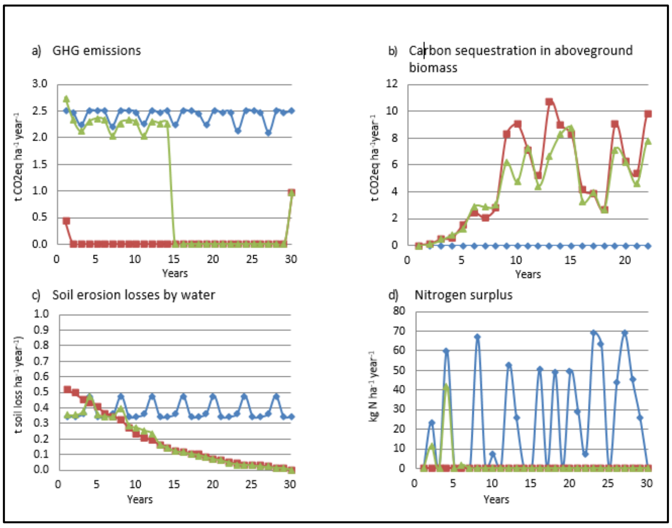


Modelling the economics of agroforestry at field- and farm-scale

Project name	AGFORWARD (613520)
Work-package	6: Field- and farm-scale evaluation of innovations
Deliverable	Deliverable 6.18: Modelling the economics of agroforestry at field- and farm-scale
Date of report	31 August 2017 (updated 13 October 2017)
Authors	Silvestre García de Jalón, Anil Graves, Joao Palma, Josep Crous-Duran, Michail Giannitsopoulos, Paul J Burgess
Contact	a.graves@cranfield.ac.uk s.garciadejalon@gmail.com
Reviewed	Paul Burgess (18 August 2017)

Contents

AGFORWARD (Grant Agreement N° 613520) is co-funded by the European Commission, Directorate General for Research & Innovation, within the 7th Framework Programme of RTD. The views and opinions expressed in this report are purely those of the writers and may not in any circumstances be regarded as stating an official position of the European Commission

1 Context and objectives

The AGFORWARD research project (January 2014-December 2017), funded by the European Commission, is promoting agroforestry practices in Europe that will advance sustainable rural development. The project has four objectives:

1. to understand the context and extent of agroforestry in Europe,
2. to identify, develop and field-test innovations (through participatory research) to improve the benefits and viability of agroforestry systems in Europe,
3. to evaluate innovative agroforestry designs and practices at a field-, farm- and landscape scale, and
4. to promote the wider adoption of appropriate agroforestry systems in Europe through policy development and dissemination.

The third objective of the project is addressed in work-package 6 which focused on the field- and farm-scale evaluation of innovations, and work-package 7 which focused on the landscape evaluation.

Within work-package 6 deliverables 6.16 and 6.17 focus on the biophysical evaluation of agroforestry systems at the field- and farm-scale. This report (Deliverable 6.18) assesses the economics of agroforestry systems at field- and farm-scales and compares them with alternative land uses such as arable cropping, pasture and forestry. More specifically this report evaluates the financial profitability (from a farmer perspective) and the economic benefits (from a societal perspective). The report also explores how farm-scale modelling results can be up-scaled at the regional level.

2 Methodological framework

This study used biophysical and economic models to assess the economics of agroforestry systems and to compare them with arable, pasture and forestry systems. The biophysical model used in this report was the Yield-SAFE model (van der Werf et al. 2007; Palma et al. 2017). The Yield-SAFE model is a parameter-sparse, process-based dynamic model for predicting resource capture, growth, and production in agroforestry systems that has been frequently used by various research organizations in recent years. It works on a daily time-step for a specified rotation of the trees that may last a given number of years.

Numerous improvements to two models have been undertaken to assess the economics of agroforestry, arable, pasture and forestry systems:

- The Farm-SAFE model: this is a Microsoft Excel-based spreadsheet model (Graves et al. 2007; 2011) that evaluates the financial and economic costs and benefits of arable, forestry, silvoarable, and silvopastoral systems. It works at an annual time-step and assesses the economics for a whole rotation of the trees (maximum rotation length = 60 years). The model was developed during the SAFE project to initially assess the financial profitability of silvoarable systems (Dupraz et al. 2005).
- The Forage-SAFE model: this is a Microsoft Excel-based spreadsheet model (García de Jalón et al. 2017) that evaluates the management and economics of wood pasture systems. It works at a daily time-step and assesses the economics for one year in a steady state scenario. This is a new model that has been developed during the AGFORWARD project (Burgess et al. 2015).

This report assesses the profitability of agroforestry systems in multiple case studies across Europe. It also presents the improvements carried out in the Farm-SAFE and Forage-SAFE models during the AGFORWARD project. Within this report two peer-reviewed papers have been produced to show the improvements made in the Farm-SAFE model and to describe the Forage-SAFE model.

The remainder of the report is separated into six main sections. The first section briefly describes the Farm-SAFE model, shows the improvements developed in the AGFORWARD project and presents results for various agroforestry, arable and forestry systems in Europe. This is followed by a peer-reviewed paper that uses the Farm-SAFE model to predict the environmental impact of agroforestry relative agriculture and forestry. The next section introduces the Forage-SAFE model which has been produced within the framework of work-package 6. This section describes in detail how the model works as well as its applicability. It assesses the economic impact of managerial decisions on the profitability of wood pastures (e.g. tree cover density and carrying capacity). This is followed by a peer-reviewed paper that has been produced within this deliverable has been incorporated. The next section presents a methodology developed to up-scale farm-level results to the regional level. The region of Britany (France) was used as a case study to show the applicability of the approach. The last section describes the main conclusions of this report.

3 The Farm-SAFE model

Farm-SAFE is a Microsoft Excel-based spreadsheet model (Graves et al. 2007; 2011) that evaluates the financial and economic costs and benefits of arable, forestry and silvoarable systems. Farm-SAFE was developed within the framework of the SAFE project which aimed to provide guidelines on the viability of silvoarable systems in Europe and the extrapolation of plot-scale results to individual farms (Dupraz et al. 2005). The model integrates biophysical outputs of Yield-SAFE with financial/economic data for analyses and environmental outputs at farm-scale. The main objectives of Farm-SAFE were described in Graves et al. (2011). These were:

- To use a common conceptual framework of farm economics including net margins
- To account for the effect of time on the value of money by discounting
- To compare the profitability of the systems. Discounted future benefits and costs of each system should be aggregated and a net present value, infinite net present value, and equivalent annual value calculated.
- To determine the feasibility of the systems. In particular, the effect of introducing the new agroforestry system on existing farm could be studied in terms of annual labour requirements, cash flow requirements and net benefit effects.
- To examine the sensitivity of each system to changes in input values

Within the AGFORWARD project (Burgess et al. 2015), the application and objectives of the Farm-SAFE model has been extended, so that in addition to assessing the financial performance of arable, forestry and agroforestry systems, it can quantify and compare the environmental externalities. In combination with the Yield-SAFE model, Farm-SAFE can now evaluate the provision of ecosystem services. For instance, in addition to calculating the economic value of "provisioning" services (i.e. yields) of trees, crops, and livestock, which are frequently obtained from Yield-SAFE, the economic value of the "supporting" (e.g. soil nutrients) and "regulating" services (e.g. carbon capture, water quality, GHG emissions) of agroforestry systems can also were evaluated by using a Life Cycle Assessment that has been implemented within Farm-SAFE. The cultural services (e.g. aesthetic pleasure, recreation potential) of agroforestry systems could also be evaluated within Farm-SAFE by using a range of social, and environmental economic research methods to identify, quantify, and rank social perceptions and preferences for agroforestry products and systems. However, on the whole, it has been difficult to obtain economic values for cultural services.

The development of an ecosystem services approach in AGFORWARD allows a more complete comparison of the long-term impacts of agroforestry relative to arable, livestock or forestry monoculture systems that includes both the non-market and market costs and benefits of the systems. Farm-SAFE thus helps identify and quantify the financial risks and uncertainty associated with agroforestry systems in a systematic manner, as well as now identifying where and how agroforestry can be used to offer improved resource efficiency and ecosystem benefits for stakeholders.

3.1 Financial analysis

In Farm-SAFE, the financial performance of arable, forestry and silvoarable system was assessed on the basis of the annual net margins per hectare. The net margin was calculated as revenues from harvested products (grain, straw, timber and firewood) and grants minus variable costs (e.g. crop seed, tree planting, fertiliser, crop and tree protection, pruning, thinning, cutting and other costs) and assignable fixed costs (e.g. installation and repairs of infrastructure, fuel and energy, machinery, insurance and labour and rented machinery costs).

Because people generally prefer to receive goods and services in the present rather than the future, revenues and costs were discounted and converted into financial net present values (NPV_F: € ha^{-1}), denoted using Equation 1:

$$NPV_F = \sum_{t=0}^{n} \left(\frac{(R_t - VC_t - FC_t)}{(1+i)^t} \right) \qquad Eq.1$$

where R_t, VC_t, and FC_t were respectively revenue, variable costs, and assignable fixed costs in year t (€ ha^{-1}), i was the discount rate, and n was the time horizon for the analysis. See Appendix to see the disaggregated revenues, variable costs, and assignable fixed costs in various case studies in Europe. A discount rate of 4% was chosen, as this is marginally above the discount rate of 3.5% used by the UK Government for cost-benefit analysis (HM Treasury, 2003). Although the costs were obtained in terms of pounds sterling, in this paper they are report in terms of Euros, assuming an exchange rate of £1 being equivalent to €1.389.

The financial profits of the different systems were compared in terms of a financial equivalent annual value (EAV_F: € ha^{-1} year^{-1}) using Equation 2:

$$EAV_F = NPV_F \left(\frac{(1+i)^n}{(1+i)^n - 1} \right) i \qquad Eq.2$$

The remainder of this section presents some results of the financial performance of the arable, forestry and agroforestry systems in six case studies in Europe.

3.1.1 Case study from Bedfordshire, United Kingdom

The arable system is a four-year crop rotation of wheat, wheat, barley and oilseed; the forestry system is a poplar tree plantation; and the silvoarable system is poplar tree with cropped alleys with the same rotation of the arable system. The financial assumptions for the Bedfordshire study can be found in Tables A.1, A.7, A.9 and A.10 in the Appendix. The EAV was estimated for a time horizon of 30 years at a 5% discount rate with and without grants.

The equivalent annual value (EAV) of an arable, forestry and silvoarable system was calculated for a location in Bedfordshire in the United Kingdom (Table 1). The analysis indicated that the EAV, with grants (based on arrangements in 2015 from UK Agro Business Consultants, 2015), for the arable system (561 € ha^{-1}) was more profitable for the farmer than the silvoarable (467 € ha^{-1}) and forest systems (131 € ha^{-1}). Without grants, the profitability of the silvoarable system (72 € ha^{-1}) was between that for the arable (314 € ha^{-1}) and forest systems (-17 € ha^{-1}). Since grants are paid by society it can be argued that the societal benefits of the system are best considered without the inclusion of grants. The forestry system without grants turned out to have a negative EAV.

Table 1. Equivalent Annual Value (EAV) of an arable, forestry and silvoarable system in Bedfordshire in the United Kingdom. Results shown for a time horizon of 30 years at a 5% discount rate.

	Arable[1]	Silvoarable[2]	Forestry[3]
EAV with grants (€ ha^{-1} year^{-1})	561	467	131
EAV without grants (€ ha^{-1} year^{-1})	314	72	-17

[1]: the arable system was a rotation of wheat, wheat, barley and oilseed rape

[2]: the silvoarable system was the same rotation as the arable system with 113 poplar trees per hectare.

[3]: the forestry system was hybrid poplars planted at a density of 156 trees per hectare.

Figure 1 shows the cumulative annual net margins with grants of the arable, forestry and silvoarable systems along the rotation turn. The arable system presents the highest cumulative annual net margins with grants at the end of the rotation.

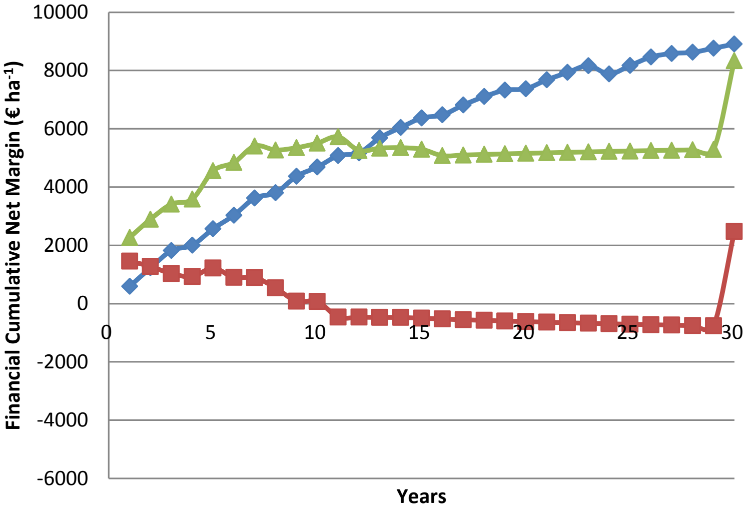


Figure 1. Modelled cumulative net margin with grants of the arable system (blue line: a rotation of wheat, wheat, barley and oilseed rape), the silvoarable system (green line: same rotation as the arable system with poplar hybrids) and the forest system (red line)

The silvoarable system receives around 472 € ha^{-1} as tree establishment payments. This makes the cumulative annual net margins with grants higher than the arable system. Only in the first and second year the forestry system presents higher cumulative net margin than the arable system due to the grants received for planting trees. It is worth noting that from year 8 to year 29 the cumulative net margin of the forestry system is below zero.

Figure 2 depicts the change in the crop revenue (crop yield and by-product) of the silvoarable system during the rotation. The crop component revenue decreases as the trees grow, due to light, water and nutrient competition. After year 16 the crop revenue is lower than the fixed and variable costs and consequently planting the crop is no longer profitable. Therefore, from year 17 onwards there is no crop component in the system. Farm-SAFE captures this phenomenon through annually calculating the moving average of the last three years. Thus when the mean net margin without grants in the last three years is lower than zero the model assumes that the farmer does not plant an arable crop. Other time periods and threshold values for this calculation can also be specified in Farm-SAFE.

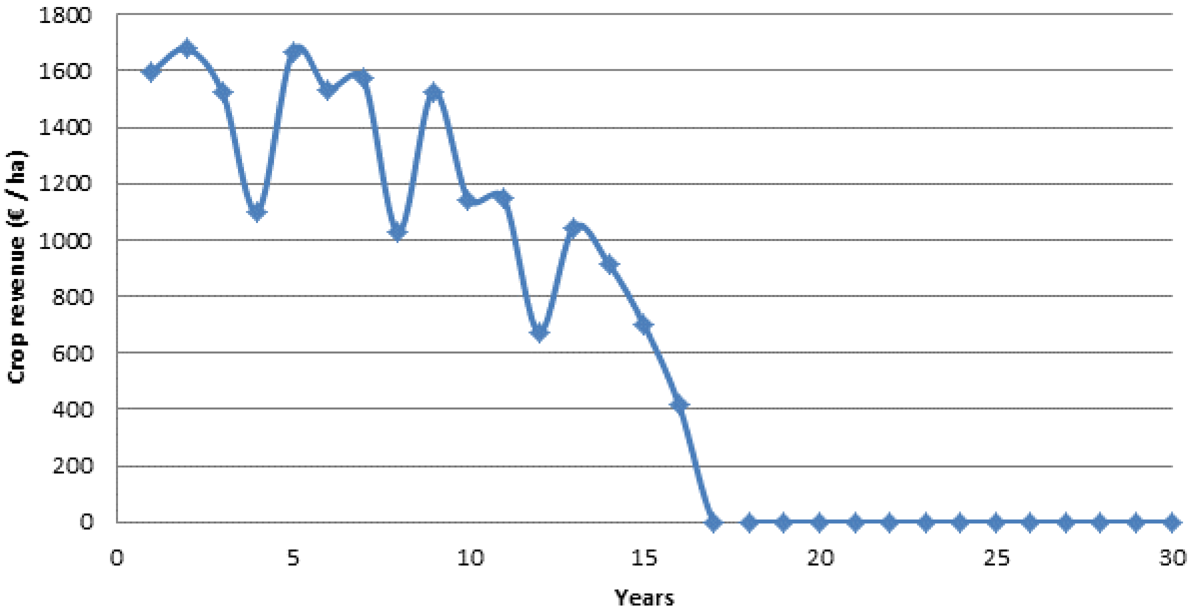


Figure 2. Modelled change in the crop revenue (crop yield and by-product) during the rotation of the silvoarable system

3.1.2 Case study from Schwarzbubenland, Switzerland

The arable system is a four-year crop rotation of oilseed rape, wheat, grass and wheat; the forestry system is a cherry tree plantation for timber production; and the agroforestry system is grassland with cherry trees used for fruit production. The EAV was estimated for a time horizon of 60 years at a 5% discount rate with and without grants. The financial assumptions for the Swiss study can be found in Tables A.2, A.7, A.9 and A.10 in the Appendix.

Table 2 shows the EAV with and without grants of the three systems. The agroforestry system seems to be the most profitable if grants are considered in the analysis. However, without grants the agroforestry system is the least profitable system. In this case study, grants were a main factor in the relative profitability of the systems. Thus, it could be argued that in this case, grant eligibility would be a key driver of adoption of agroforestry. It is also worth noting that all three systems without grants are not profitable.

Table 2. Equivalent Annual Value (EAV) of an arable, forestry and agroforestry system in Schwarzbubenland, Switzerland. Results shown for a time horizon of 60 years at a 5% discount rate.

	Arable[1]	Agroforestry[2]	Forestry[3]
EAV with grants (€ ha^{-1} year^{-1})	1,359	1,450	303
EAV without grants (€ ha^{-1} year^{-1})	-734	-1,354	-789

[1]: the arable system was a rotation of oilseed rape, wheat, grassland and wheat

[2]: the agroforestry system was grassland with cherry tree for fruit production planted at 80 trees per hectare.

[3]: the forestry system was cherry tree for timber production planted at a density of 816 trees per hectare.

The evolution of the cumulative net margin of the three systems is shown in Figure 3. During the first 15 years, the cumulative net margin of the agroforestry system lower than € 10,000 per hectare. However at the end of the rotation the agroforestry system is marginally more profitable than the arable and substantially more profitable than the forestry systems. The cumulative net margin of the forestry system is close to zero from year zero to year 59. It is only in year 60 that revenue from the harvested timber during clear felling that raises the cumulative net margin to approximately € 5,000 per hectare.

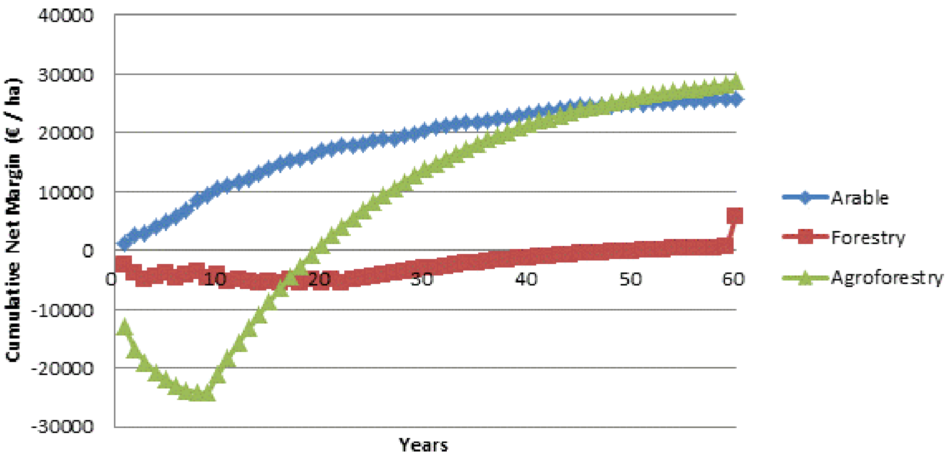


Figure 3. Modelled cumulative net margin with grants of the arable system (blue line: a rotation of oilseed rape, wheat, grassland and wheat), the agroforestry system (green line: grassland with cherry tree for fruit production), and the forestry system (red line: cherry tree for timber production)

3.1.3 Case study from Neu Sacro, Germany

The arable system is a two-year rotation of wheat and sugar beet; the forestry system is short rotation coppice (SRC) poplar trees for bioenergy production; and the agroforestry system is a rotation of wheat and sugar beet with SRC poplar. The EAV was estimated for a time horizon of 28 years at a 5% discount rate with and without grants. The financial assumptions for the German study can be found in Tables A.3, A.7, A.9 and A.10 in the Appendix.

The EAV of the three systems is shown in Table 3. The difference between the EAV of the arable and agroforestry systems is not very large. The arable system presents higher EAV due to the crop is more profitable than the SRC poplar. The grants are the same for the three systems. The EAV without grants of the forestry system is below zero which demonstrates that the system without grants is not profitable.

Table 3. Equivalent Annual Value (EAV) of an arable, forestry and agroforestry system in Neu Sacro. Results shown for a time horizon of 28 years at a 5% discount rate.

	Arable[1]	Agroforestry[2]	Forestry[3]
EAV with grants (€ ha^{-1} $year^{-1}$)	559	508	120
EAV without grants (€ ha^{-1} $year^{-1}$)	391	340	-48

[1]: the arable system was a rotation of wheat and sugar beet

[2]: the agroforestry system was a rotation of wheat and sugar beet with SRC poplar and planted at 968 trees per hectare.

[3]: the forestry system was SRC poplar planted at a density of 10,000 trees per hectare.

