribution from cover crops
C
      IMPLICIT NONE

    INTEGER MAXPILAY ...............................................................             !
Maximum number of PI layers
    PARAMETER (MAXPILAY=3)
    INTEGER MAXCOVERC ..............................................................
    ! Max.no.of cover crop
    PARAMETER (MAXCOVERC=19)
C  Passed to/from subroutine
               REAL COVERINFO1(12,0:MAXCOVERC-1) ! LAYER 1
               REAL COVERINFO2(12,0:MAXCOVERC-1) ! LAYER 2
               REAL COVERINFO3(12,0:MAXCOVERC-1) ! LAYER 3  ........................
            REAL COVERD(12,MAXPILAY) ............!OUT: total cover crop distribution
               INTEGER COVERC ..................................................
    !IN: type of cover crop

C INTEGER local to subroutine
            INTEGER NUMCOVCROP, I, J, MO
             CHARACTER*40 TEMP, CNAME(0:MAXCOVERC-1)
C
C Set default array descriptors
C
            I=1
            J=1
C
C Set default number of crops to number of crops previously parameterised
C
        NUMCOVCROP=1
           !PRINT*,'COVERC=', COVERC
C
C Try to open COV_CROP.DAT
C
        OPEN(77,FILE='COV_CROP.DAT',STATUS='OLD',ERR=111)
           GOTO 101
C
C Record error in file name
C
111   CONTINUE
           WRITE(*,*)'Warning! Check the file name!'
           WRITE(*,*)'The name must be COV_CROP.DAT'
C
C Read in parameters from COV_CROP.DAT
C
```

DIVERFARMING

```
101   CONTINUE
           IF(COVERC.NE.0)THEN
           READ(77,9,ERR=110)TEMP,I
               GOTO 114
           ENDIF
110   CONTINUE
      WRITE(*,*)'Warning! The crop name is wrong!'
114   CONTINUE
        READ(77,10,ERR=112)(COVERINFO1(J,I),J=1,12),
     and      (COVERINFO2(J,I),J=1,12),
     and      (COVERINFO3(J,I),J=1,12)
     GOTO 115
112   CONTINUE
           WRITE(*,*)'Warning! Error in cover crop parameters!'
            WRITE(*,*)'Check format of cover crop parameter file, COV_CROP.DAT'
115   CONTINUE   ..................................................................
C
C Set crop name and crop number
C
            CNAME(I)=TEMP
            NUMCOVCROP=I ..........................................................
C
C Save the parameters needed in COVERD(12,MAXPILAY)
C
            IF(COVERC.EQ.I)THEN
               DO 977 MO=1,12
                COVERD(MO,1) = COVERINFO1(MO,I)
                COVERD(MO,2) = COVERINFO2(MO,I)
                COVERD(MO,3) = COVERINFO3(MO,I)
977             CONTINUE
           ELSE
               GOTO 101
           ENDIF
C
C Format statements for parlis...
C
C Line 1: Crop Name; Line 2: Crop Number
9     FORMAT(A40/I3)
C Line 3: first layer (12 values)
10    FORMAT(12(F10.4,2X)/
C Line 4: second layer (12 values)
     and       12(F10.4,2X)/
C Line 5: third layer (12 values)
     and      12(F10.4,2X))
C
C Record error in the format of COV_CROP.DAT
C
C Close channel 77
C
      CLOSE(77)
```

```
C
C Leave routine
C
      END
C-------------------------------------------------------------
```

```
C
C-----------------------------------------------------------
      SUBROUTINE MODFACTS_MINER(LAYERSOILW,LAYERWMAX,LAYERWSAT,WILTP,
     &                    WRATED,WRATER,STYPE,THISTEMP,TRATE,
     &                     PH,PHP1,PHP2,PHRATE,ICOVER,CRRATE,ITFUNC,IMFUNC)
C
C Subroutine to calculate the rate modifying factors
C
C-------------------------------------
C Minimum rate depending on soil type
C-------------------------------------
        IF(STYPE.EQ.1)THEN
             WMIN  = 0.2
             WMINR = 0.2
             WMIND = 0.2
           ELSEIF(STYPE.EQ.2)THEN
             WMIN  = 0.15
             WMINR = 0.15
             WMIND = 0.15
        ELSE
             WMIN  = 0.1
             WMINR = 0.1
             WMIND = 0.1
           ENDIF
C-----------------------------------------------------------
```

```
C------------------------------------------------------------
      SUBROUTINE ECOSSE_SITE_RUN(ISWAIT)
C
C Subroutine to run ECOSSE for SITE
...

INTEGER IS_IRR(0:MAXGROW)          !   Irrigation: 1=YES, 0=No (default)
REAL WIRR(0:MAXGROW)               ! IN(SETFILE): total water used for the irrigation over the whole
period (Hm3/ha/year)
...