The evolution of the cumulative net margins is shown in Figure 4. As aforementioned, the difference between the arable and the agroforestry systems is relatively small. The curves are quite close to each other over the twenty-eight-year rotation. This is due to the main revenue of the agroforestry system which comes from the crop component. The revenue from the short rotation coppice is considerably lower than from the rotation of wheat and sugar beet.

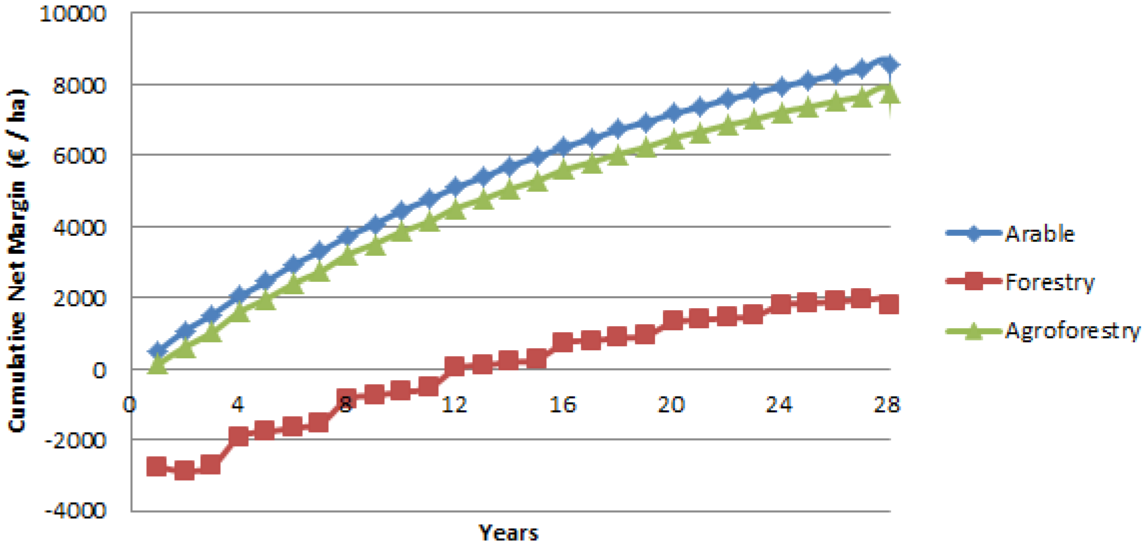


Figure 4. Modelled cumulative Net Margin with grants of the arable system (a rotation of wheat and sugar beet), the forestry system (SRC poplar) and the agroforestry system (a rotation of wheat and sugar beet with SRC poplar).

3.1.4 Case study from Cambridgeshire, United Kingdom

The arable system is organic wheat; the forestry system is organic apple trees; and the agroforestry system is organic wheat and apple trees. The EAV was estimated for a time horizon of 15 years at a 5% discount rate with and without grants. The financial assumptions for this case study can be found in Tables A.4, A.8, A.9 and A.10 in the Appendix.

The results show that the agroforestry system has the highest EAV with grants (Table 4). The arable system has the lowest EAV. However, without grants the arable system is the most profitable system. This shows the important influence of the grants when assessing the financial profitability of the systems. In this case, the farmer was able to obtain agri-environment payments for using the tree strip area as an area for pollinators.

Table 4. Equivalent Annual Value (EAV) of an arable, forestry and agroforestry system in Cambridgeshire, United Kingdom. Results shown for a time horizon of 15 years at a 5% discount rate

	Arable[1]	Agroforestry[2]	Forestry[3]
EAV with grants (€ ha^{-1} $year^{-1}$)	556	871	652
EAV without grants (€ ha^{-1} $year^{-1}$)	361	201	176

[1]: the arable system was organic wheat

[2]: the silvoarable system included organic wheat and apple trees planted at 85 trees per hectare.

[3]: the forestry system was organic apple trees planted at a density of 765 trees per hectare.

Figure 5 shows the evolution of the cumulative net margins over 15 years. The arable system that starts off by providing the highest net margin in year 1, in year 15, has the lowest cumulative net margin. However, this is due to the arable system in this case also having the lowest grants. It is also worth noting that the apple trees of the forestry and agroforestry systems are dwarf trees and they do not produce much shade, and this is predicted to limit the yield reduction of the crop component in the silvoarable system.

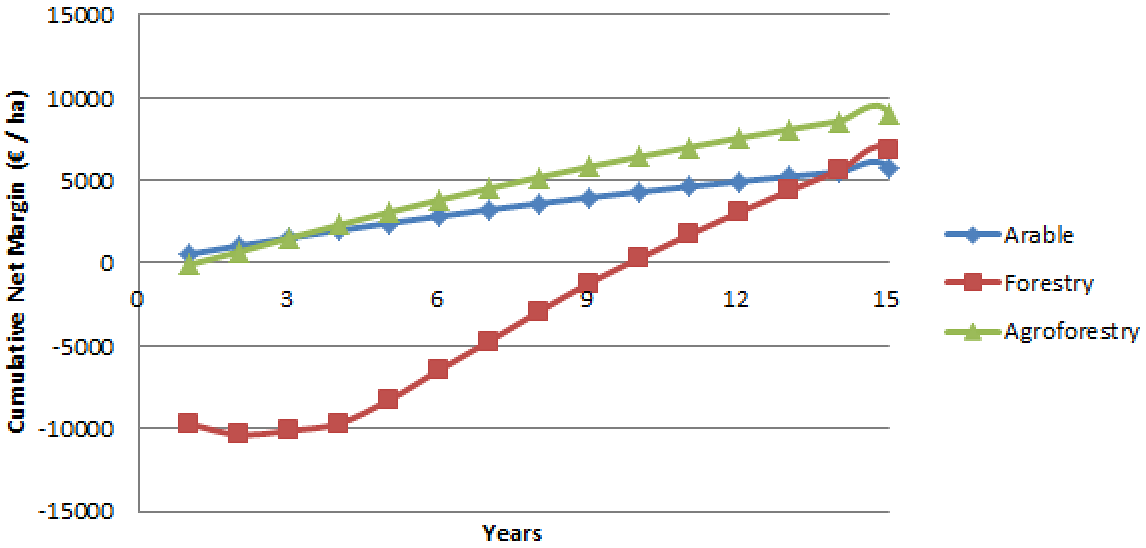


Figure 5. Modelled cumulative net margin with grants of the arable system (organic wheat), the forestry system (organic apple trees) and the agroforestry system (organic wheat and apple trees)

3.1.5 Case study from Extremadura, Spain

The arable system is a two-year crop rotation of oat and grassland; the forestry system is holm oak trees; and the agroforestry system is a dehesa with holm oak and grassland. The financial assumptions can be found in Tables A.5, A.8, A.9 and A.11 in the Appendix. The EAV was estimated for a time horizon of 60 years at a 5% discount rate with and without grants. It is worth noting that holm oak is usually planted for a rotation of more than 60 years (holm oaks can easily be over 200 years of age). However, since the MS Excel Yield-SAFE model version has a running limit of 60 years, the rotation here was also taken to be 60 years for this analysis.

The EAV of the three systems is notably lower than in the other case studies (Table 5). With grants, the arable system was the most profitable option, followed by the dehesa and the holm oak forest. However without grants, the dehesa was by far the most profitable option. This could explain why dehesa in Extremadura occupies around 1,237,000 hectares and represents (MAPA, 2008).

Table 5. Equivalent Annual Value (EAV) of an arable, forestry and agroforestry system in Extremadura, Spain. Results shown for a time horizon of 60 years at a 5% discount rate.

	Arable[1]	Agroforestry[2]	Forestry[3]
EAV with grants (€ ha^{-1} $year^{-1}$)	298	183	74
EAV without grants (€ ha^{-1} $year^{-1}$)	40	148	-120

[1]: the arable system was a rotation of oat and grassland

[2]: the agroforestry system was a dehesa with holm oak and grassland planted at 50 trees per hectare.

[3]: the forestry system was holm oak trees planted at a density of 600 trees per hectare.

Figure 6 shows the cumulative net margin over time with grants for the arable, dehesa and forestry systems. The cumulative net margin is highest for the arable system. However, without grants the cumulative net margin of the dehesa would finish higher than the cumulative net margin of the arable system. In the forestry system the main revenue was the planting grants obtained in the first years. The price of holm oak timber at the age of sixty years is almost negligible.

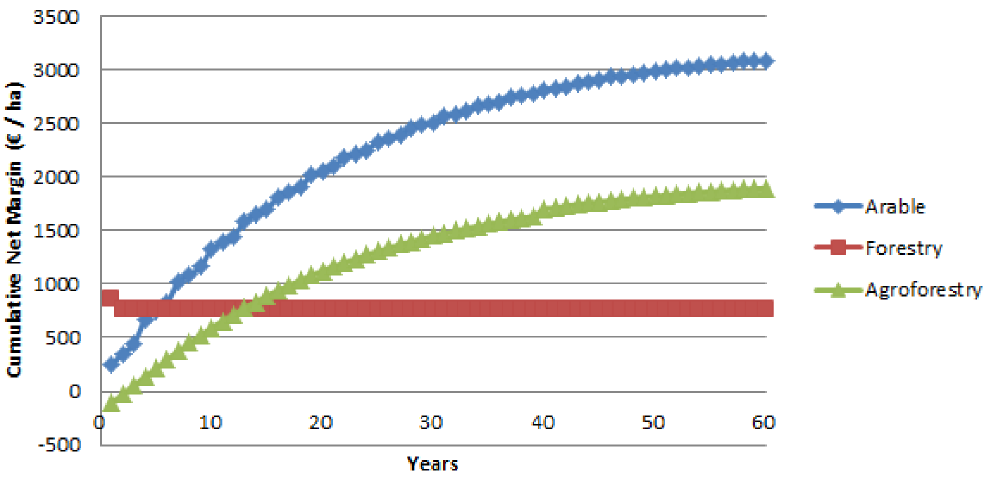


Figure 6. Modelled cumulative net margin with grants of the arable system (rotation of oat and grassland), the forestry system (holm oak trees) and the agroforestry system (dehesa with holm oak and grassland).

3.1.6 Case study from Restinclières, France

The arable system is a six-year rotation of wheat, wheat, sunflower, wheat, oilseed and sunflower; the forestry system is walnut trees for timber production; and the agroforestry system is a silvoarable system with a rotation of wheat and oilseed and walnut tree for timber production. The EAV was estimated for a time horizon of 50 years at a 5% discount rate with and without grants. The financial data for the system can be found in Tables A.6, A.8, A.9 and A.11 in the Appendix.

The EAV of each system is shown in Table 6. With and without grants, the silvoarable system has the highest EAV followed by the arable and forestry systems. The high per cubic metre value of timber of large walnut trees makes the agroforestry system very profitable. Because of the low tree density, walnut trees in the silvoarable system were assumed to reach greater diameters than in the forestry system, which leads to higher revenues. The forestry without grants results in a negative EAV.

Table 6. Equivalent Annual Value (EAV) of an arable, forestry and silvoarable system in Restinclières, France. Results shown for a time horizon of 50 years at a 5% discount rate.

	Arable[1]	Agroforestry[2]	Forestry[3]
EAV with grants (€ ha^{-1} $year^{-1}$)	506	670	178
EAV without grants (€ ha^{-1} $year^{-1}$)	140	246	-60

[1]: the arable system was a six years rotation of wheat, wheat, sunflower, wheat, oilseed and sunflower.

[2]: the silvoarable system was an alley cropping system with a rotation of wheat and oilseed and walnut tree for timber production planted at 170 trees per hectare.

[3]: the forestry system was walnut trees for timber production planted at 210 trees per hectare.

Figure 7 shows the change in the cumulative net margins of the three systems. Until year 50 the arable system is considerably higher than the other two systems. However, in year 50, the elevated price of the timber makes the cumulative net margin of the silvoarable system higher than the arable system.

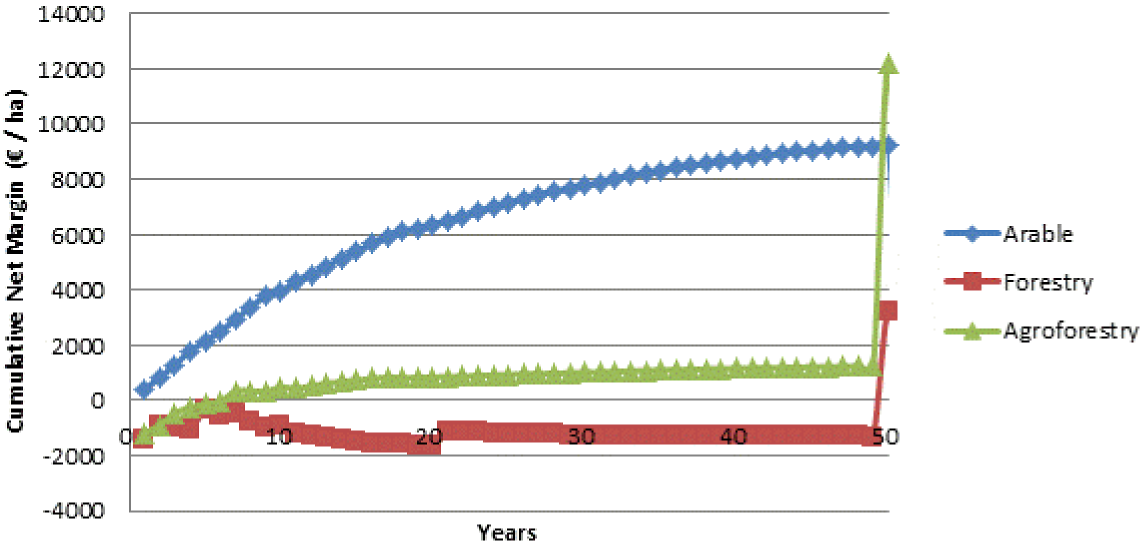


Figure 7. Modelled cumulative net margin with grants of the arable system (a rotation of wheat, wheat, sunflower, wheat, oilseed and sunflower), the agroforestry system (rotation of wheat and oilseed and walnut tree for timber production), and the forestry system (walnut trees for timber production)

Figure 8 shows the evolution of the crop revenue (crop yield and by-product) of the silvoarable system. As can be seen, the crop component after year 17 is not profitable and consequently the farmer stops planting the crop until the trees are clear felled at the end of the rotation.

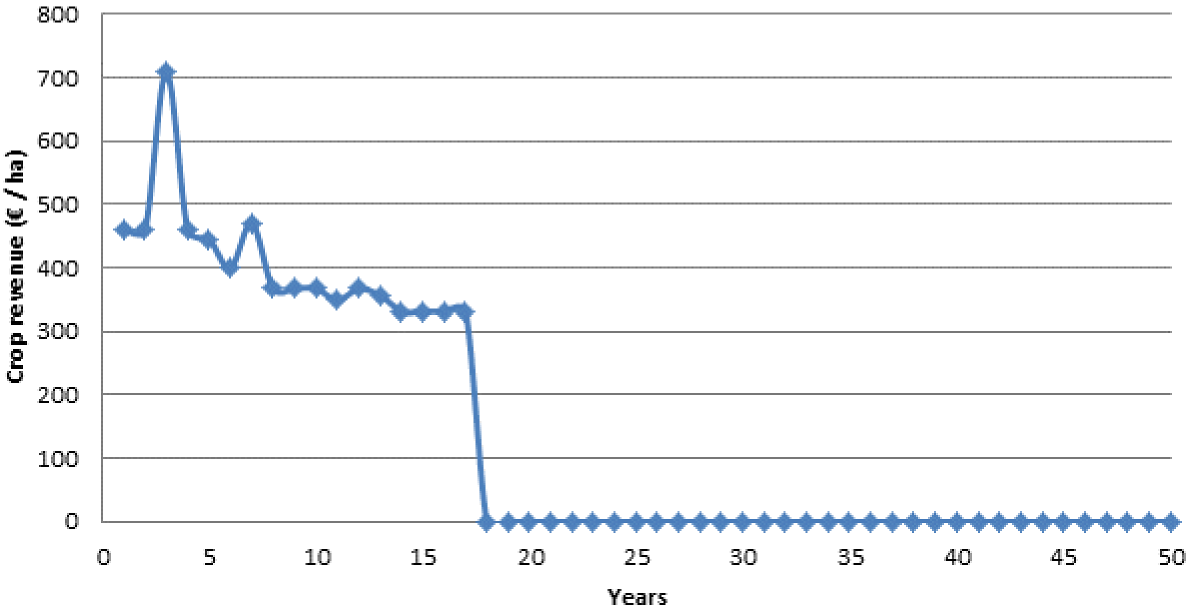


Figure 8. Modelled evolution along the rotation turn of the crop revenue (crop yield and by-product) of the silvoarable system.

3.1.7 Case study from Suffolk, United Kingdom

Table 7 shows the EAV of an arable, forestry and agroforestry system in Suffolk, UK. The arable system is a rotation of wheat, fallow and potatoes, the agroforestry system is a rotation of wheat, fallow and potatoes with SRC willow planted at 1,320 trees per hectare, and the forestry system is SRC willow planted at a density of 15,000 trees per hectare.

Table 7. Equivalent Annual Value (EAV) of an arable, forestry and agroforestry system in Suffolk, UK. Results shown for a time horizon of 21 years at a 5% discount rate.

	Arable[1]	Agroforestry[2]	Forestry[3]
EAV with grants (€ ha^{-1} $year^{-1}$)	719	785	357
EAV without grants (€ ha^{-1} $year^{-1}$)	299	365	14

[1]: the arable system was a rotation of wheat, fallow and potatoes.

[2]: the agroforestry system was a rotation of wheat, fallow and potatoes with SRC willow and planted at 1,320 trees per hectare.

[3]: the forestry system was SRC willow planted at a density of 15,000 trees per hectare.

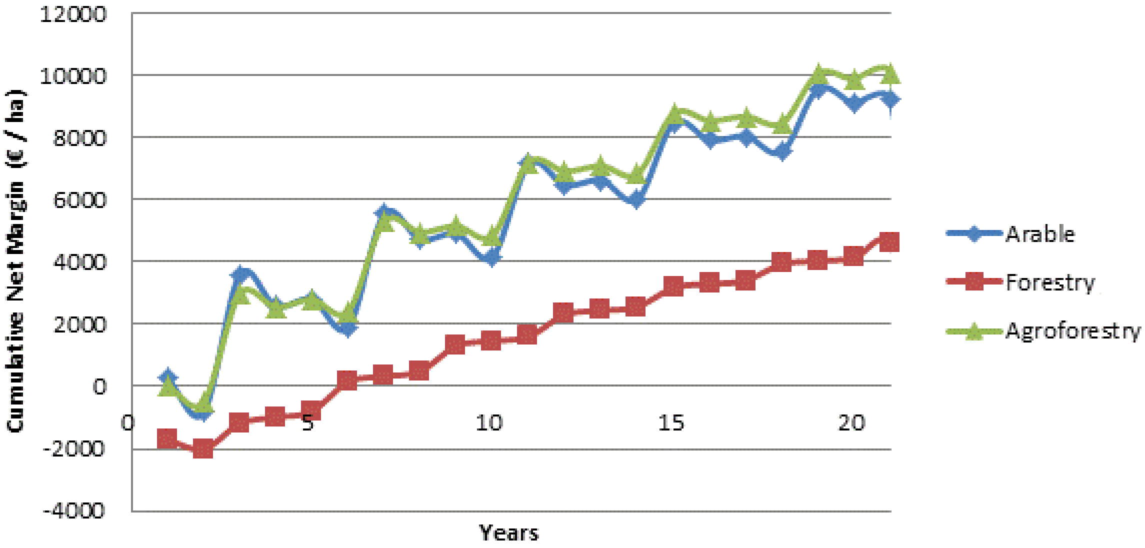


Figure 9. Modelled cumulative net margin with grants of the arable system (a rotation of wheat, fallow and potatoes), the forestry system (SRC willow) and the agroforestry system (a rotation of wheat, fallow and potatoes with SRC willow).

3.2 Estimating the optimal rotation age

For this deliverable, the Farm-SAFE model was written in the “R” software. The “R” version calculates the same financial costs and revenues as the Farm-SAFE model in Microsoft Excel at the plot level, but it does not allow calculations at the “unit-” or “farm-level”. The advantages of the “R”, compared to the Excel, version are that the model is more computationally powerful, it can be used to easily run a large number of simulations, and it can be easily linked to other models written in R. One of the improvements of the Farm-SAFE model in “R” software is the calculation of the economically optimal rotation age. Now the end-user can analyse the economic results of cutting the trees in different years. Figure 10 and Figure 11 show the NPV and EAV with and without grants for each year cutting the trees. Thus, the end-user can assess when it would be most profitable to cut the trees.