C  Add irrigation to rainfall for the season of growth and month considered
           IR_MON = IHARV - NIRR(COUNTER)
C
           IF(IS_IRR(COUNTER) == 1 .AND. sum_ts >= IR_MON .AND. sum_ts < IHARV) THEN
           RAIN   = RAIN+WIRR(COUNTER)
           precip = RAIN
           ENDIF
C--------------------------------------------
```

```
C-------------------------------------------

  SUBROUTINE SETFILE(ATM,IDATEFC,NSOILJ,STYPE,IDRAINJ,IROCKJ,LCROP,
...
...

C   After reading the irrigation info the number of days used to irrigate are rounded to months and the
total amount of water expressed in mm
           IF(TIMESTEP.EQ.0 .OR. TIMESTEP.EQ.1)THEN
            NIRR(I) = 0
            WIRR(I) = 0
           ELSEIF(TIMESTEP.EQ.2)THEN
             WIRR(I) = (WIRR(I)*10**5)/(NIRR(I))
        ELSEIF(TIMESTEP.EQ.3)THEN
             App = NIRR(I)/30
             NIRR(I) = NINT(App)+1
             WIRR(I) = (WIRR(I)*10**5)/(NIRR(I))
           ENDIF
```

ANNEX 3: Input and management files

Management.txt (Site specific Mode)

```
1           # Soil code number
2           # Dryness class (1=normal soil, 2=dry, 3=vertisols)
2           # Drainage class (1=low, 2=moderate, 3=high)
3           # Depth to impermeable layer (1=50cm, 2=100cm, 3=150cm)
23          # Previous crop code
85          # Yield of previous crop [t/ha]
14.4        # Atmospheric N deposition [kg N/ha]
1           # Date field reaches field capacity (1=01/01; 2=01/06)
3           # Timestep (0=30 min, 1=daily, 2=weekly, 3=monthly)
0           # Crop model type (0=SUNDIAL, 1=MAGEC)
9           # Number of years in simulation
0           # Timesteps from 01/01 to harvest of previous crop
2010        # First year of simulation
108         # End of simulation [number of timesteps]
0           # Fixed end of simulation? (0=no, 1=yes)
37.81       # Latitude [decimal degrees]
300         # Water table depth [cm], if > 150 cm there is no effect
2010.txt  # Year 2 climate file
2011.txt  # Year 2 climate file
2012.txt  # Year 3 climate file
2013.txt  # Year 3 climate file
2014.txt  # Year 3 climate file
2015.txt  # Year 3 climate file
2016.txt  # Year 3 climate file
2017.txt  # Year 3 climate file
2018.txt  # Year 3 climate file
16           # Number of crops
27           # CROP 1:Crop code# 2010#melon May-July
0            # Irrigation 1=yes, 0=no (default)
0            # Number of days irrigation occurs
0            # Irrigation water quantity (Hm3/ha/year)
5            # Timesteps to sowing date from 01/01/01#May2010
0            # Crop N uptake at harvest (0=calculate internally) [kg N/ha]
7            # Timesteps to harvest date from 01/01/01#Feb 2011
25           # Expected_M_yield [t/ha]
1            # Crop residues incorporated (0=No, 1=Yes
0            # Number of fertiliser applications
0            # Number of organic manure applications
23           # CROP 2: Crop code# 2010_2011#cabbage Nov-February
1            # Irrigation 1=yes, 0=no (default)
32           # Number of days irrigation occurs
0.0024       # Irrigation water quantity (Hm3/ha/year)
11           # Timesteps to sowing date from 01/01/01#May 2011
0            # Crop N uptake at harvest (0=calculate internally) [kg N/ha]
14           # Timesteps to harvest date from 01/01/01#Jul 2011
```

```
88           # Expected yield [t/ha]
1            # Crop residues incorporated (0=No, 1=Yes
1            # Number of fertiliser applications
1            # Number of organic manure applications
6.18         # Amount of fertiliser applied [kg N/ha]
11           # Timesteps to fertiliser application
0            # Percentage NO3
0            # Percentage NH4
0            # Percentage urea
1           # Volatilisation of ammonium #Does fert. contain ammonium salts other than ammonium sulphate
(0=No, 1=Yes)
0            # Has fertiliser been labelled (0=No, 1=Yes)
12           # Amount of manure applied [t/ha fresh manure]
9            # Timesteps to manure application
15           # Type of manure
0            # is manure been labelled (0=No, 1=Yes)
27           # CROP M 3: Crop code# 2011#melon May-July
0            # Irrigation 1=yes, 0=no (default)
0            # Number of days irrigation occurs
0            # Irrigation water quantity (Hm3/ha/year)
17           # Timesteps to sowing date from 01/01/01#May 2011
0            # Crop N uptake at harvest (0=calculate internally) [kg N/ha]
19           # Timesteps to harvest date from 01/01/01#Jul 2011
25          # Expected_M_yield [t/ha]
1            # Crop residues incorporated (0=No, 1=Yes
0            # Number of fertiliser applications
0            # Number of organic manure applications

....