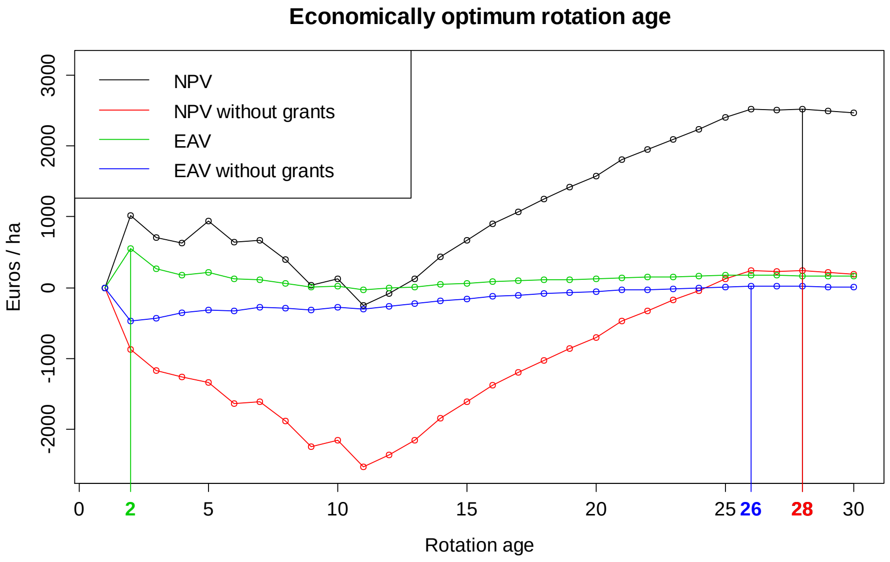


Figure 10. . Estimates of the net present value (NPV) and the equivalent annual value (EAV) of the forestry system (with and without grants) makes it possible to determine the most profitable rotation age of the forestry system (poplar tree) in Bedfordshire

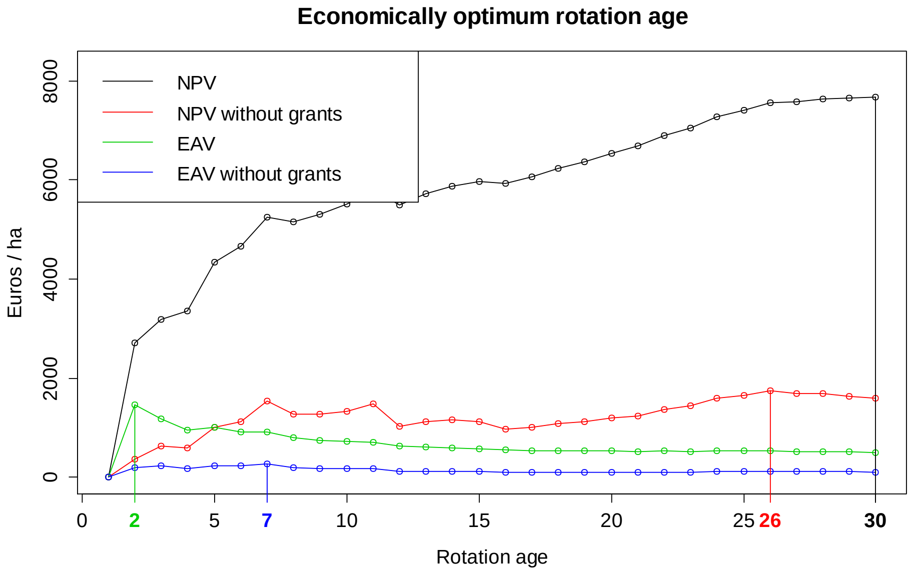


Figure 11. Estimates of the net present value (NPV) and the equivalent annual value (EAV) of the forestry system (with and without grants) makes it possible to determine the most profitable rotation age of the silvoarable system (poplar tree) in Bedfordshire

3.3 Ecosystems services

The Farm-SAFE financial and economic model of arable, forestry, and agroforestry systems has been adapted to include several environmental externalities such as greenhouse gas (GHG) emissions and sequestration, soil erosion losses, and nonpoint-source pollution from fertiliser use.

3.3.1 Greenhouse gas emissions

In order to incorporate negative externalities of GHG emissions, Life Cycle Assessment (LCA) data were used. Farm-SAFE was adapted to incorporate an analysis of GHG emissions and sequestration in aboveground biomass. In doing this, the resources and energy used in the production system (inputs) and the emissions released into the environment (outputs) were measured and included in the economic analysis.

In order to include the GHG emissions in the assessment a 'cradle-to-farm gate' perspective was used. Figure 12 shows the LCA system boundaries for an arable system. Operations assumed to take place outside the farm gate such as cooling, drying, crop storage, and further processing of the outputs were not taken into consideration. The establishment of the farm itself, the construction of the infrastructure and transportation were also excluded from the analysis.

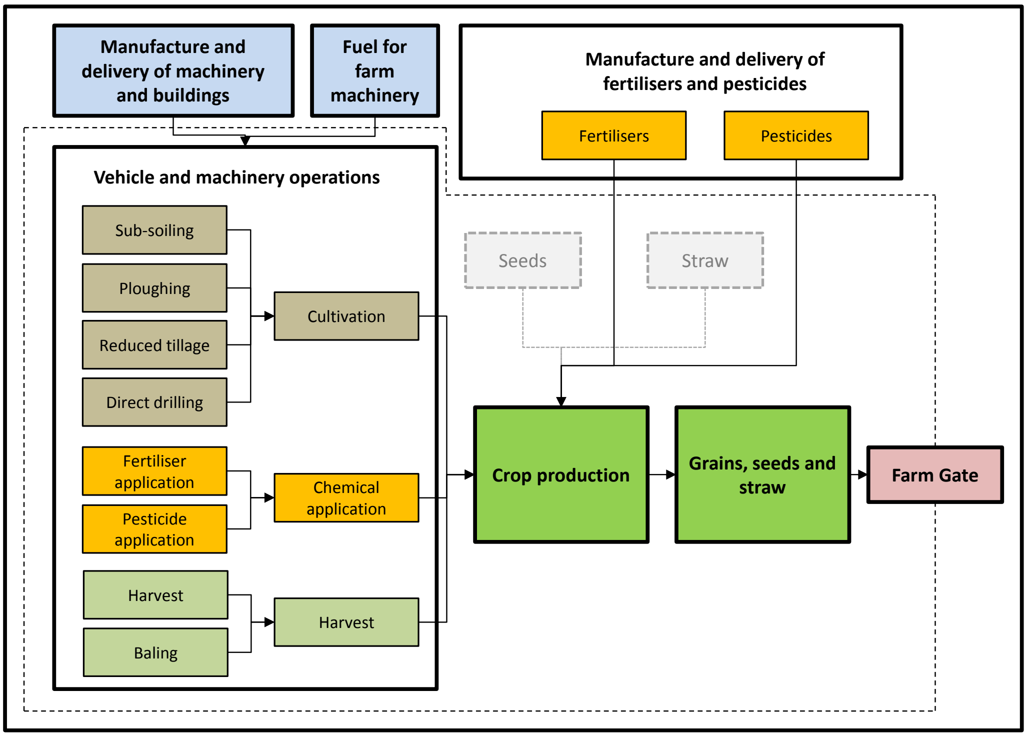
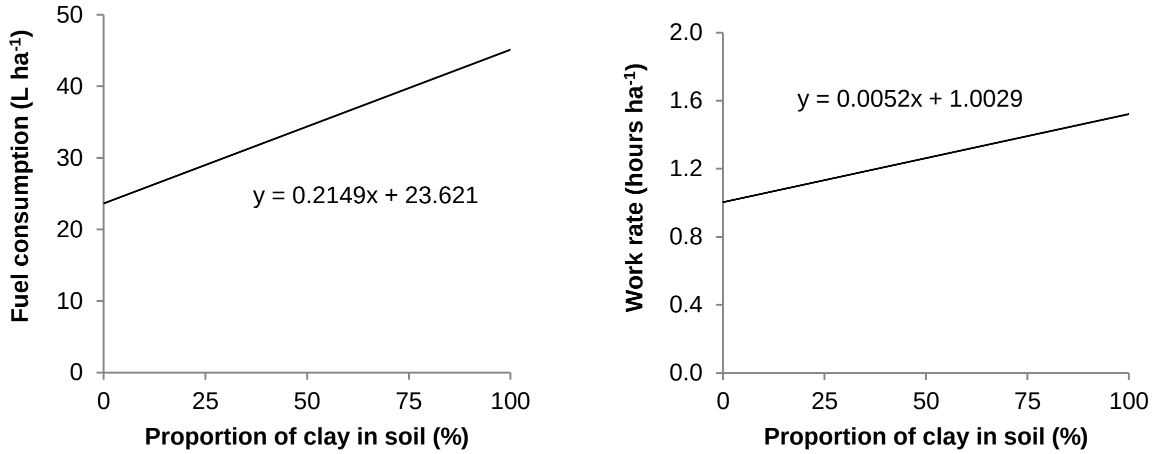


Figure 12. System diagram for the Life Cycle Assessment (LCA) of arable cropping, showing the system boundary and which inputs were included in the analysis of GHG emissions. Source: Kaske (2015).

One of the model innovations developed during AGFORWARD is the flexibility for the user to change the tractor size and soil type. For some field operations, these factors are associated with the fuel consumption and work rate which affects the GHG emissions. Equations of these relationships are calculated and used to interpolate values. Figure 13 shows an example of the equation used for the relationship between the clay content of the soil and a) fuel consumption and b) work rate. As shown, in both cases the higher the clay content percentage in the soil the higher fuel consumption and work rate.



a) Ploughing with four furrows

b) Subsoiling of tramlines (3 leg sub-soiler)

Figure 13. Assumed relationship of the effect on the proportional clay content of the soil on a) fuel consumption for ploughing, and b) the work rate of sub-soiling.

Figure 14 shows the changes in the annual carbon emissions in the arable, forestry and silvoarable systems in Bedfordshire, United Kingdom. The arable system shows the highest carbon emissions followed by the silvoarable and the forestry systems. During the first sixteen years the carbon emissions of the arable and silvoarable systems are very similar. However, after year sixteen there is no longer a crop component in the silvoarable system and consequently, the annual emissions are notably reduced.

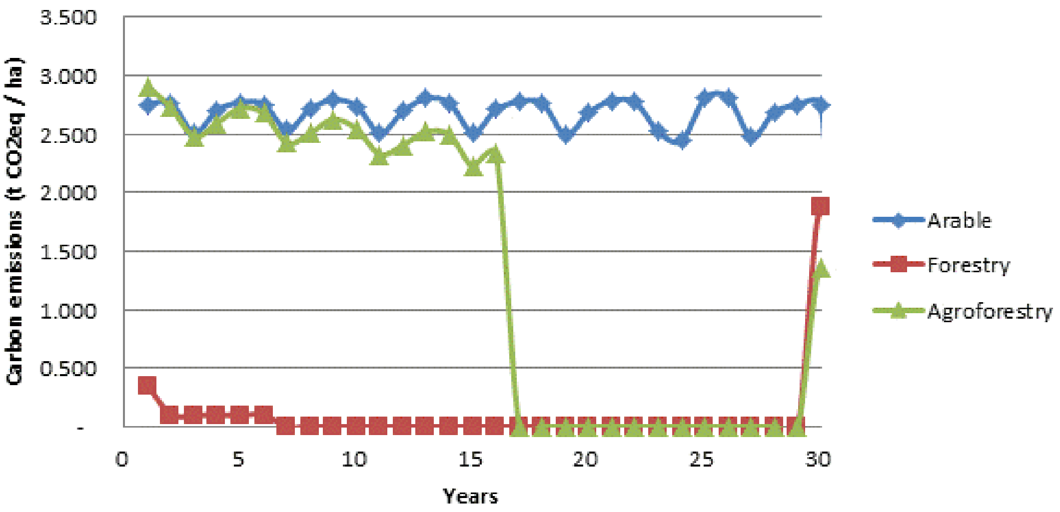


Figure 14. Modelled carbon emissions associated with machinery use from an arable, silvoarable and forestry system in Bedfordshire, United Kingdom

Figure 15 shows the change in the potential annual carbon sequestration of the arable, forestry and agroforestry systems in Bedfordshire, United Kingdom. The forestry system shows the highest carbon sequestration followed by the agroforestry and the arable systems. For the arable system, it was assumed that there is no annual carbon sequestration because all sequestered carbon is in effect released shortly after production and use of the products.

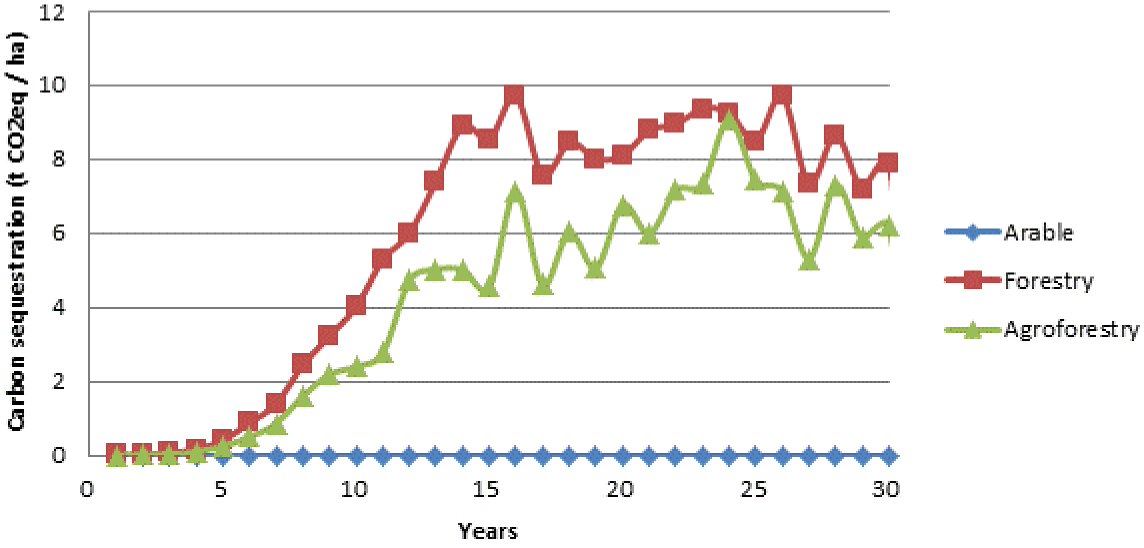


Figure 15. Modelled annual sequestered carbon for an arable, agroforestry, and forestry system in Bedfordshire, UK

Figure 16 shows the annual carbon emissions in the arable, forestry and agroforestry systems in Schwarzbubenland, Switzerland. The arable system shows the highest carbon emissions followed by the agroforestry and the forestry systems.

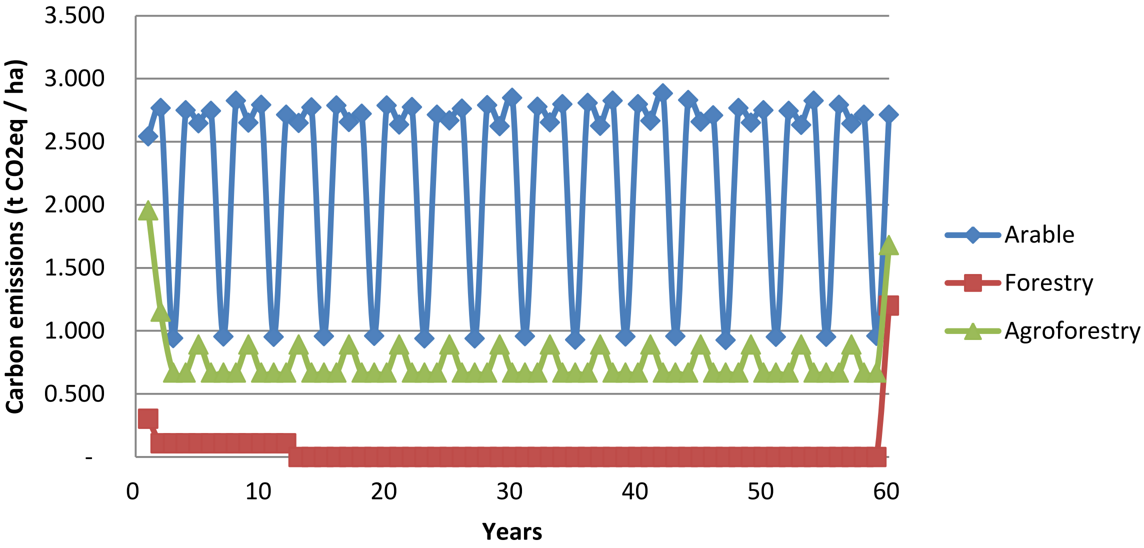


Figure 16. Modelled annual carbon emissions for the arable, agroforestry and forestry systems in Schwarzbubenland, Switzerland

Figure 17 shows the change in the potential annual carbon sequestration of the arable, forestry and agroforestry systems in Schwarzbubenland, Switzerland. The forestry system shows the highest carbon sequestration followed by the agroforestry and the arable systems. In the forestry system, a thinning in year twenty-eight produces a sharp decrease in the quantity of sequestered carbon.

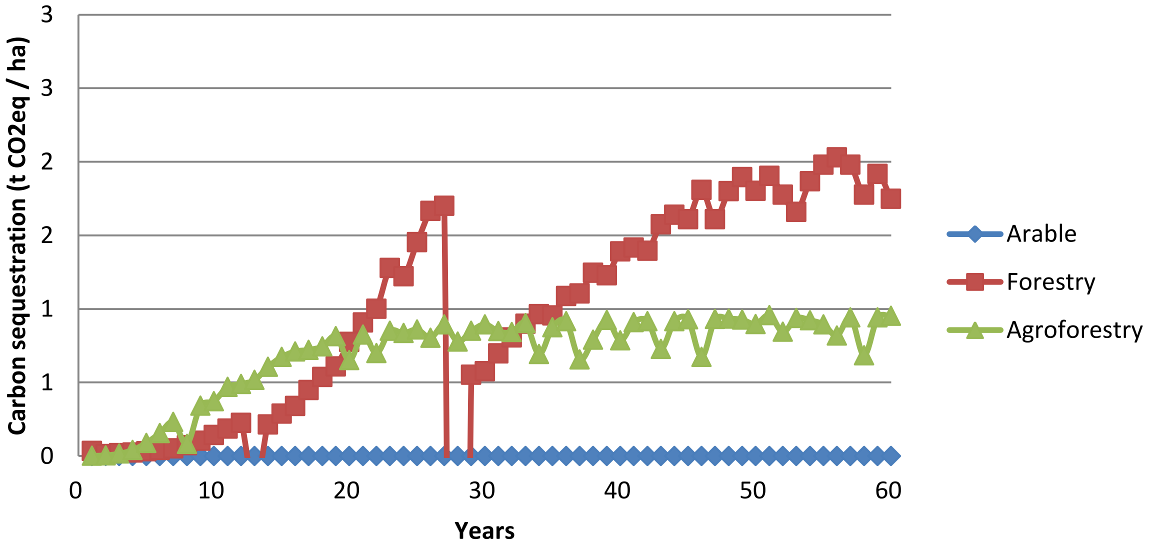


Figure 17. Modelled annual sequestered carbon for the arable, agroforestry and forestry system in Schwarzbubenland, Switzerland

3.3.2 Soil erosion losses

Soil erosion losses can be evaluated using of the Revised Universal Soil Loss Equation (RUSLE) (Equation 1), which is frequently used to calculate the annual soil loss in different production systems. The RUSLE equation is described as:

$$A = R * K * LS * C * P \qquad \text{(Equation 1)}$$

Where *A* is the estimated average soil loss in tons per acre per year; *R* is the rainfall-runoff erosivity factor; *K* is the soil erodibility factor; *L* is the slope length factor; *S* is the slope steepness factor; *C* is the cover-management factor; *P* is the support practice factor.

When comparing soil loss in arable, forestry and silvoarable systems in the same geographical area, the factors *R, K, LS and P* were considered to be the same and only changes in the *C*-factor were used to assess the differences among the systems. Figure 18 shows the K factor values used in Farm-SAFE to calculate soil erosion losses.

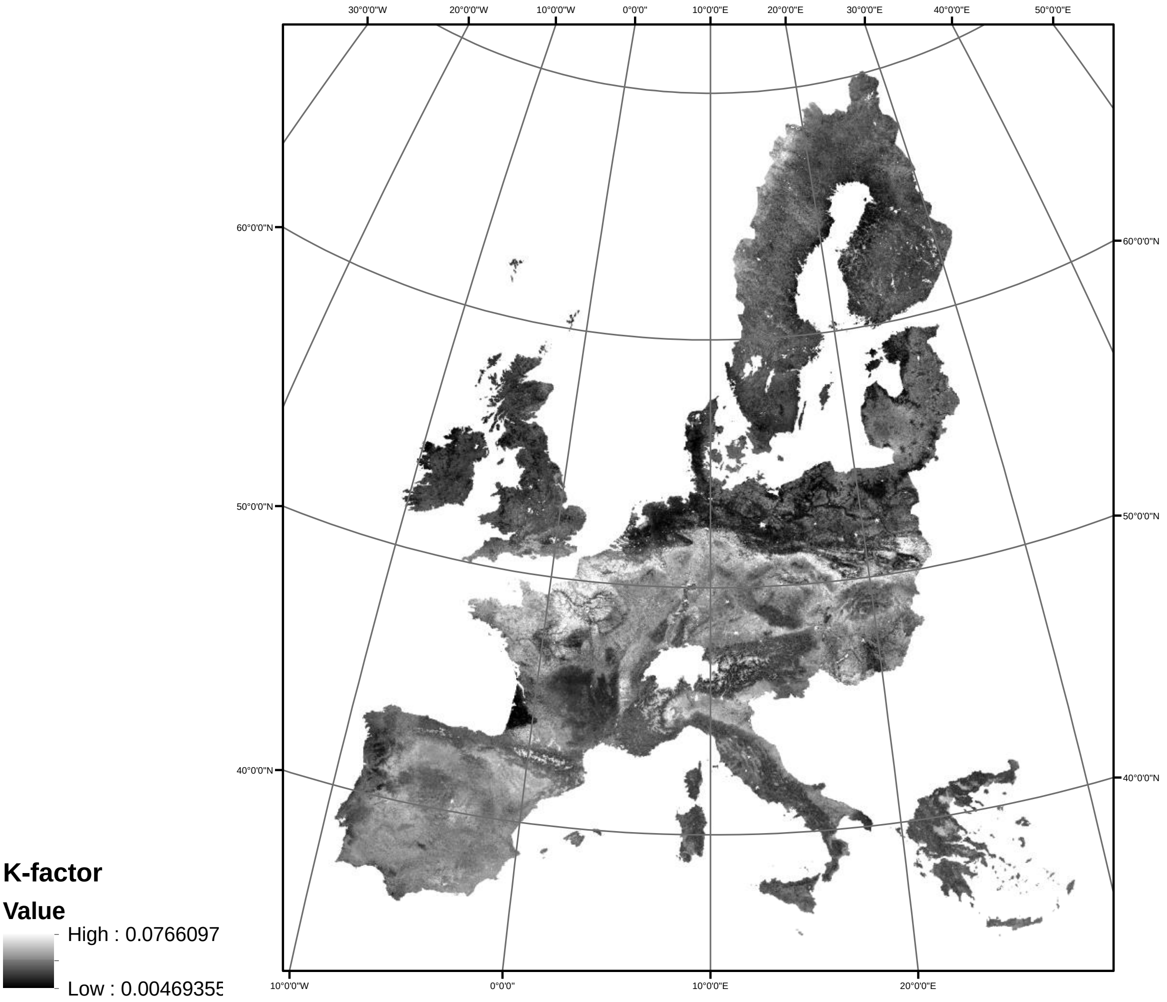


Figure 18. *K* factor values used in Farm-SAFE to calculate soil erosion losses by water through the RUSLE equation (Source: European Soil Data Centre, http://esdac.jrc.ec.europa.eu/).

Figure 19 and Figure 20 show the modelled soil erosion losses (annual and cumulative) for each land use in Bedfordshire.

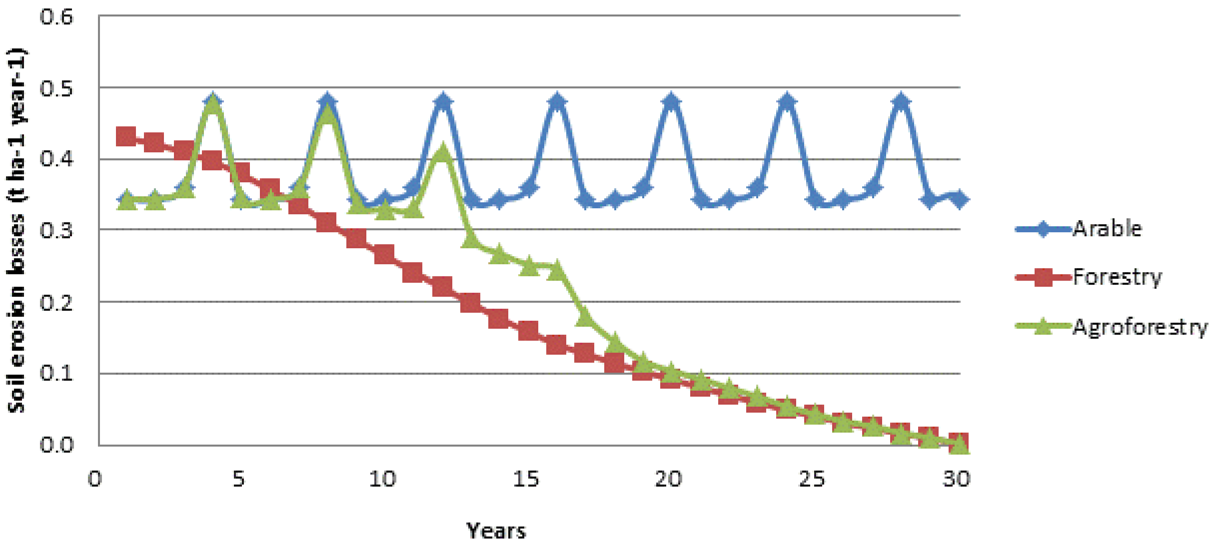


Figure 19. Modelled annual soil erosion losses by water for the arable, agroforestry and forestry system in Bedfordshire, UK

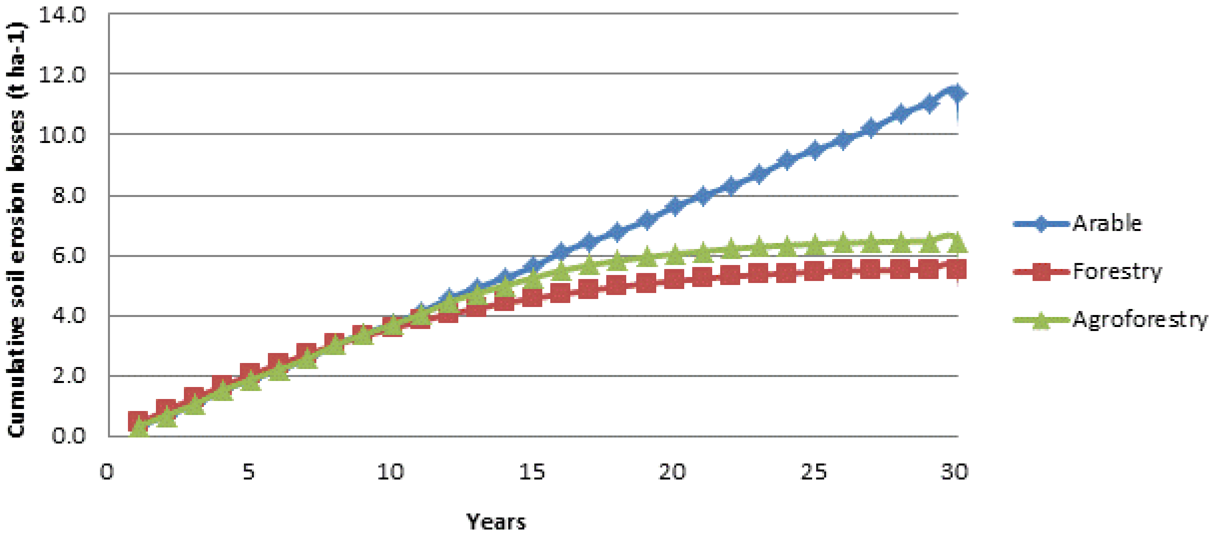


Figure 20. Modelled cumulative soil erosion losses by water for the arable, agroforestry and forestry system in Bedfordshire, UK

3.3.3 Nitrogen and phosphorus surplus

The emissions of Nitrogen (N) and Phosphorus (P) have been incorporated in the assessment of Farm-SAFE. The differences among arable, forestry and silvoarable systems are calculated as a function of the N and P fertilizer rates and the N and P leaching rates of each system. Figure 21 and Figure 22, show the nitrogen surplus in the case study for Bedfordshire (UK). Figure 23 and Figure 24, show the phosphorous surplus in the same case study.

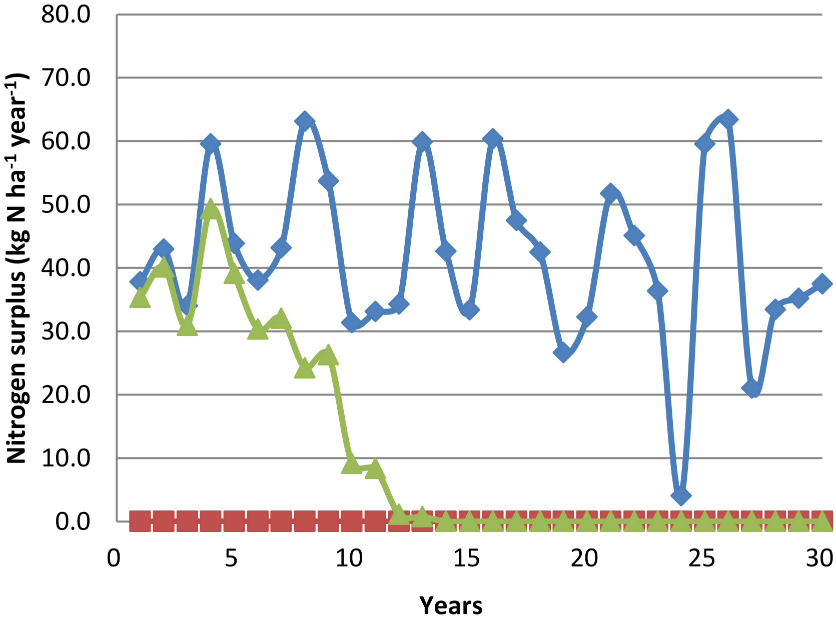


Figure 21. Modelled annual nitrogen surplus for the arable (blue line), agroforestry (green) and forestry (red) systems in Bedfordshire, UK

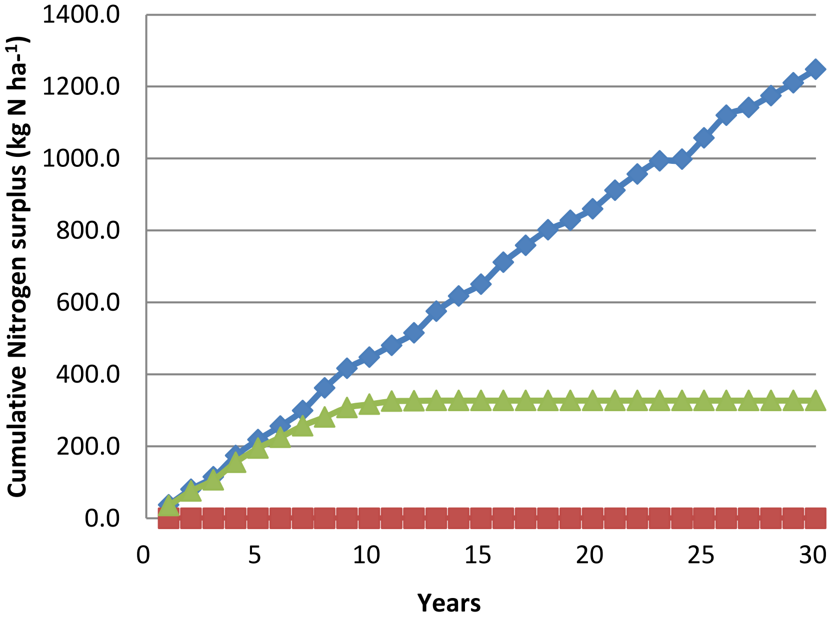


Figure 22. Modelled cumulative nitrogen surplus for the arable (blue line), agroforestry (green line) and forestry (red line) systems in Bedfordshire, UK

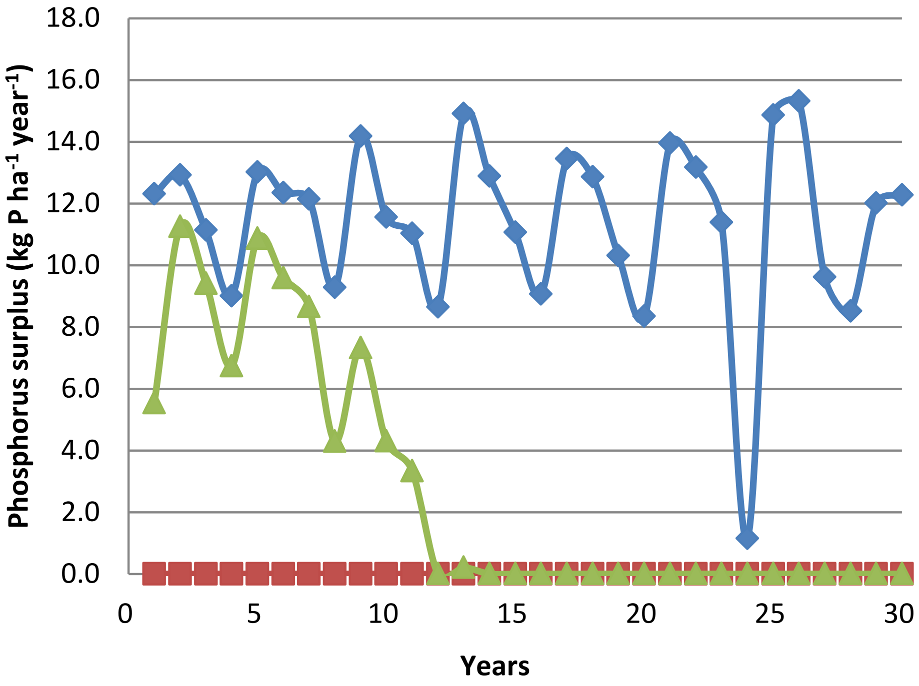


Figure 23. Modelled annual phosphorus surplus for the arable (blue line), agroforestry (green line) and forestry (red line) systems in Bedfordshire, UK

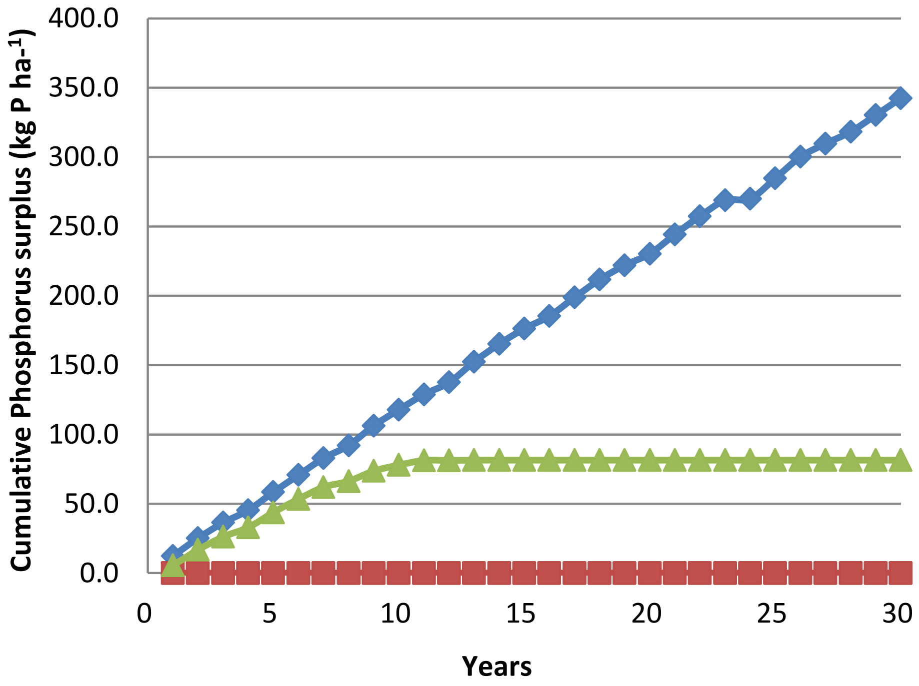


Figure 24. Modelled cumulative phosphorus surplus for the arable (blue line), agroforestry (green line) and forestry (red line) system in Bedfordshire, UK

3.4 Economic analysis

Whilst the financial analysis aimed to show a plot-level profitability indicator from a farmer perspective the economic analysis attempted to provide a plot-level profitability indicator from a societal perspective. The economic appraisal built upon the NPV_F (see Equation 1) and included benefits and costs from the five environmental externalities converted into monetary terms (EE_t) in each year *t*. The NPV for the economic appraisal (NPV_E) was denoted as:

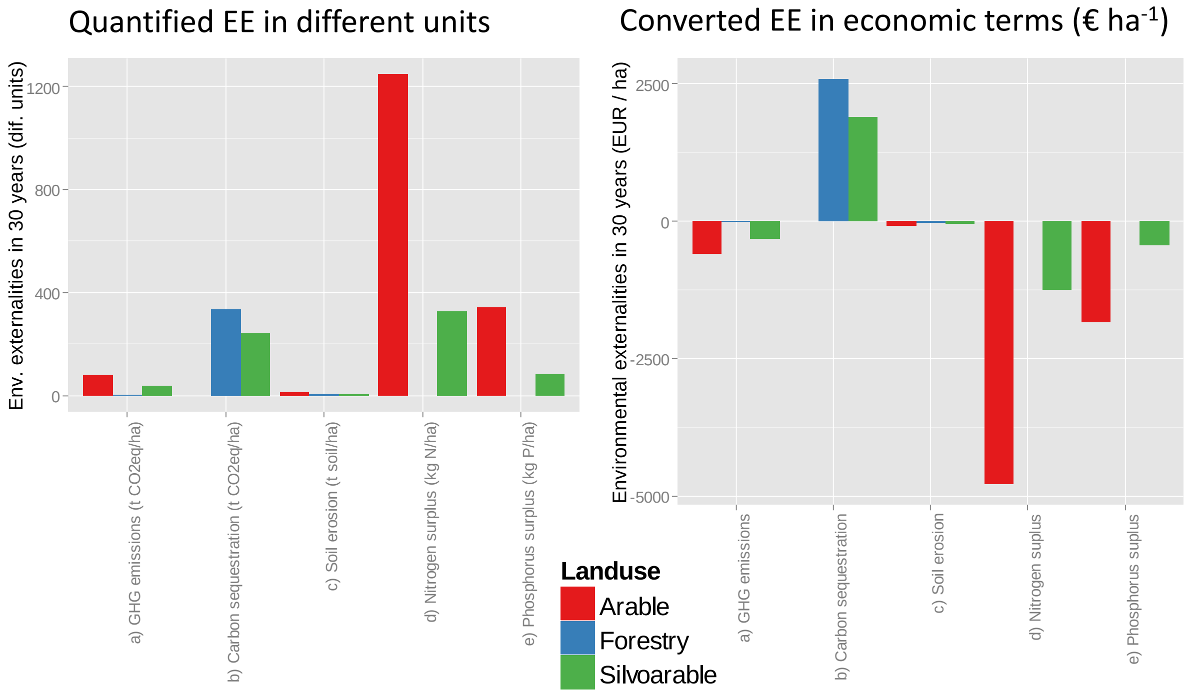
$$NPV_E = \sum_{t=0}^{n} \left(\left(\frac{(R_t - VC_t - FC_t)}{(1+i)^t} \right) + \left(\frac{EE_t}{(1+j)^t} \right) \right) \qquad Eq.(3)$$

where *j* is the assumed discount rate for environmental costs and benefits (which was assumed to be 4% as in the financial analysis). From the NPV_E, the economic EAV was calculated as in Equation 2.

The final goal of Farm-SAFE is to allow the end-user to assess the financial and economic profitability of the different land uses. In doing so, Farm-SAFE first quantifies the environmental externalities using the different indicator units and subsequently, converts them into monetary terms.

3.4.1 The case study of Bedfordshire, United Kingdom

Figure 25 shows the quantified environmental externalities and how much they represent in monetary terms at the end of the rotation age in Bedfordshire (30 years).


Quantified EE in different units

Converted EE in economic terms (€ ha^{-1})

Figure 25. The quantity and derived economic value of five environmental externalities (GHG emissions, carbon sequestration, soil erosion, nitrogen surplus, and phosphorus surplus) for the arable, silvoarable and forestry for the case study in Bedfordshire case study, UK

Figure 26 shows the results of the financial and economic analysis in Bedfordshire, UK. As shown, including grants, agroforestry is the most profitable land-use system in the economic analysis, i.e. when the environmental externalities are internalised.

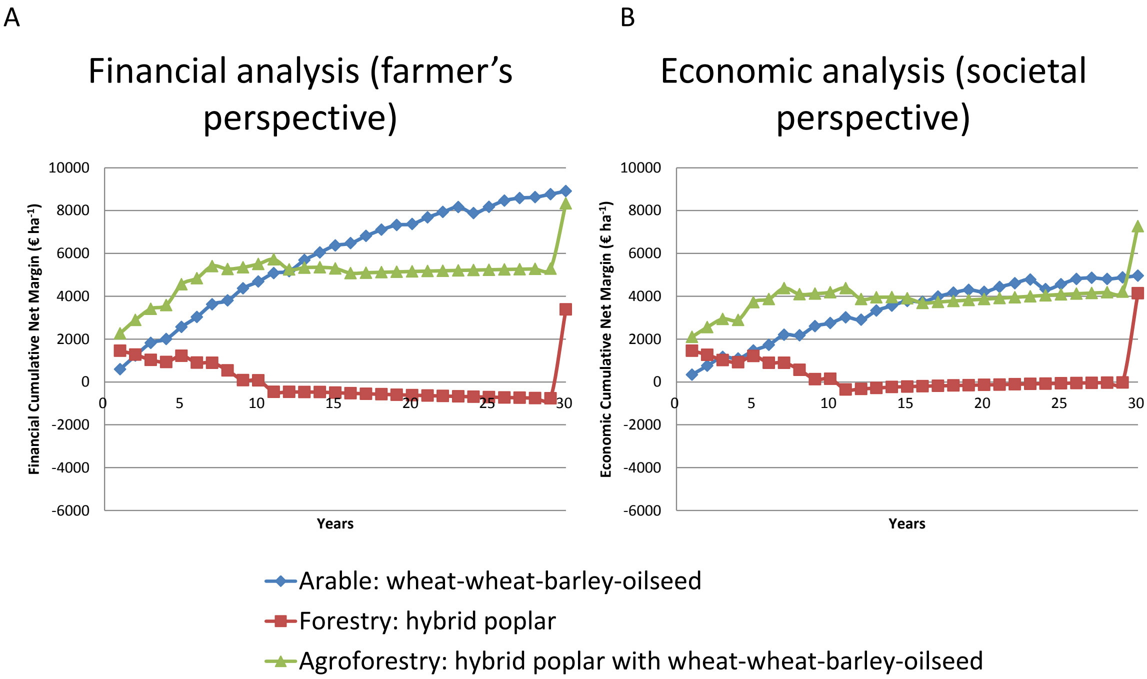


Figure 26. Comparison of A) the cumulative financial net margin of the arable, agroforestry and forestry system with B) an economic analysis of the same systems including five externalities for the case study in Bedfordshire, UK

Table 8 shows the EAV of the arable, forestry and silvoarable systems in Bedfordshire, including the GHG emissions in the economic assessment. The carbon price used for the calculations is 7.63 € per tonne of CO_2 which can be obtained by farmers in the UK (UK Forestry Commission, available at: www.forestry.goc.uk/carboncode). It is worth noting that this is a very conservative value, and other values, such as mitigation values and social cost values are higher. As shown, the forestry system has the lowest GHG emissions and the highest potential for sequestration. Internalising GHG emissions reduces the difference in the economic profitability between the arable system and the forestry and silvoarable system. Starting from the assumption of no grants, the inclusion of the societal cost of GHG emissions reduces the difference between the EAV of the arable and the silvoarable system from 242 € ha^{-1} to 159 € ha^{-1}. These results highlight how including environmental costs can change the relative societal advantage of different land uses.