16           # number of cultivations
4            # Time steps to cultivation date#Oct 2010
3            # Cultivation 1
0            #vigour
10           # Time steps to cultivation date#Oct 2010
3            # Cultivation 2
0            #vigour
16           # Time steps to cultivation date#April 2011
3            # Cultivation 3
0            #vigour

....
```

Input.txt (limited data mode)

```
4          # Mode of equilibrium run
1            # Number of soil layers (max 10)
30           # Depth of bottom of SOM layer 1 [cm]
57460        # C content [kgC/ha] for this soil under ara in SOM layer 1
1.12         # Bulk density [g/cm3] for this soil under ara in SOM layer 1
8.00          # pH for this soil under ara in SOM layer 1
15.54           # % clay by weight for this soil under ara in SOM layer 1
41.89           # % silt by weight for this soil under ara in SOM layer 1
2.57          # % sand by weight for this soil under ara in SOM layer 1
56952       # C content [kgC/ha] for this soil under gra in SOM layer 1
1.12         # Bulk density [g/cm3] for this soil under gra in SOM layer 1
8.00          # pH for this soil under gra in SOM layer 1
42.81           # % clay by weight for this soil under gra in SOM layer 1
26.76           # % silt by weight for this soil under gra in SOM layer 1
30.43           # % sand by weight for this soil under gra in SOM layer 1
57750        # C content [kgC/ha] for this soil under for in SOM layer 1
1.12         # Bulk density [g/cm3] for this soil under for in SOM layer 1
8.00          # pH for this soil under for in SOM layer 1
15.54           # % clay by weight for this soil under for in SOM layer 1
41.89           # % silt by weight for this soil under for in SOM layer 1
2.57          # % sand by weight for this soil under for in SOM layer 1
56952      # C content [kgC/ha] for this soil under nat in SOM layer 1
1.12         # Bulk density [g/cm3] for this soil under nat in SOM layer 1
8.00          # pH for this soil under nat in SOM layer 1
15.54           # % clay by weight for this soil under nat in SOM layer 1
41.89           # % silt by weight for this soil under nat in SOM layer 1
2.57           # % sand by weight for this soil under nat in SOM layer 1
56952       # C content [kgC/ha] for this soil under mis in SOM layer 1
1.12         # Bulk density [g/cm3] for this soil under mis in SOM layer 1
8.00          # pH for this soil under mis in SOM layer 1
15.54           # % clay by weight for this soil under mis in SOM layer 1
41.89           # % silt by weight for this soil under mis in SOM layer 1
2.57           # % sand by weight for this soil under mis in SOM layer 1
56952        # C content [kgC/ha] for this soil under src in SOM layer 1
1.12         # Bulk density [g/cm3] for this soil under src in SOM layer 1
8.00          # pH for this soil under src in SOM layer 1
15.54           # % clay by weight for this soil under src in SOM layer 1
41.89           # % silt by weight for this soil under src in SOM layer 1
2.57          # % sand by weight for this soil under src in SOM layer
58000        # C content [kgC/ha] for this soil under inter in SOM layer 1#LU7
1.13         # Bulk density [g/cm3] for this soil under inter in SOM layer 1
8.00          # pH for this soil under inter in SOM layer 1
15.76           # % clay by weight for this soil under inter in SOM layer 1
41.67           # % silt by weight for this soil under inter in SOM layer 1
42.57          # % sand by weight for this soil under inter in SOM layer 1
57500        # C content [kgC/ha] for this soil under inter in SOM layer 1#LU8
1.12         # Bulk density [g/cm3] for this soil under inter in SOM layer 1
```