Table 8. Equivalent Annual Value (EAV) of an arable, forestry and silvoarable system in Bedfordshire in the United Kingdom. Results shown for a time horizon of 30 years at a 5% discount rate.

	Arable[1]	Silvoarable[2]	Forestry[3]
EAV with grants (€ ha^{-1} year^{-1})	561	467	131
EAV without grants (€ ha^{-1} year^{-1})	314	72	-17
Emissions of CO_2eq in 30 years (t CO_2eq ha^{-1})	81	42	3
EAV of CO_2eq emissions (€ ha^{-1} year^{-1})	-40	-21	-1
Potential sequestration of CO_2eq in 30 years (t CO_2eq ha^{-1})	0	129	177
EAV of CO_2eq potential sequestration (€ ha^{-1} year^{-1})	0	64	88
EAV with grants and GHG externalities (€ ha^{-1} year^{-1})	521	510	218
EAV without grants and GHG externalities (€ ha^{-1} year^{-1})	274	115	70

[1]: the arable system was a rotation of wheat, wheat, barley and oilseed rape

[2]: the silvoarable system was the same rotation as the arable system with poplar hybrids planted at 113 trees per hectare.

[3]: the forestry system was hybrid poplars planted at a density of 156 trees per hectare.

3.4.2 The case study of Schwarzbubenland, Switzerland

An economic assessment was also used in the Schwarzbubenland case study. The approach was similar to the one used in the Bedfordshire case study but only GHG emissions and above-ground carbon sequestration were included in the assessment. Table 9 shows the EAV of the arable, forestry and silvoarable systems in Switzerland, including the GHG emissions in the economic assessment. As in the Bedfordshire case study the arable system has the highest carbon emissions and the lowest rate of carbon sequestration. With grants, the agroforestry system is the most profitable land use (with and without GHG emissions). However, without grants, it is the least profitable land use (with and without the GHG emissions).

Table 9. Equivalent Annual Value (EAV) of an arable, forestry and silvoarable system in Schwarzbubenland, Switzerland. Results shown for a time horizon of 60 years at a 5% discount rate.

	Arable[1]	Agroforestry[2]	Forestry[3]
EAV with grants (€ ha^{-1} year^{-1})	1,359	1,450	303
EAV without grants (€ ha^{-1} year^{-1})	-734	-1,354	-789
Emissions of CO_2eq in 60 years (t CO_2eq ha^{-1})	137	52	3
EAV of CO_2eq emissions (€ ha^{-1} year^{-1})	-55	-21	-1
Potential sequestration of CO_2eq in 60 years (t CO_2eq ha^{-1})	0	42	50
EAV of CO_2eq potential sequestration (€ ha^{-1} year^{-1})	0	17	20
EAV with grants and GHG externalities (€ ha^{-1} year^{-1})	1,303	1,515	322
EAV without grants and GHG externalities (€ ha^{-1} year^{-1})	-789	-1,359	-770

[1]: the arable system was a rotation of oilseed rape, wheat, grassland and wheat

[2]: the agroforestry system was grassland with cherry tree for fruit production planted at 80 trees per hectare.

[3]: the forestry system was cherry tree for timber production planted at a density of 816 trees per hectare.

4 Modelling and valuing the environmental impacts of arable, forestry and agroforestry systems: a case study

This is the pre-submission version of the following paper which has been published in Agroforestry Systems. The following citation should be used for this paper: García de Jalón, S., Graves, A., Palma, J.H.N., Williams, A., Upson, M.A., Burgess, P.J. (2017). Modelling and valuing the environmental impacts of arable, forestry and agroforestry systems: a case study. *Agroforestry Systems* DOI: 10.1007/s10457-017-0128-z

4.1.1 Abstract

The use of land for intensive arable production in Europe is associated with a range of externalities that typically imposes costs on third parties. The introduction of trees in arable systems can potentially be used to reduce these costs. This paper assesses the profitability and environmental externalities of a silvoarable agroforestry system, and compares this with the profitability and environmental externalities from an arable system with no trees and a forestry system. A silvoarable experimental plot of poplar trees planted in 1992 in Bedfordshire, Southern England, was used as a case study. The Yield-SAFE model was used to simulate the growth of the silvoarable, arable, and forestry land uses along with the associated environmental externalities, including carbon sequestration, greenhouse gas emissions, nitrogen and phosphorus surplus, and soil erosion losses by water. The Farm-SAFE model was then used to quantify the monetary value of these effects. The study assesses both the financial profitability from a farmer perspective and the economic benefit from a societal perspective. The arable system was the most financially profitable followed by the silvoarable and forestry systems. However, when the environmental externalities were included, silvoarable agroforestry provided the greatest societal benefit. This suggests that the appropriate integration of trees in arable land can provide greater well-being benefits to society overall, than either arable farming without trees, or the forestry systems alone.

4.2 Introduction

The objectives of the EU Common Agricultural Policy, in concise form, are to ensure i) viable food production, ii) balanced territorial development, and iii) sustainable management of natural resources, with a focus on greenhouse gas emissions, biodiversity, soil and water (Article 110 in EU, 2013). Silvoarable agroforestry (the integration of trees with arable production) is a land use practice that could help achieve these objectives.

Over recent decades, many agricultural systems in Europe have been simplified through intensification and mechanisation in order to reduce management cost and labour (Dupraz et al. 2005; Burgess and Morris, 2009, Quinkenstein et al. 2009), whilst at the same time becoming increasingly reliant on external inputs such as nutrients, pesticides, and machinery (Nemecek et al. 2011; Palma et al. 2007). These systems have enabled the competitive production of high quantities of safe and low cost food for consumers without the need to expand the area of agricultural land. However, many systems have resulted in significant negative environment costs that are borne by society as a whole, rather than individual producers or consumers. These costs, or externalities, include water pollution (leaching and runoff of nitrogen, phosphorus and pesticides), soil degradation (e.g. erosion, compaction and loss of soil organic matter and soil biodiversity), and greenhouse gas (GHG) emissions such as CO_2 and N_2O (Nemecek et al. 2011; Renzulli et al. 2015). These environmental externalities are rarely accounted for in the profitability analysis of agricultural systems, since usually they have no market value.

Various studies have found that environmental externalities from arable systems can be reduced by the appropriate integration of trees (Jose, 2009; Mosquera-Losada et al. 2011; Quinkenstein et al. 2009; Smith et al. 2012), such as the potential for mitigating climate change through carbon sequestration (Nair et al. 2009; Nair and Nair, 2014), reducing soil degradation (Graves et al. 2015), and reducing adverse impacts on water quality from agrochemical use (Nair, 2011a; Palma et al. 2007). However, whilst planting trees on arable land can help reduce environmental externalities, the uptake of silvoarable systems remains relatively slow. This could be a result of the cost of tree planting and management reducing immediate profitability and the uncertainty regarding the long-term financial benefits from harvesting mature trees. In the EU, efforts have been made to promote adoption of silvoarable systems through policy (Article 222) and projects such as SAFE (Dupraz et al. 2005) and AGFORWARD (Burgess et al. 2015) have been funded to provide scientific guidance on the costs and benefits of implementing silvoarable systems across Europe.

For long rotation systems such as agroforestry and forestry systems, modelling becomes essential. In recent years various biophysical models such as Hi-sAFe (Dupraz et al. 2004), SCUAF (Young et al. 1998), WaNuLCAS (van Noordwijk and Lusiana, 1999), and Yield-SAFE (Van der Werf et al. 2007) have been developed to simulate the growth and interaction of trees and crops in silvoarable systems. Some economic models have also been developed to assess the financial profitability of silvoarable systems. These for example, include ARBUSTRA (Liagre, 1997), Farm-SAFE (Graves et al. 2011), and POPMOD (Thomas, 1991).

The Farm-SAFE model (Graves et al. 2011) integrates the Yield-SAFE outputs with financial and economic analysis. Yield-SAFE simulates the biophysical growth of trees and crops, it can be adapted to quantify the impact of selected environmental externalities, and it can be used to determine the financial and economic impacts of different arable, silvoarable and forestry land uses. Within the AGFORWARD project, the Farm-SAFE model has been adapted to assess both the financial profitability from a farmer perspective and the economic profitability from a societal perspective. Using the adapted Farm-SAFE model, this paper evaluates and compares the biophysical development, financial profitability, and social impact of environmental externalities for arable, forestry, and silvoarable poplar systems to provide a more complete assessment of the societal benefits and costs of these land uses.

4.3 Methods and data

The methodological framework of this study is separated into five stages: i) simulation of the biophysical growth of trees and crops for the Bedfordshire case study, ii) assessment of financial performance, iii) quantification of the environmental externalities, iv) conversion of the environmental externalities into monetary terms, and v) assessment of full economic performance through inclusion of the environmental externalities in the analysis.

4.3.1 Bedfordshire case study

The case study is based on an experiment in Silsoe in Bedfordshire, England comprising 2.5 ha of silvoarable (poplar + cultivated crops) and forestry (poplar + fallow land) treatments surrounded by one hectare of conventionally cropped arable land (Burgess et al. 2005). The site is located in a relatively flat area at 59 m above mean sea level. The mean soil texture is 55% clay, 26% silt, and 19%

sand. Annual rainfall ranges from 410 mm to 867 mm and mean annual temperature from 9.1°C to 11.3°C.

Four poplar hybrid varieties, including Beaupré (*Populus trichocarpa* x *P. deltoides*), were planted in 1992. The four hybrids were planted at a spacing of 6.4 m in a North-South orientation along rows spaced 10 m apart. Tree height and diameter at breast height was measured at intervals until 2011, when the poplars were harvested, 19 years after planting (Upson, 2014). The arable crops from 1992 to 2003 included spring wheat, winter wheat, winter barley and spring beans; after 2003 the understorey reverted to grass (Burgess et al. 2005; Upson 2014).

4.3.2 Biophysical simulation

Because poor management led to crop failure in some years, a standardised crop rotation of wheat, wheat, barley and oilseed rape was assumed for the financial and economic analysis. The crop yields and the tree growth were simulated using the Yield-SAFE biophysical model (van der Werf et al. 2007) calibrated using the tree growth of the Beaupré hybrid and the relative crop yields obtained in the silvoarable system relative to the arable control (Burgess et al. 2005). Daily climatic data were retrieved from CliPick (Palma et al. 2015). In this way, crop and tree growth simulations were derived for three systems: i) a control arable system, ii) a silvoarable system (Beaupré at a density of 156 trees per hectare and arable cropping for 14 years), and iii) a forestry system (Beaupré at a density of 156 trees per hectare). The length of the tree rotation was specified as 30 years.

The modelled mean control crop yields of 8.78 t ha^{-1}, 6.70 t ha^{-1} and 3.49 t ha^{-1} for wheat, barley and oilseed rape respectively are similar to mean yields reported for the UK by Agro Business Consultants (2015) (Figure 27a). The simulated crop yields in the silvoarable system (Figure 27b) declined as the tree canopy expanded, with the final crop grown 14 years after tree planting (i.e. three years longer than achieved in practice).

4.3.3 Financial analysis

The financial performance of arable, forestry and silvoarable system was assessed using Farm-SAFE (Graves et al. 2011) on the basis of the annual net margins per hectare. The net margin was calculated as revenues from harvested products (grain, straw, timber and firewood) and grants minus variable costs (e.g. crop seed, tree planting, fertiliser, crop and tree protection, pruning, thinning, cutting and other costs) and assignable fixed costs (e.g. installation and repairs of infrastructure, fuel and energy, machinery, insurance and labour and rented machinery costs).

Because people generally prefer to receive goods and services in the present rather than the future, revenues and costs were discounted and converted into financial net present values (NPV_F: € ha^{-1}), denoted using Equation 1:

$$NPV_F = \sum_{t=0}^{n} \left(\frac{(R_t - VC_t - FC_t)}{(1+i)^t} \right) \qquad Eq.1$$

where R_t, VC_t, and FC_t were respectively revenue, variable costs, and assignable fixed costs in year t (€ ha^{-1}), i was the discount rate, and n was the time horizon for the analysis. A discount rate of 4% was chosen, as this is marginally above the discount rate of 3.5% used by the UK Government for cost-benefit analysis (HM Treasury, 2003). Although the costs were obtained in terms of pounds sterling, in this paper they are report in terms of Euros, assuming an exchange rate of £1 being equivalent to €1.389.

The financial profits of the different systems were compared in terms of a financial equivalent annual value (EAV_F: € ha^{-1} year^{-1}) using Equation 2:

$$EAV_F = NPV_F\left(\frac{(1+i)^n}{(1+i)^n - 1}\right)i \qquad Eq.2$$

Financial data (Table 10) related to the crops were obtained from a 2015 farm management handbook (Agro Business Consultants, 2015), e.g. a wheat grain price of £125 t^{-1}. The assumed crop prices were then assumed for the full rotation cycle. The grant receipts were based on the Basic Payment Scheme (BPS) for lowlands in England (235 € ha^{-1} yr^{-1}) also in 2016.

Table 10. Assumptions for crop revenues and costs in the analysis

Crop	Grain price (€ t^{-1})	Seed rate (kg ha^{-1})	Fertiliser rate			Variable costs[1] (€ ha^{-1})	Fixed costs (exc. labour)[2] (€ ha^{-1})	Labour costs (€ ha^{-1})
			(kg N ha^{-1})	(kg P_2O_5 ha^{-1})	(kg K_2O ha^{-1})			
Wheat	174	160	175	60	55	653	444	162
Barley	160	155	145	55	40	653	444	146
Oilseed	361	5	200	55	45	535	444	151

(1) Includes seed, fertiliser, spray and other costs.

(2) Includes costs relating to fuel and repairs, machinery, interest on working capital, installation, rent and other fixed costs.

Table 11 shows the summary of costs for the tree component in the silvoarable and forestry system. The silvicultural management was based on Savill (1991) and the associated costs and labour inputs were derived from the experimental plot in the Bedfordshire case study (Graves et al. 2007). The woodland planting grant was considered only for the forestry system which as a wide-spaced broadleaved system was eligible for support (1888.90 € ha^{-1} paid upon completion in the first year and 472.20 € ha^{-1} yr^{-1} during the first five years (Agro Business Consultants, 2015)).

4.3.4 Modelling the environmental externalities

4.3.4.1 Greenhouse gas (GHG) emissions

A Life Cycle Assessment (LCA) model (Williams et al. 2010) was integrated into the Farm-SAFE model to measure GHG emissions in carbon dioxide equivalents (CO_2e) associated with the manufacture and use of machinery and agrochemicals. The analysis focused only on CO_2 emissions and did not consider N_2O. In order to compare the arable, forestry and silvoarable systems, a functional unit of one hectare was used in the analysis. Equation 3 shows the emissions that were included in the LCA:

$$Emi.CO_2e_t = M_m + M_f + M_p + F \qquad Eq.3$$

where $Emi.CO_2e_t$ is the total emitted GHG (t CO_2e ha^{-1} yr^{-1}) in year t, and other factors include the emissions from the manufacture of field machinery (M_m), fertiliser (M_f) and pesticides (M_p) and the emissions associated with the fuel used for field operations (F). For the arable system and silvoarable intercrop area, machinery operations included cultivation, agrochemical application, harvesting and baling. In the forestry system and the tree component of the silvoarable system, the machinery operations included site preparation (ground preparation, full weeding, marking out, planting, tree protection and grass sward establishment), agrochemical application (localised weeding) and harvesting (pruning, epicormics removal, grass sward maintenance and clear felling). Nursery costs were not included. The GHG emissions of the silvoarable system were calculated by adding the GHG emissions of the intercrop area and the tree component area together. Emissions from manufacture of machinery was based on a per hectare utilisation rate calculated from the estimated life expectancy of the machinery (Nix, 2014). Emissions from manufacturing field diesel, fertiliser, and pesticides were calculated from the per hectare quantities used. Emissions to the atmosphere from field diesel, fertiliser, and pesticides were also traced back to the quantities used.

Table 11. Summary of costs associated with the tree component of the systems.

Tree operations	**Units**	**Forestry**	**Silvoarable**
Establishment cost (total)	**(€ ha^{-1})**	**753.28**	**753.28**
Costs of individual plants	(€ $tree^{-1}$)	1.33	1.33
Costs of individual tree protection	(€ $tree^{-1}$)	0.27	0.27
Costs of tree mulch	(€ $tree^{-1}$)	0.40	0.40
Costs of ground preparation	(€ ha^{-1})	48.93	48.93
Labour for planting trees	(min $tree^{-1}$)	3.00	3.00
Labour for tree protection	(min $tree^{-1}$)	0.40	0.40
Labour for tree mulch	(min $tree^{-1}$)	1.70	1.70
Weeding cost (total)	**(€ ha^{-1})**	**10.40**	**22.93**
Single herbicide for tree row	(min m^{-2})	0.08	0.00
Annual cost of herbicide	(€ $tree^{-1}$)	0.00	0.002
Removal of mulch	(min $tree^{-1}$)	1.50	0.00
Grass cut between tree rows	(€ ha^{-1})	0.00	20.00
Labour to establish grass sward	(min m^{-2})	0.50	0.00
Labour to maintain grass sward	(min m^{-2})	0.30	0.00
Labour to tree maintenance	(min $tree^{-1}$)	1.20	1.20
Pruning cost (total)	**(€ ha^{-1})**	**805.06**	**805.06**
Height first prune	(m)	1.00	1.00
Labour first prune	(min $tree^{-1}$)	1.00	1.00
Height last prune	(m)	8.00	8.00
Labour last prune	(min $tree^{-1}$)	15.00	15.00
Removal of prunings	(min $tree^{-1}$)	4.00	4.00
Harvest cost (total)	**(€ ha^{-1})**	**583.96**	**583.96**
Tree cutting	(min $tree^{-1}$)	7.00	7.00
Admin. and insurance and other cost (total)	**(€ ha^{-1})**	**90.00**	**90.00**
Administrative, insurance and tax cost	(€ ha^{-1})	9.00	9.00
Average annual maintenance costs	(€ ha^{-1} $year^{-1}$)	51.28	51.40

A 'cradle-to-field gate' approach was applied i.e. emissions associated with grain drying, crop storage and downstream processing were excluded. The construction of farm infrastructure was also excluded. The GHG emissions from land-use change were not included.

4.3.4.2 Aboveground-biomass carbon sequestration

Estimates for aboveground carbon sequestration were obtained from the simulated tree growth. It was assumed that the carbon sequestered by the arable crops and tree branches would be quickly lost to the atmosphere after harvest and hence they were excluded from the analysis. Equation 4 was used to convert the simulated biomass into carbon dioxide equivalent sequestration (t CO_2e ha^{-1} yr^{-1}):

$$Seq.CO_2e_t = 0.50\,\beta_{timber,t} * \frac{Atomic\ weight\ CO_2}{Atomic\ weight\ C} \qquad Eq.4$$

where *Seq.CO₂e*$_t$ was the sequestered carbon dioxide equivalent (t CO_2e ha^{-1} yr^{-1}) in time t, where 0.50 is assumed to be the carbon content of dry timber (Nair, 2011), β_{timber} is the annual increment in timber mass on a dry weight basis, and the final component converts carbon to a carbon dioxide equivalent.

4.3.4.3 Soil erosion losses by water

The Revised Universal Soil Loss Equation (RUSLE) was used in Farm-SAFE to calculate the annual soil loss by water (Equation 5):

$$A_t = R\ K\ L\ S\ C_t\ P \qquad Eq. 5$$

where A_t was the estimated average soil loss in year t (t ha^{-1} yr^{-1}), *R* is the rainfall-runoff erosivity factor, *K* is soil erodibility, *L* is slope length, *S* is slope steepness, *C* relates to cover-management, and *P* relates to support practice. The values for *R*, *K*, *L* and *S,* determined by climatic, soil and topographic characteristics, were obtained from the European Soil Data Centre (ESDAC) database for the geographical location of the Bedfordshire case study (see Panagos et al. 2014; Panagos et al. 2015a; Panagos et al. 2015c).

In order to compare soil erosion losses between arable, forestry, and silvoarable systems in the same geographical location, the dynamic change in the cover-management factor (C_t) in year t was calculated for each system drawing on Palma et al. (2007) using Equation 6:

$$C_t = Cov_{crop,t}\ C_{crop} + Cov_{tree,t}\ C_{tree} \qquad Eq. 6$$

where $Cov_{crop,t}$ is the proportion of cropped land in year *t*, C_{crop} is the cover-management factor of the crop component, $Cov_{tree,t}$ is the proportion of land under the tree component in year *t*, and C_{tree} the cover-management factor of the tree component. A common value for the *P* factor, among the three land uses, was obtained from the ESDAC database (Panagos et al. 2015d).

This approach represents a development of the approach reported by Palma et al. (2007). In Palma et al. (2007), the land cover proportion of the crop and tree component were static (time-invariant), whereas our approach considers the change in land cover proportions, and hence the decrease in C_t, as the tree grows.

4.3.4.4 Nitrogen surplus

The nitrogen surplus ($N_{sur;}$ kg N ha^{-1} yr^{-1}) in year *t* of the different land use systems was calculated using the approach of Palma et al. (2007) and Feldwisch et al. (1998) (Equation 7):

$$N_{sur} = N_{fert} + N_{adep} + N_{fix} + N_{min} - D - V - U - \mathrm{I} \qquad Eq. 7$$

where N_{fert} is the addition of N fertiliser, N_{adep} is the atmospheric deposition, N_{fix} is the biotic N fixation, N_{min} is the mineralisation, *D* is the denitrification, *V* is the volatilisation, *U* is the crop and tree uptake and *I* is the immobilisation.

Annual nitrogen fertilisation (N_{fert}) for winter wheat, barley and oilseed rape was assumed to be 175, 145 and 200 kg N ha^{-1} respectively (Agro Business Consultants, 2013). Atmospheric deposition (NA_{dep}) was estimated by summing values of deposition of oxidized and reduced nitrogen from EMEP (2003). Since there was no legume crop N fixation (N_{fix}) was assumed to be 1 kg N ha^{-1} yr^{-1} for non-symbiotic organisms (Wild, 1993). N mineralisation (N_{min}) and immobilisation (*I*) were assumed to reach a long-term steady state equilibrium where the amount of mineral nitrogen released by the soil would be equal to the amount annually returned to the soil in the form of organic matter (Vlek et al. 1981; Noy-Meir and Harpaz, 1977). Denitrification (*D)* was assumed to be 30 kg N ha^{-1} yr^{-1} (Palma et al.

2007). Since organic fertilisation was not considered, nitrogen volatilisation (*V)* was assumed to be derived from mineral *N* application. Following van Keulen et al. (2000) it was estimated as 5% of N_{fert}. Nitrogen uptake (*U)* was estimated as:

$$U = \begin{cases} \dfrac{Y_c}{\alpha} + \lambda * \beta_t & if \quad Y_c < \dfrac{Y_{max}}{2} \\ \dfrac{4 * Y_c - Y_{max}}{2 * \alpha} + \lambda * \beta_t & if \quad Y_c \geq \dfrac{Y_{max}}{2} \end{cases} \qquad Eq. 8$$

where Y_c is the harvested crop yield, Y_{max} is the maximum harvested crop yield (kg ha^{-1} yr^{-1}), β_t is the increment in above-ground tree biomass (kg ha^{-1} yr^{-1}), α is a unitless coefficient dependant on the biomass of the crop residue and the harvested product (Equation 9), and *λ* is a unitless coefficient used to derive tree nitrogen uptake from β_t (Equation 10). The α coefficient was given as:

$$\alpha = \frac{1}{NC_c + NC_r * \frac{Y_r}{Y_c}} \qquad Eq. 9$$

where NC_c and NC_r were the N content in the crop grain and residue, respectively (a content of 1% and 0.4% N in the grain and residue was assumed (van Keulen and Wolf, 1986)), and Y_r was the residue yield (kg ha^{-1} yr^{-1}). The *λ* coefficient was given as:

$$\lambda = C_{tab} + C_{tbg} * RSR \qquad Eq. 10$$

where C_{tab} and C_{tbg} were the N content in the aboveground and belowground tree biomass, respectively. A content of 0.66% and 0.41% concentration of N in the tree above ground and below ground biomass respectively was assumed (Gifford, 2000a,b). *RSR* was the root to shoot ratio of the tree (unit-less). A root to shoot ratio of 0.25 for broadleaved tree species was assumed (IPCC, 1996).

4.3.4.5 Phosphorus surplus

An approach similar to N was used to measure phosphorus surplus (P_{sur}; kg P_2O_5 ha^{-1} yr^{-1}). Equation 11 shows the P inputs and outputs considered in the analysis to estimate differences among land-use systems:

$$P_{\text{sur}} = \text{P}_{\text{fert}} + \text{PA}_{dep} - \text{U} \qquad Eq. 11$$

where P_{fert} is the addition of P fertiliser, PA_{dep} is the atmospheric deposition and *U* is the crop and tree P uptake (all units in kg P_2O_5 ha^{-1} yr^{-1}).

Phosphorus fertilisation (P_{fert}) for winter wheat, spring barley and oilseed rape was assumed to be 60, 55 and 55 kg P_2O_5 ha^{-1} yr^{-1}, respectively (Agro Business Consultants, 2013). Atmospheric deposition *(*PA_{dep}*)* was assumed to be 0.33 kg P_2O_5 ha^{-1} yr^{-1} (Tipping et al. 2014). The same equations as in N were used to calculate P uptake. A content of 0.25% and 0.2% P in the grain and residue respectively was assumed (Sandaña and Pinochet, 2014). A content of 0.04% concentration of P in the tree biomass was assumed (Ovington and Madgwick, 1958).

4.3.5 Valuation of the environmental externalities

The environmental externalities were converted into monetary terms using the benefit transfer method which estimates economic values for a study site by transferring available data from previous studies undertaken in another location (Johnston et al. 2015).

The valuation of CO_2e was based on the value of €7.8 (t $CO_2e)^{-1}$ currently received by farmers planting woodland in the UK (UK Forestry Commission, 2015). Although the Department for Energy and Climate Change (DECC, 2009, 2012) predicts that these values will increase over time up to €233 (t $CO_2e)^{-1}$ at some stage between 2015 and 2045), the current value is used in this study.

Using Graves et al. (2015) the valuation of soil erosion losses was based on the annual off-site cost of dredging of water courses. Jacobs (2008) estimated an annual off-site cost of dredging water courses in England and Wales of €12.9 million with an agricultural apportionment of 95%, giving a total cost (adjusted to 2009 prices) of €12.2 million. As Anthony et al. (2009) reported a sediment load of 1.9 million t yr^{-1} a unit cost of removal of around €6.41 t^{-1} sediment was estimated.

The value for the N surplus was based on the costs of nitrate removal in freshwater. For the purposes of this study we assumed that, over a long period, the rate of nitrate leaching would be similar to the nitrogen surplus, and that water draining from the site is used for drinking water. Oxera (2006) estimated the upper and lower bound of the cost of nitrate removal to two difference water work sizes, expressed as population equivalents (PE). This study selected the more conservative estimate (PE > 100,000) which was given as € 1.9 kg NO_3^{1-} removed from freshwater. The same cost-based approach used for N surplus was used to value P surplus. Again it was assumed that, over a long period, the rate of phosphorus loss would be equivalent to the phosphorus surplus. Using the costs associated with chemical dosing under new phosphate treatment standards (Ofwat, 2005), the standard estimate for large works (PE > 80,000) is equivalent to € 5.2 kg P (Ofwat, 2005).

4.3.6 Economic analysis

Whilst the financial analysis aimed to show a plot-level profitability indicator from a farmer perspective the economic analysis attempted to provide a plot-level profitability indicator from a societal perspective. The economic appraisal built upon the NPV_F (see Equation 1) and included benefits and costs from the five environmental externalities converted into monetary terms (EE_t) in each year *t*. The NPV for the economic appraisal (NPV_E) was denoted as:

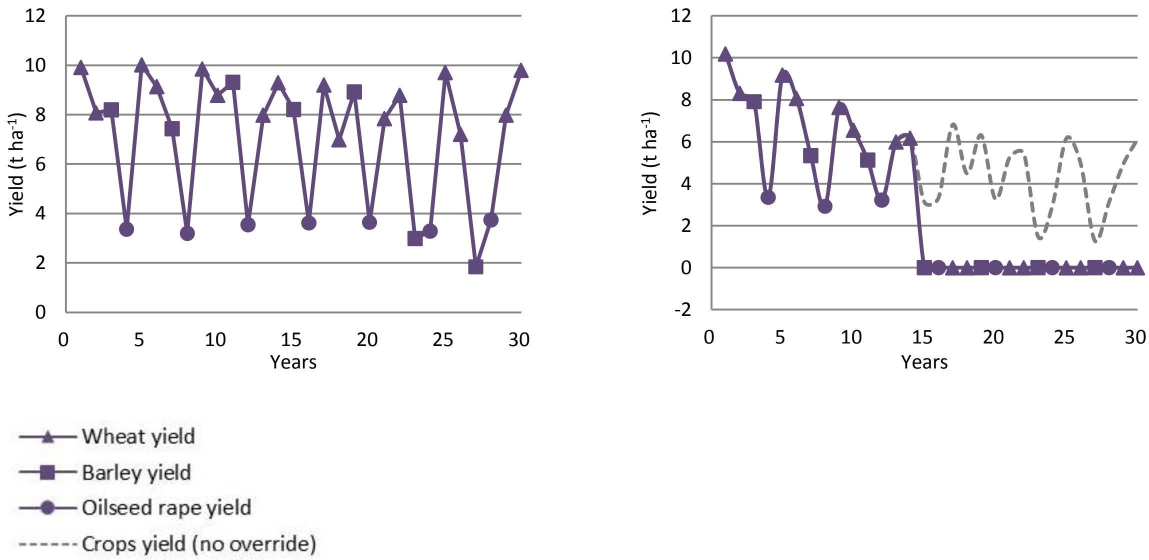
$$NPV_E = \sum_{t=0}^{n}\left(\left(\frac{(R_t - VC_t - FC_t)}{(1+i)^t}\right) + \left(\frac{EE_t}{(1+j)^t}\right)\right) \qquad Eq.(12)$$

where *j* is the assumed discount rate for environmental costs and benefits (which was assumed to be 4% as in the financial analysis). From the NPV_E, the economic EAV was calculated as in Equation 2.

4.4 Results

4.4.1 Biophysical simulation

As partly described in the methodology, the average yields in the control arable system matched the mean values for wheat, barley and oilseed rape in south-eastern England (Figure 27a) (Agro Business Consultants, 2015). In the silvoarable system, crop yields (per cropped area) were firstly modelled assuming intercropping for all of the 30 years of the tree rotation (Figure 27b). However, from Year 15 onwards, the crop component of the silvorable system was no longer profitable due to tree competition for water and sunlight. During the first 14 years, the mean wheat, barley and oilseed rape were 7.76, 6.13, and 3.16 t ha^{-1} respectively. These represent mean yield reductions of 15, 26 and 6% respectively.

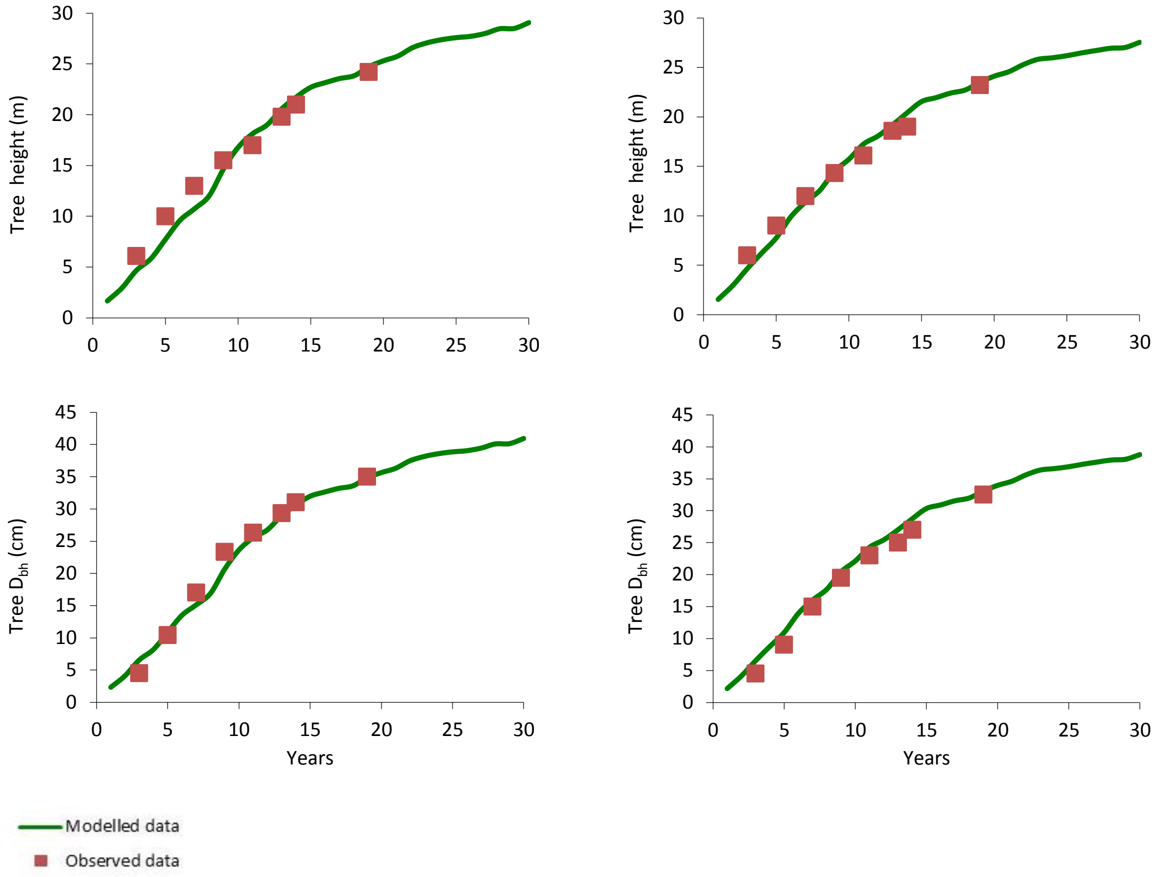


a: Arable system

b. Silvoarable system

Figure 27. Modelled crop yields (per cropped area) in a) the control arable and b) the silvoarable system

The observed and modelled tree diameter and height, showed that overall tree diameter and height in the forestry system (Figure 28a) was higher than in the silvoarable system (Figure 28b). Over the 30 years, it is estimated that 1.2 ha of separate forestry and arable systems would be needed to produce the crop and timber yields obtained in the silvoarable system, i.e. 0.35 ha of arable crops and 0.85 ha of the forestry system i.e. the land equivalent ratio was 1.2.


a: Forestry system

b: Silvoarable system

Figure 28. Observed and modelled height and diameter at breast height (D_{bh}) of the poplar trees in a) the forestry and b) the silvoarable system.

4.4.2 Financial analysis

The biophysical simulation was used to provide the yield data for assessment of the financial profitability of the arable, forestry, and silvorable system, with grants (Figure 29a) and without grants (Figure 29b). Figure 29 shows the discounted financial cumulative net margin of the three land-uses. The cumulative net margin in Year 30 indicates the NPV_F. In both analyses with and without grants, the arable system was the most profitable land-use (NPV_F = 9,674 € ha^{-1}) followed by the silvoarable system (NPV_F = 5,940 € ha^{-1}) and the forestry system (NPV_F = 2,939 € ha^{-1}). As forestry grants were lower than in the other land uses, the difference in profitability was reduced relative to arable and silvoarable land uses, when excluding grants in the analysis. In the silvoarable system, the cumulative net margin did not substantially increase between Year 12 and 29. This was because as the trees developed, the yield and profitability of the crop component decreased, and after Year 14, cultivating the crop component was no longer profitable.

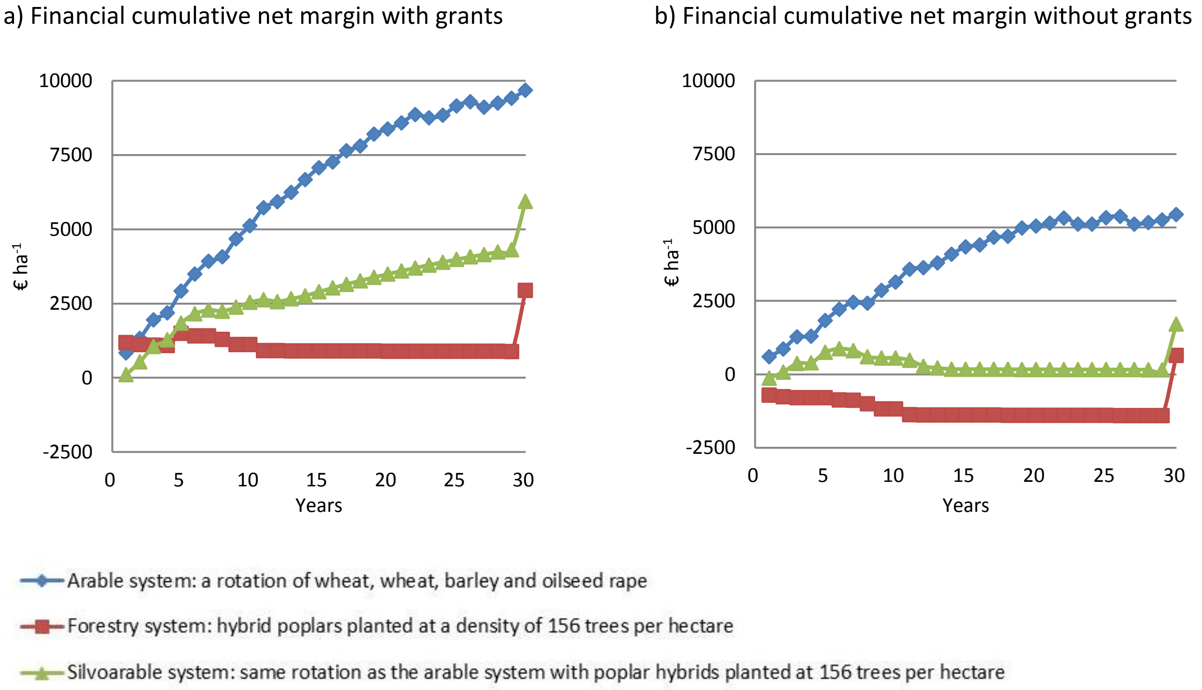


Figure 29. Financial cumulative net margin (assuming a discount rate of 4%) in the arable, forestry and silvoarable system a) with grants and b) without grants

4.4.3 Environmental externalities

The environmental externalities assessed in this study were modelled for all three systems. The overall GHG emissions for the arable system were higher than for both the forestry and silvoarable land uses (Figure 30a). Although the GHG emission from the crop and tree component in the silvoarable system was greater than for the arable system in year 1, the emissions from the silvoarable system were subsequently lower whilst there was a crop (until year 14) and emissions were almost negligible due to the cessation of cropping from year 15.

Carbon sequestered in aboveground timber (Figure 30b) in the forestry system was greater than in the silvoarable system, as the trees initially benefited from reduced competition for water. Because carbon stored in the crop was assumed to be rapidly returned to atmosphere after harvest, the aboveground biomass in the arable system was negligible.

Soil erosion loss by water (Figure 30c) was low in all three land-uses. This was mainly because the area was relatively flat and extreme rainfall events are relatively rare. However, the capacity of tree canopy growth to reduce the annual rate of soil erosion is evident in both the forestry and silvoarable systems.

The N and P surpluses (Figure 30d and Figure 30e respectively) in the arable system were notably greater than in the forestry and silvoarable systems. In the silvoarable system, N and P surplus was greatest in the initial years of the rotation, but as the trees developed, their uptake of N and P increased and N and P surpluses were reduced.

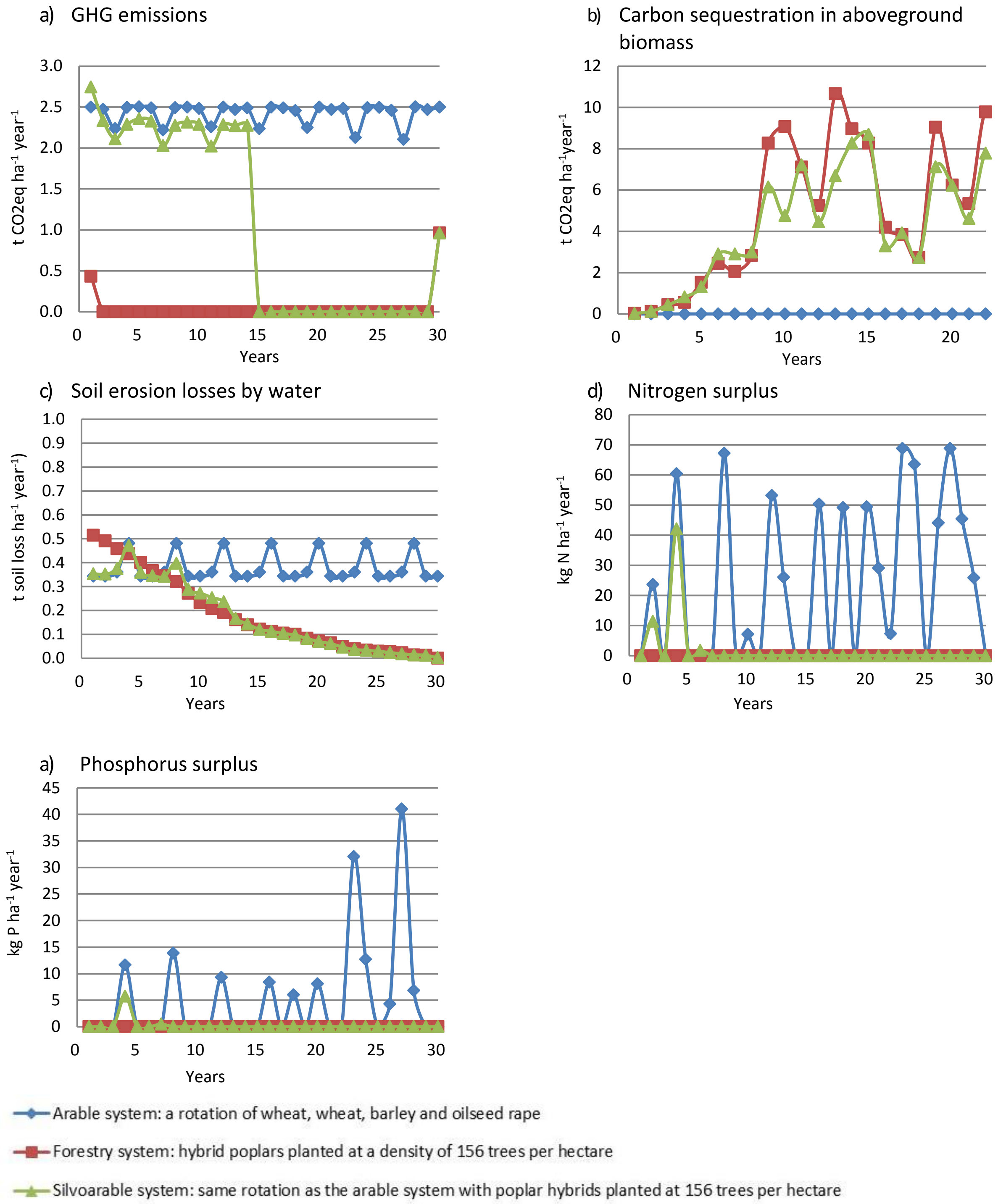


Figure 30. Modelled environmental externalities of the arable, forestry, and silvoarable system over a time horizon of 30 years in terms of a) GHG emissions, b) aboveground carbon sequestration, c) soil erosion, d) nitrogen surplus, and e) phosphorus surplus.