```
8.07         # pH for this soil under inter in SOM layer 1
15.54          # % clay by weight for this soil under inter in SOM layer 1
41.89          # % silt by weight for this soil under inter in SOM layer 1
2.57         # % sand by weight for this soil under inter in SOM layer 1
56952       # C content [kgC/ha] for this soil under inter in SOM layer 1#LU9
1.12        # Bulk density [g/cm3] for this soil under inter in SOM layer 1
8.07         # pH for this soil under inter in SOM layer 1
15.54          # % clay by weight for this soil under inter in SOM layer 1
41.89          # % silt by weight for this soil under inter in SOM layer 1
2.57         # % sand by weight for this soil under inter in SOM layer 1
0           # ara long term average plant C input [kgC/ha/yr] (used in modes 1 and 3 only)
0           # gra long term average plant C input [kgC/ha/yr] (used in modes 1 and 3 only)
0           # for long term average plant C input [kgC/ha/yr] (used in modes 1 and 3 only)
0           # nat long term average plant C input [kgC/ha/yr] (used in modes 1 and 3 only)
0           # mis long term average plant C input [kgC/ha/yr] (used in modes 1 and 3 only)
0           # src long term average plant C input [kgC/ha/yr] (used in modes 1 and 3 only)
0           # Almonds long term average plant C input [kgC/ha/yr] (used in modes 1 and 3 only)
0           # Citrus long term average plant C input [kgC/ha/yr] (used in modes 1 and 3 only)
0           # Vineyards long term average plant C input [kgC/ha/yr] (used in modes 1 and 3 only)
21.0        # Jan long term average monthly precipitation [mm]
16.0       # Feb long term average monthly precipitation [mm]
33.0       # Mar long term average monthly precipitation [mm]
29.0       # Apr long term average monthly precipitation [mm]
28.0       # May long term average monthly precipitation [mm]
10.0       # Jun long term average monthly precipitation [mm]
2.0       # Jul long term average monthly precipitation [mm]
16.0       # Aug long term average monthly precipitation [mm]
33.0        # Sep long term average monthly precipitation [mm]
28.0        # Oct long term average monthly precipitation [mm]
30.0        # Nov long term average monthly precipitation [mm]
23.0        # Dec long term average monthly precipitation [mm]
7.0       # Jan long term average monthly temperature [degC]
7.7       # Feb long term average monthly temperature [degC]
10.3      # Mar long term average monthly temperature [degC]
12.8       # Apr long term average monthly temperature [degC]
16.4      # May long term average monthly temperature [degC]
21.5      # Jun long term average monthly temperature [degC]
24.3      # Jul long term average monthly temperature [degC]
23.8       # Aug long term average monthly temperature [degC]
18.7       # Sep long term average monthly temperature [degC]
15.0      # Oct long term average monthly temperature [degC]
9.7       # Nov long term average monthly temperature [degC]
7.1       # Dec long term average monthly temperature [degC]
37.51      # Latitude [decimal deg]
300         # Water table depth at start [cm]
2           # Drainage class
2       # Soil type (1=normal, 2=dry, 3=vertsols)
-999        # C accumulated before change [kgC/ha/yr] (only for mode 4 - if not use a dummy a value)
-999        # CH4 emission before change [kgC/ha/yr]
-999        # CO2 emission before change [kgC/ha/yr]
```

```
-999         # DOC loss before change [kgC/ha/yr]
10           # Number of growing seasons to simulate
7, 0.,0         # Year 2010 land use and plant C input [kgC/ha/yr] (Not used in mode 7. If plant input set to zero it is obtained from RothC instead)
7, 0.,0         # Year 2010 land use and plant C input [kgC/ha/yr] (Not used in mode 7. If plant input set to zero it is obtained from RothC instead)
7, 0.,0         # Year 2010 land use and plant C input [kgC/ha/yr] (Not used in mode 7. If plant input set to zero it is obtained from RothC instead)
7, 0.,0         # Year 2010 land use and plant C input [kgC/ha/yr] (Not used in mode 7. If plant input set to zero it is obtained from RothC instead)
7, 0.,0         # Year 2010 land use and plant C input [kgC/ha/yr] (Not used in mode 7. If plant input set to zero it is obtained from RothC instead)
7, 0.,0         # Year 2010 land use and plant C input [kgC/ha/yr] (Not used in mode 7. If plant input set to zero it is obtained from RothC instead)
7, 0.,0         # Year 2010 land use and plant C input [kgC/ha/yr] (Not used in mode 7. If plant input set to zero it is obtained from RothC instead)
7, 0.,0         # Year 2010 land use and plant C input [kgC/ha/yr] (Not used in mode 7. If plant input set to zero it is obtained from RothC instead)
7, 0.,0         # Year 2010 land use and plant C input [kgC/ha/yr] (Not used in mode 7. If plant input set to zero it is obtained from RothC instead)
7, 0.,0         # Year 2010 land use and plant C input [kgC/ha/yr] (Not used in mode 7. If plant input set to zero it is obtained from RothC instead)
2009.txt  # Year 1 climate file
2010.txt  # Year 1 climate file
2011.txt  # Year 2 climate file
2012.txt  # Year 3 climate file
2013.txt  # Year 3 climate file
2014.txt  # Year 3 climate file
2015.txt  # Year 3 climate file
2016.txt  # Year 3 climate file
2017.txt  # Year 3 climate file
2018.txt  # Year 3 climate file
```

CROP_SUN.dat

```
Miscanthus
 33
     5599.         0.9       -0.20        1.00       1.190
      111.       -0.92       1.000        167.       0.070       1.000
      0.46        0.09       0.144       0.115
      0.09         0.0       0.067         1.5
         5         5.0        25.0         150
     2181.        0.93      -1.717       1.000
      0.51        830.        0.34       0.012
```