4.4.4 Economic analysis

The final stage of our analysis was to assess the profitability of the three land use systems by including the economic value of the environmental externalities. Table 12 shows the annual economic value of the environmental externalities as well as the financial and economic profitability of the systems. The externality with the greatest cost was N surplus. In the arable system, a mean nitrogen surplus of about 25 kg N ha^{-1} was associated with an environmental cost of 186 € ha^{-1} yr^{-1}. Soil erosion loss by water was the externality with the lowest economic impact; its greatest value was in the arable system where a mean annual loss of 0.4 t soil ha^{-1} was estimated to cause an economic impact costing 2.5 € ha^{-1} yr^{-1}.

The results show that both with and without grants, the arable system was the most financially profitable land-use (EAV$_F$ with grants = 559 € ha^{-1} yr^{-1}) followed by the silvoarable (EAV$_F$ with grants = 344 € ha^{-1} yr^{-1}) and the forestry system (EAV$_F$ with grants = 170 € ha^{-1} yr^{-1}). However, these results were altered when the environmental externalities were included. In this case, the societal benefit of the silvoarable system (EAV$_E$ with grants = 331 € ha^{-1} yr^{-1}) was similar to that of arable system (EAV$_E$ with grants = 328 € ha^{-1} yr^{-1}) and greater than that of the forestry (EAV$_E$ with grants = 203 € ha^{-1} yr^{-1}).

Table 12. Financial and Economic Equivalent Annual Value (EAV) of an arable, forestry and silvoarable system in Bedfordshire in the United Kingdom. Results shown for a time horizon of 30 years at a 4% discount rate.

	Arable[1]	Silvoarable[2]			Forestry[3]
		Crop component	Tree component	Combined	
Financial analysis					
EAV$_F$ with grants (€ ha^{-1} yr^{-1})	559.4	335.2	8.3	343.5	170.0
EAV$_F$ without grants (€ ha^{-1} yr^{-1})	314.8	90.6	8.3	98.9	37.4
Environmental externalities					
CO$_2$eq emissions (t CO$_2$eq ha^{-1} yr^{-1})	2.4	1.1	0.0	1.1	0.0
EAV CO$_2$eq emissions (€ ha^{-1} yr^{-1})	-19.7	-11.2	-0.3	-11.5	-0.3
CO$_2$eq sequestration (t CO$_2$eq ha^{-1} yr^{-1})	0.0	0.0	4.0	4.0	4.7
EAV CO$_2$eq sequestration (€ ha^{-1} yr^{-1})	0.0	0.0	30.0	30.0	35.0
Soil erosion losses by water (t soil loss ha^{-1} yr^{-1})	0.4	-	-	0.2	0.2
EAV Soil erosion losses (€ ha^{-1} yr^{-1})	-2.5	-	-	-1.5	-1.6
Nitrogen surplus (kg N ha^{-1} yr^{-1})	24.6	-	-	2.2	0.0
EAV Nitrogen surplus (€ ha^{-1} yr^{-1})	-186.3	-	-	-27.9	0.0
Phosphorus surplus (kg P ha^{-1} yr^{-1})	5.1	-	-	0.2	0.0
EAV Phosphorus surplus (€ ha^{-1} yr^{-1})	-22.8	-	-	-1.6	0.0
Economic analysis					
EAV$_E$ with grants and environmental externalities (€ ha^{-1} yr^{-1})	328.1	-	-	330.9	203.1
EAV$_E$ without grants and environmental externalities (€ ha^{-1} yr^{-1})	83.5	-	-	86.3	70.5

[1]: the arable system was a rotation of wheat, wheat, barley and oilseed rape

[2]: the silvoarable system was the same rotation as the arable system with poplar hybrids planted at 156 trees per hectare.

[3]: the forestry system was hybrid poplars planted at a density of 156 trees per hectare.

4.5 Discussion

Analyses of agroforestry economics in Europe tend to focus on their financial performance relative to arable and forestry counterfactuals (Graves et al. 2007), whilst at the same time noting that the lack of externalities in economic assessments is a gap in research that needs to be filled. This analysis advances knowledge of the overall contribution of land use systems to society by taking both a financial and economic perspective of the relative value of arable, forestry, and silvoarable systems. This we do by linking LCA and valuation data to increased knowledge of the effect of environmental externalities on society.

The estimated mean CO_2e emission in the arable system was 2.4 t CO_2e ha^{-1} yr^{-1}. Camargo et al. (2013) estimated values for wheat, barley and oilseed rape of 1.5-2.0 t CO_2e ha^{-1} yr^{-1}. Williams et al. (2010) estimated a global warming potential for wheat of around 0.7 t CO_2e produced t^{-1}, which assuming a yield of 9 t ha^{-1} would be equivalent to 6.3 CO_2e ha^{-1} yr^{-1}. This higher value included the contribution of N_2O emissions and operations beyond the field-gate such as crop storage and drying. Compared to the arable system, CO_2e emissions in the silvoarable system were reduced by 56%, but CO_2e emissions per produced tonne of crop yield increased by 4.4% in the silvoarable system.

Mean carbon sequestration in the silvorable system (determined only as carbon stored as timber) was 4 t CO_2e ha^{-1} yr^{-1}. Palma et al. (2007) estimated values between 1.83 and 8.8 t CO_2e ha^{-1} yr^{-1} for poplar trees in a silvoarable system in the Netherlands. Compared to the forestry system, carbon sequestration in the silvoarable system was reduced by 15%. Lehman and Gaunt (2004) and Harmand et al. (2004) reported that compared to arable systems, agroforestry systems were unlikely to lead to significant long-term belowground soil carbon sequestration as organic matter produced is relatively quickly decomposed.

Soil erosion loss by water in the three land uses was lower than 0.4 t ha^{-1} yr^{-1}; a value that is relatively low compared to other areas in Europe (Panagos et al. 2015). This can be explained by the relatively-flat case study area and the lack of extreme rainfall events. Hence the economic cost of soil erosion was at 1.5-2.5 € ha^{-1} yr^{-1} was also low. Compared to the arable system, soil erosion loss in the silvoarable system was reduced by about 50%. Whilst the absolute effect was low in this case-study, on more steep slopes and in areas with more extreme rainfall, the benefits could be substantial.

Annual loss of N was the costliest environmental externality. In the arable system, the mean N loss was about 25 kg N ha^{-1} yr^{-1} which is within the range of estimated annual N losses from temperate European arable systems of 10-100 kg N ha^{-1} yr^{-1} (Hadas et al. 1999; Nemeth, 1996; Hoffmann and Johnsson, 2003; Ersahin, 2001; Di and Cameron, 2002; Webster et al. 2003). In the silvoarable system, the mean annual N loss during the years when the intercrop was cultivated (0-14 years) was 4.7 kg N ha^{-1}, which is equivalent to an 80% reduction compared to the arable control. This was a result of a lower fertiliser rate per hectare because 20% of the area was not cropped (-20%) and nitrogen uptake by the trees and grass in the tree rows. This is greater than the 37% reduction reported by Udawatta et al. (2002) in young temperate agroforestry systems. However Udawatta et al only reported the reduction for the first three years, greater reductions could be anticipated as the trees grow. In fact, when only the first three years of the rotation were considered, the reduction of N loss was 36% in the silvorable system is similar to that observed by Udawatta et al. (2002). Similar reduction effects were seen in the case of P loss which was the second most expensive environmental externality. Whilst in the arable system, P loss was 5.1 kg P ha^{-1} yr^{-1}, in the silvoarable system it was 0.44 kg P ha^{-1} yr^{-1} during the years when the crop was cultivated.

There are a number of recommendations for future research that flow from this paper. As with all case study research it is important to consider that specific conditions change with location, and new analyses are likely to be required to assess the performance of competing land use systems at other sites. Many environmental processes operate at a landscape scale, where surrounding topography and land uses become important, for example, having a bearing on rates of soil erosion, N and P losses into water bodies, if the plots are located far, rather than near to them. Further research could build on the results of this study through a bottom-up approach to upscale the provision and economic value of the environmental externalities at the landscape level. Detailed spatial data would be necessary to adequately conduct this upscaling. It should be noted however, that whilst modelling environmental externalities at a landscape scale is desirable for some environmental processes, it can also lead to a reduction in specific detail (Tscharntke et al. 2005; Palma et al. 2007). Whilst we have made good progress in quantifying and valuing a number of environmental externalities, others such as habitat for wildlife, landscape diversity, pollination services, air quality, noise reduction, need yet to be assessed. Past research has indicated that trees have the potential to improve such ecosystem services (Sing et al. 2015; Faber et al. 2002) and if these more environmental externalities are included in future analyses, the economic profitability of forestry and silvoarable system may increase further relative to arable systems.

4.6 Conclusions

Based on an experimental plot in Bedfordshire, this paper modelled the financial profitability and valued the environmental externalities for an arable, silvoarable and forestry system. The results showed that the arable system was the most financially profitable land use but produced the most negative externalities. The silvoarable system whilst more profitable than the forestry system also produced greater negative externalities. The inclusion of the economic value of GHG emissions, carbon sequestration and loss of soil, N and P showed that silvoarable systems provided a similar societal benefit as the arable system, and a greater benefit that the forestry system. The expense of removing N and P in freshwater meant that these cost were particularly high in the arable system. The results showed that planting trees in arable systems could potentially reduce nutrient surpluses and provide a large economic benefit to society. Inclusion of other environmental externalities associated could increase the relative value of incorporating trees in agricultural systems.

5 The Forage-SAFE model

The development of Forage-SAFE model aims to provide a better understanding of the management and economics of wood pastures systems. The model simulates the daily balance between the produced and demanded food for livestock to estimate annual farm net margin. Forage-SAFE allows modification of a large number of biophysical and financial parameters related to the tree, pasture and livestock components in order to analyse their effect on profitability. The model estimates optimal managerial decisions that maximises net farm income such as tree cover density, carrying capacity and composition of livestock species. A conference paper presenting the model is described below:

Forage-SAFE: a tool to assess the management and economics of wood pasture systems

García De Jalón S.[1,*], Graves A.[1], Moreno G.[2], Palma J.H.N.[3], Crous-Duran J.[3], Oliveira T.[3]
and Burgess P.J.[1]
[1]Cranfield University, Cranfield, Bedfordshire, MK43 0AL, UK
[2]Forestry School, INDEHESA. Universidad de Extremadura, Plasencia 10600, Spain
[3]Technical University of Lisbon, Tapada da Ajuda, 1349-017 Lisboa, Portugal

This paper has been presented to the 15th International Conference on Environmental Science and Technology in Rhodes, Greece in 31st August - 2nd September 2017.

5.1.1 Abstract

The Forage-SAFE model has been developed to better understand the impact of trees on the profitability of wood pastures. It assesses the daily balance between the demand for and production of forage to estimate an annual farm net margin. The model allows the modification of selected biophysical and financial parameters related to the tree, pasture and livestock components (such as tree cover density, carrying capacity and livestock species) which can be optimised to maximise net farm income. A case study in a dehesa wood pasture in South-western Spain was used to show the applicability of the model. The case study results showed that net margin was maximised at around 27% tree cover for a carrying capacity of 0.4 livestock unit per hectare from which 61% were ruminants and 39% Iberian pigs. The analysis also showed that high carrying capacities were positively correlated with tree cover profitability. This was accentuated as the proportion of Iberian pigs increased.

Keywords: Forage-SAFE, wood pasture, tree cover, bio-economic, profitability

5.2 Introduction

Wood pastures are silvopastoral agroforestry systems with irreplaceable ecological, social, and cultural values. They occupy around 20.3 million ha in the 27 EU member states, equivalent to around 4.7% of all European land (Plieninger et al. 2015).

Wood pastures are complex systems where three agro-silvo-pastoral components can interact over time. This makes it difficult to evaluate the economic impact of management decisions on farm profitability. For instance, trees have the potential to increase on-farm fodder production for livestock e.g. Moreno and Pulido 2009; López-Díaz et al. 2016. However, measuring the economic impact or the marginal effect of trees on farm profitability based on observed data can be difficult and expensive. Thus modelling approaches are useful to identify optimal managerial decisions in wood pasture systems. The Forage-SAFE model was developed to provide a tool that can simulate the daily demand for and production of grasses and other forages to assess annual profits in wood pastures. The aim in developing the model was to provide a better understanding of the economic impact of farm-management decisions of the tree, pasture and livestock components.

5.3 Methodological structure of Forage-SAFE

Forage-SAFE is a dynamic bio-economic model developed in Microsoft Excel. It contains some macros in Microsoft Visual Basic for Applications (VBA) to facilitate model usability and run various optimization problems.

A total of 304 parameters can be set in Forage-SAFE to define the biophysical, managerial and economic characteristics of wood pasture systems. The biophysical characteristics included production data of pasture, fruit, timber, firewood and browse. The managerial characteristics included data related to the livestock (species, type, age, calendar, weight and consumption), the trees (planting, tree protection, pruning, thinning, cutting and browsing) and pasture and fodder crops (e.g., planting, fertilising, spraying, harvesting and baling). The economic variables included revenues (sale of livestock and tree products, and other services) and farm costs (variable, fixed, subcontracted labour and rented machinery, and unpaid labour).

Forage-SAFE includes seven spreadsheets:

i) Biophysical input data: this is the principal spreadsheet where end-users set biophysical and managerial variables. Annual results are shown in this sheet. It is divided into three parts: i) biophysical and managerial input data, ii) main annual results with button links to graphical results, and iii) estimation of ‘locally’ optimal values of tree cover, carrying capacity and distribution of livestock species to maximise production and profitability.
ii) Financial input data: to insert financial data.
iii) Graphs: main graphical results provided at a daily resolution.
iv) Livestock demand: calculations of daily food and energy demanded by each livestock species (e.g., cows, sheep, pigs) and type (e.g. suckler cow, growing cow and male adult cow).
v) Production NO TREE: calculations of the daily production of pasture and duration of energy content in areas beyond the tree canopy.
vi) Production TREE: calculations of the daily production of pasture and duration of energy content in areas under the tree canopy. It also calculates browse and acorn production.
vii) Biophysical analysis: calculations of the daily balance between energy and food production and demand in the wood pasture.

5.3.1 Fodder and tree production

5.3.1.1 Energy from the pasture

The model calculated the energy produced from the pasture (MJ ha^{-1} d^{-1}) as the product of pasture produced on day *d* (kg dry matter (DM) ha^{-1} d^{-1}) and the energy content (MJ kg DM^{-1}). The model calculated the daily balance between the produced and consumed pasture in order to quantify the pasture that was not consumed by the livestock and was available in subsequent days, updating the energy content each day.

Equation 1 shows the discretised equation to measure the potential change of available energy from pasture (A*EP*) on day *t* (MJ ha^{-1} d^{-1}):

$$\frac{dAEP_t}{dt} = PP_t * ECP + SEP_t \qquad \textit{Eq.1}$$

Where PP_t is the pasture production in terms of dry weight (kg DM ha^{-1} d^{-1}) on day *t*, *ECP* is the energy content in the pasture (MJ kg DM^{-1}), and SEP_t is the surplus energy from the accumulated pasture (MJ ha^{-1} d^{-1}), i.e. pasture previously produced that has not been consumed.

The surplus of pasture was calculated on a daily basis as the difference between pasture production and consumption. Equation 2 shows how the model calculated the surplus of energy from accumulated pasture on day *t* (SEP_t):

$$\begin{gathered} SEP_t = \\ SP_{t-1} * ECP * D_{t-1} + \\ SP_{t-2} * ECP * D_{t-2} * D_{t-1} + \\ SP_{t-3} * ECP * D_{t-3} * D_{t-2} * D_{t-1} + \qquad \textit{Eq.2} \\ \ldots + \\ SP_{t-n} * ECP * D_{t-n} * D_{t-(n-1)} * D_{t-(n-2)} * D_{t-(n-3)} * \ldots * D_{t-(n-(n-1))} \end{gathered}$$

where *SP* is the surplus from pasture produced on day *t* (kg ha^{-1} d^{-1}), and *D* is the pasture senescence coefficient which indicates the retention of energy content over time. As pasture senescence is affected by weather conditions *D* varies for each time instant. For example under extreme heat the retention of energy decreases more rapidly than at more normal temperatures. For instance, in arid Mediterranean climates the retention of energy content in summer is lower than in autumn. This is also affected by microclimatic conditions caused by the tree effect on pasture.

The model separately calculates the available energy from pasture in treeless areas and areas under tree canopy. Equation 1 shows how the available energy from pasture in treeless areas varies along time. In areas under the tree canopy, the available energy is similarly calculated but adds the effect of tree density on pasture growth (see Equation 3). The Gompertz equation was used to simulate the effect of tree density.

$$\frac{dAEPwt_t}{dt} = (PPwt_t * (1 - e^{(-e^{-b*(\delta - C)})})) * ECPwt + SEPwt_t \qquad \textit{Eq.3}$$

where $AEPwt_t$ is the available energy from pasture in areas under the tree canopy, $PPwt_t$ is the dry weight of pasture production, *ECPwt* is the energy content of the pasture, and $SEPwt_t$ is the surplus of energy from the accumulated pasture. The pasture production under tree canopy is multiplied by a value between 0 and 1 derived from a Gompertz equation where δ is the proportion of tree cover and *b* and *C* are constants.

Finally the available energy from pasture in the system combining treeless areas and areas under tree canopies is calculated by Equation 4:

$$AEP_t = (1 - \delta) * AEPwot_t + \delta * AEPwt_t \qquad \textit{Eq.4}$$

where δ is the proportion of tree cover, AEP_{wot} is the available energy from pasture in treeless areas and AEP_{wt} is the available energy from pasture in areas under tree canopy.

End-users need to insert daily grass production data. This can be modelled data from an agroforestry model (e.g. Yield-SAFE, van der Werf et al. 2007, Modelo Dehesa, Hernández Díaz-Hambrona et al. 2008; Iglesias et al. 2016, and SPUR2, Hanson et al. 1994) or real data.

5.3.1.2 Energy and resources from the tree

Fruit and browse were included in the model as sources of food to feed the livestock. Daily fruit production was simulated by a normal probability distribution. The day of the year of highest production and the standard deviation in terms of number of days need to be inserted to simulate the daily fruit production. The produced energy from tree fruit was calculated as the product of the dry weight of fruit and the energy content per dry weight. Browse production was considered as a food supplement when pasture production did not meet the demand of the ruminants. Browse can be restricted for specific dates when pruning is allowed. Pruning costs associated with browsing can be considered in the analysis if required. Forage-SAFE also allows the inclusion of farm products that provide economic revenues such as timber, firewood, cork, wool and milk.

5.3.2 Livestock demand for fodder

The fodder demand by livestock was calculated for each livestock species (cattle, sheep and Iberian pigs) and type (growing, suckler and male adults). The model calculated the total energy demand on day t (DE; units: MJ ha^{-1} d^{-1}) using Equation 5:

$$DE_t = \sum_{s=1}^{3}\sum_{y=1}^{3}(n_{t,s,y} * de_{t,s,y}) \qquad \textit{Eq.5}$$

where $n_{t,s,y}$ is the number of animals per hectare of species s of type y on day t, and $de_{t,s,y}$ is the associated energy demand per animal species and type (MJ $animal^{-1}$). Forage-SAFE included two distinct ways to calculate each animal's demand for energy. One way was by setting the consumption of each animal (DM kg $animal^{-1}$) according to specific characteristics such as species, type, weight and physiological state (gestation, lactation and maintenance). The other way was to use the utilised metabolisable energy (UME) equation (Hodgson 1990). The equation was calculated for a "reference animal" defined by Hodgson (1990) as a lactating dairy cow with a live weight (W) of 500 kg and milk yield (Y) of 10 kg d^{-1} (UME; units: MJ LU^{-1} d^{-1}) and then converted into kilocalories. Equation 6 shows the UME equation used to calculate the demand of a lactating dairy cow per day:

$$UME_t = 8.3 + 0.091 * W_t + 4.94 * Y_t \qquad \textit{Eq.6}$$

where W_t and Y_t indicated the weight and milk yield respectively on day t.

5.3.3 Assessing the profitability of the wood pasture

The daily comparison of energy produced by the pasture, browse and fruit in kilocalories (MJ) with the demanded energy from livestock was used to estimate how much supplementary food as forage, concentrates or acorns was needed to meet the livestock demand. Gross and net margins were used to assess farm profitability:

Gross margin was defined as the revenue from any product and/or service of the wood pasture (e.g. animal sale, wool, milk, firewood and hunting) plus farming subsidies minus variable costs. Variable costs were separately measured for the livestock (animal purchase, forage and concentrates, veterinary and medicines, bedding and miscellaneous), the crop (seed and plants, fertiliser, crop protection, baling and other costs), and the tree (planting, tree protection, pruning, thinning, cutting and other costs (see Equation 7).

Net margin was defined as the gross margin minus labour and rented machinery costs and other fixed costs (installation and repairs of infrastructure, fuel and energy, machinery, interest on working capital, and other costs) (see Equation 8).

5.3.4 Optimising managerial decisions

Forage-SAFE includes an optimisation solver to optimise managerial decisions in terms of maximum production, or gross or net margin. Thus Forage-SAFE can suggest what tree cover, carrying capacity and livestock species composition are optimal, assuming everything else is held constant. Forage-SAFE used the Generalized Reduced Gradient (GRG) algorithm of the nonlinear solving method as not all the equations of the model were linear. The GRG algorithm estimated a 'locally' rather than 'globally' optimal solution. Hence there was no other set of values for the decision variables close to the current values that yielded a better value for the objective function (maximise production or gross and net margin). The objective functions (Equations 7 and 8) used in Forage-SAFE to maximise annual gross margin (GM) and net margin (NM), respectively were:

$$Max. GM = \sum_{t=1}^{365}\sum_{c=1}^{3} PI_{t,c} + \sum_{t=1}^{365}\sum_{c=1}^{3} SI_{t,c} - \sum_{t=1}^{365}\sum_{c=1}^{3} VC_{t,c} \qquad \textit{Eq.7}$$

$$Max. NM = GM - \sum_{t=1}^{365}\sum_{c=1}^{3} SC_{t,c} - \sum_{t=1}^{365}\sum_{c=1}^{3} FC_{t,c} \qquad \textit{Eq.8}$$

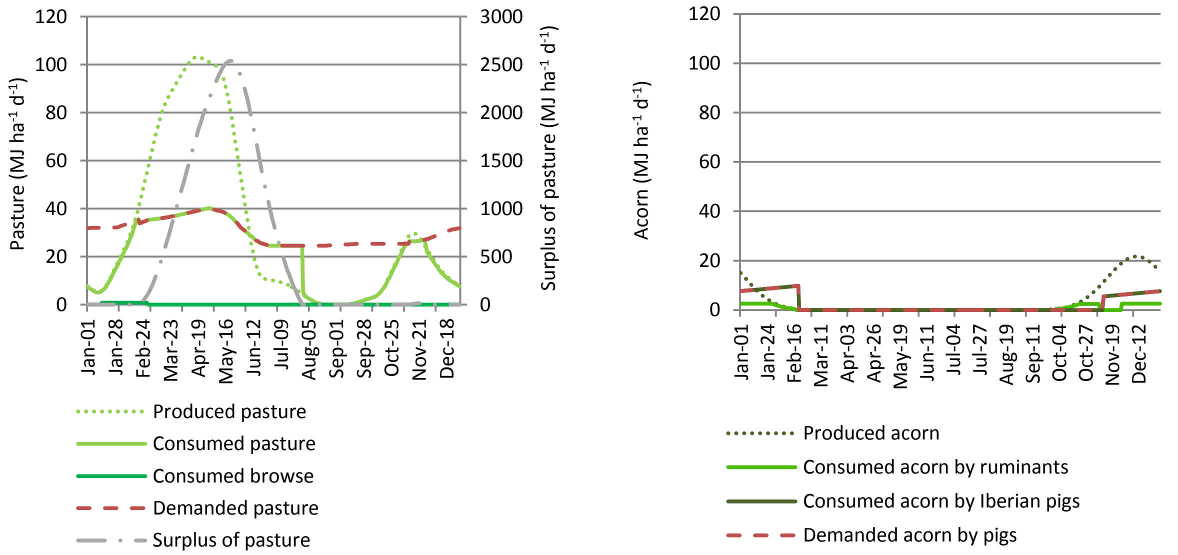
where $PI_{d,c}$ is the revenue from sale products of the component *c* (livestock, tree and crop) on day *t*, *SI* is the revenue from subsidies, *VC* is the variable costs, *SC* is the labour and rented machinery costs, and *FC* is other fixed costs.

5.4 Results: an example in a dehesa wood pasture

A case study in a dehesa in Extremadura, Spain was used to show the applicability of the model. Figure 31 shows the daily production, demand, consumption and surplus of pasture, browse and acorns in a modelled dehesa wood pasture. The left graph shows the daily energy balance for pasture and browse. Production was concentrated between February and early June and to a lesser extent between October and December. Likewise there was a surplus of pasture between March and July and from October to November. Overall, from early August to early October and from early December to late January the provision of food energy from the system did not meet the livestock demand. Thus farmers would need to use extra forage or concentrates to satisfy the livestock demand.

From early June to late September pasture production was almost negligible. However during this period livestock did not need extra forage or concentrates until mid-August due to the surplus of pasture that was not consumed in the spring. During the spring, pasture production in treeless areas was higher than in areas under tree canopies. However, in early summer the retention of energy in the surplus pasture decreased faster in treeless areas than in areas under tree canopy. Thus when the pasture was dry with very low energy content in treeless areas, under the tree canopy the accumulated pasture was still fresh and provided a source of food for the livestock. This allowed an extension of the grazing period without external food. In a similar, but to a lesser extent, this also occurred in the winter when due to protection from frosts the pasture under the tree canopy also retained a higher energy content. Browse was also used to feed ruminants in late January and this met some of the energy demands.

The right graph shows the production and consumption of acorns. Iberian pigs were in the field from November to February coinciding with the period of maximum fruit production. It was assumed that pigs would have priority over ruminants, i.e. they would only eat acorns if pigs had previously satisfied their demand for acorns. Thus most acorns were used to feed the Iberian pigs.



(a) (b)

Figure 31. Produced (dotted lines), consumed (continuous lines), surplus (dashed and dotted line) and demanded (dashed lines) energy from pasture, browse and acorn in the dehesa case study at 0.37 LU ha^{-1} (39.9% sheep, 38.5% cattle and 21.6% Iberian pigs). Figure (a) shows the daily energy balance of pasture and browse, Figure (b) shows the energy balance of acorns.

Table 13 shows the estimated annual food production, consumption and extra requirements of the modelled dehesa at a carrying capacity 0.37 LU ha^{-1} (39.9% sheep, 38.5% cattle and 21.6% Iberian pigs) under different tree cover densities. The first part of the table shows annual production pasture and acorn. Maximum annual pasture production was attained at 0% tree cover (1465 kg DM ha^{-1}), and then decreased as tree cover increased. Acorn production increased with increasing tree cover until 50% tree cover beyond which inter-tree competition decreased production. The maximum pasture consumption by livestock was reached at 30% percent tree cover (876 kg DM ha^{-1}). Browse consumption increased as tree cover increased. The proportion of the energy that was in the pasture which was consumed ranged from 60% at no tree cover to 95% at full tree cover. This was mainly the low production at full tree cover and due to the energy content in the pasture under tree canopies lasted longer than in treeless areas.

The lowest value of extra forage needed to meet livestock demand was 370 kg DM ha^{-1} in a dehesa with 40% tree cover and the highest value was 988 kg DM ha^{-1} at 100% tree cover. In a treeless dehesa the forage needed was 408 kg DM ha^{-1}. Therefore a treeless dehesa needed 10.3% more forage than in a dehesa at 40% tree cover. The demand for acorns by Iberian pigs was met by ensuring that the tree cover was 20% or above.

The highest gross and net margin (183 € ha^{-1} and 37 € ha^{-1} respectively) were achieved at 20% tree cover. Whilst the gross margin included the revenue from the trees it did not include the associated labour costs which were considered in the net margins (e.g. tree planting, pruning and cutting, see Equations 1-3).

The estimated net margin at 0% and 10% tree cover negative. This indicated that at the specified carrying capacity and livestock composition, the system without trees was not economically sustainable. For this reason, at 0% and 10% tree cover the Iberian pigs were replaced by ruminants in the analysis. Thus at 0% and 10% tree cover with only ruminants the net margin was 25 € ha^{-1} and 27 € ha^{-1} respectively.

Table 13. Production, consumption, supplementary needs to satisfy livestock demand and farm profitability in the modelled dehesa (0.37 LU ha^{-1}: 39.9% sheep, 38.5% cattle and 21.6% Iberian pigs). Bold and underlined figures indicate the best and worst values from a financial perspective.

Indicator	**Tree cover (%)**										
	0%	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**100%**
Production											
Pasture (kg DM ha^{-1})	**1465**	1431	1397	1363	1328	1279	1181	1010	781	529	281
Acorns (kg ha^{-1})	0	134	263	374	454	**493**	492	460	409	350	290
Consumption											
Pasture (kg DM ha^{-1})	874	875	876	**876**	875	870	848	799	705	502	267
Browse (kg DM ha^{-1})	0	3	5	8	10	13	15	18	20	23	**26**
Acorns (kg ha^{-1})	0	107	210	270	276	281	**286**	286	284	265	229
Extra supplementary needs											
Forage needed (kg DM ha^{-1})	408	406	400	372	**370**	372	389	436	528	738	988
Acorns needed (kg ha^{-1})	201	94	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Farm profitability											
Gross margin (€ ha^{-1})	124 [a]	129 [a]	**183**	181	179	177	175	173	159	118	70
Net margin (€ ha^{-1})	25 [a]	27 [a]	**37**	33	29	24	20	16	1	-43	-93

(a) Only sheep and cows were considered in the analysis since acorn production did not meet the Iberian pigs demand.

5.5 Conclusions

This paper presents a bio-economic model that assesses the management and economics of wood pasture systems. A dehesa case study was selected to show the applicability of Forage-SAFE. The model quantified and compared on a daily time-step the energy demanded by livestock and the energy provided by the system. It was also used to calculate how much extra forage was needed to satisfy the livestock demand and the impact of this on system profitability. The results showed that trees in dehesas positively contribute to profitability until a certain density where the benefits start to be outweighed by the costs. Hence profitability was reduced by both too little and too much tree cover. Although annual pasture production was maximised at 0% tree cover, the combination of pasture, browse and acorns was maximised at a tree cover around 40%. In terms of profitability, the maximum net margin was reached at around 20% tree cover. The optimal tree density in terms of net margin increased as the proportion of Iberian pigs was increased. Hence in conclusion, a daily time-step modelling approach based on livestock demand for metabolisable energy and pasture production seems to be particularly valuable in quantifying the effect of trees in buffering the strong seasonality of pasture growth and in terms of assessing its effect on profitability.

6 Up-scaling: from farm to regional scale

This section presents a methodology developed to up-scale farm-level results to the regional level. The region of Britany (France) was used as a case study to show the applicability of the approach (see location in Figure 32).

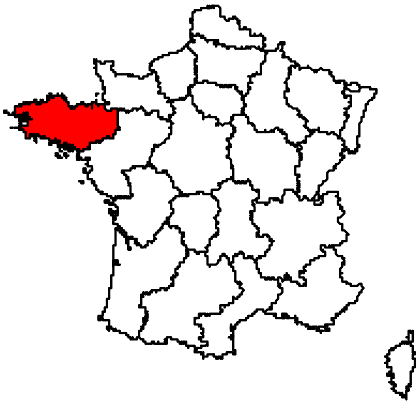


Figure 32. Location of Britany region in France

6.1 Land-use cover at regional scale

Before undertaking the up-scaling approach it was necessary to assess the current land-use cover at the regional level. The CORINE land cover dataset was used to identify the geographical location of the different land uses. Figure 33 shows the location of the different land uses in Brittany. Table 14 shows the codes and description of the CORINE land uses.

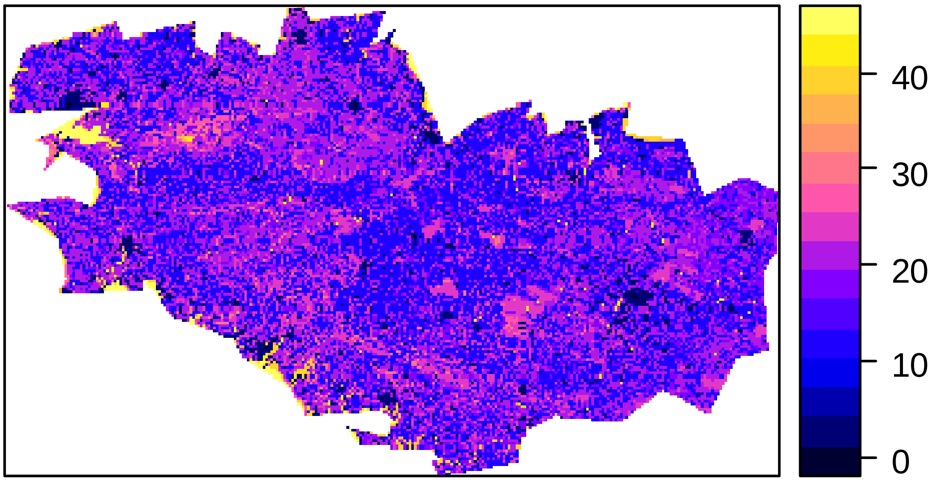


Figure 33. Land use cover in Brittany. The legend on the right shows the CORINE codes which are described in Table 14. Source: CORINE land cover.

Figure 34 shows the area measured in hectares occupied by the CORINE land uses in Brittany. As shown, ‘Non-irrigated arable land’ was the most common land use in Brittany. ‘Non-irrigated arable land’ includes cereals, legumes, fodder crops, root crops and fallow land, and does not include permanent pasture. The second most common land use in Brittany was ‘Complex cultivation patterns’ which is when small parcels of different land uses such as annual crops, pasture and/or permanent crops are juxtaposed in a small space. The third most common was ‘Pastures’ which includes dense grass cover of floral composition dominated by graminaceae and not under a rotation system.

Table 14. Codes and description of the CORINE land uses

CORINE codes	Description		
1	Continuous urban fabric	23	Broad-leaved forest
2	Discontinuous urban fabric	24	Coniferous forest
3	Industrial or commercial units	25	Mixed forest
4	Road and rail networks and associated land	26	Natural grasslands
5	Port areas	27	Moors and heathland
6	Airports	29	Transitional woodland-shrub
7	Mineral extraction sites	30	Beaches, dunes, sands
8	Dump sites	35	Inland marshes
9	Construction sites	36	Peat bogs
10	Green urban areas	37	Salt marshes
11	Sport and leisure facilities	39	Intertidal flats
12	Non-irrigated arable land	40	Water courses
16	Fruit trees and berry plantations	41	Water bodies
18	Pastures	42	Coastal lagoons
20	Complex cultivation patterns	43	Estuaries
21	Agriculture land, with areas of natural vegetation	44	Sea and ocean

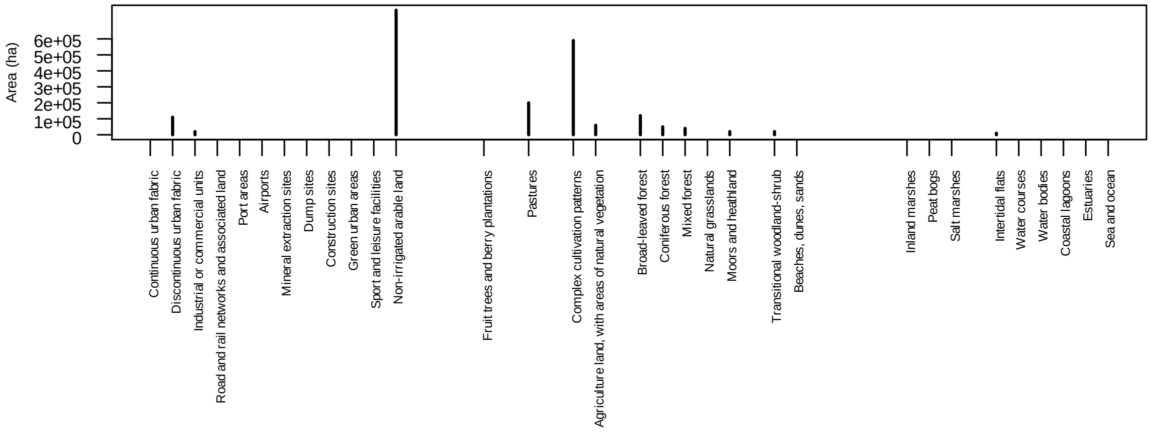


Figure 34. Area (ha) occupied by the CORINE land uses in Brittany.

6.2 Assessing farm profitability

The Farm Accountancy Data Network (FADN) was used to estimate farm profitability in Brittany. The CORINE land cover was used to geographically locate the farm profitability data from FADN. Gross and Net Margin of agricultural land uses were used as indicators of farm profitability. Figure 35 shows the gross margin (€ ha^{-1} year^{-1}) of farms in Brittany including the following farm types: (15) Specialist cereals, oilseeds and protein (COP) crops, (48) Specialist sheep and goats, (49) Specialist cattle, (60) Mixed crops, and (80) Mixed crops and livestock.

Although these values notably vary throughout time the results show that the gross margin in farms in Brittany ranges from 674 € ha^{-1} year^{-1} in farms specialised in cereals, oilseeds and protein crops to 1,149 € ha^{-1} year^{-1} in farms specialised in cattle production (Figure 35). The estimated average farm gross margin in Brittany was around 904 € ha^{-1} year^{-1}. Although the geographical distribution of the gross margin in Brittany seems to be very heterogeneous the results seems to indicate that farms in north-eastern Brittany are slightly more profitable. Figure 36 shows the net margin (€ ha^{-1} year^{-1}) of farms in Brittany. The net margin ranges from 114 € ha^{-1} year^{-1} in some farms specialised in cattle production, to 168 € ha^{-1} year^{-1} for farms specialised in cereals, oilseeds and protein crops, and to 653 € ha^{-1} year^{-1} in farms specialised in mixed crops. The estimated average farm gross margin in Brittany was around 389 ha^{-1} year^{-1}.

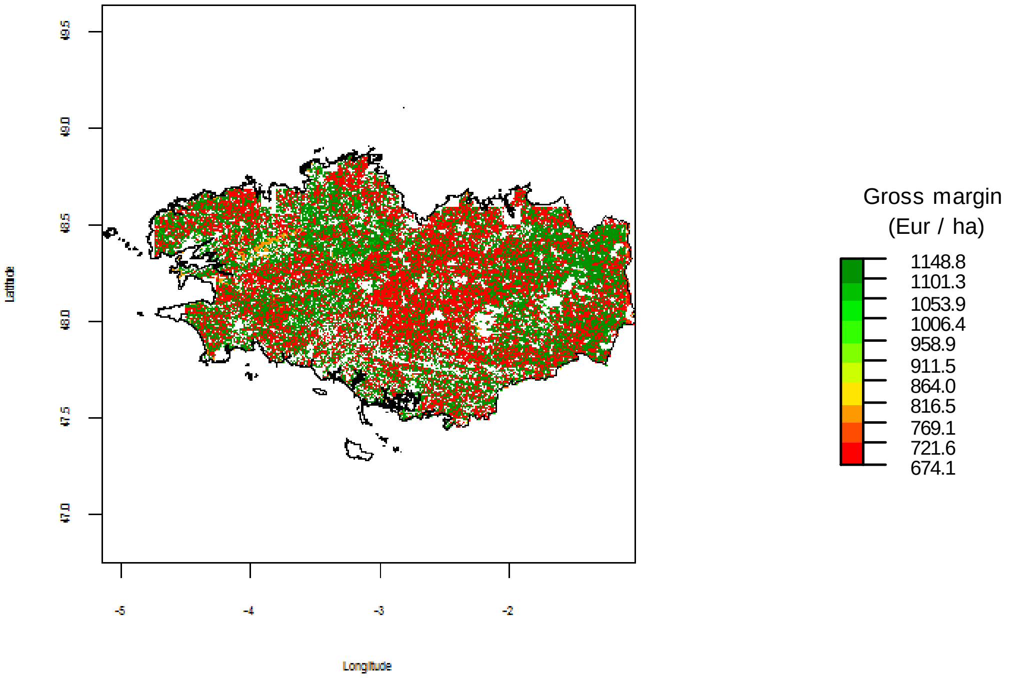


Figure 35. Gross margin of farms in Brittany. Source FADN and CORINE land cover.

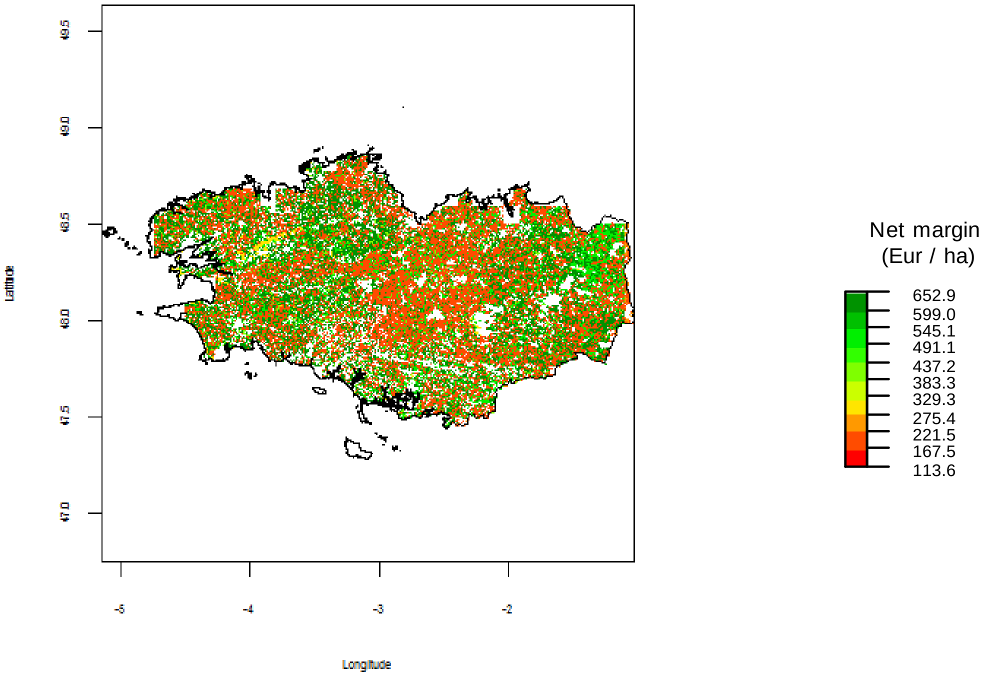
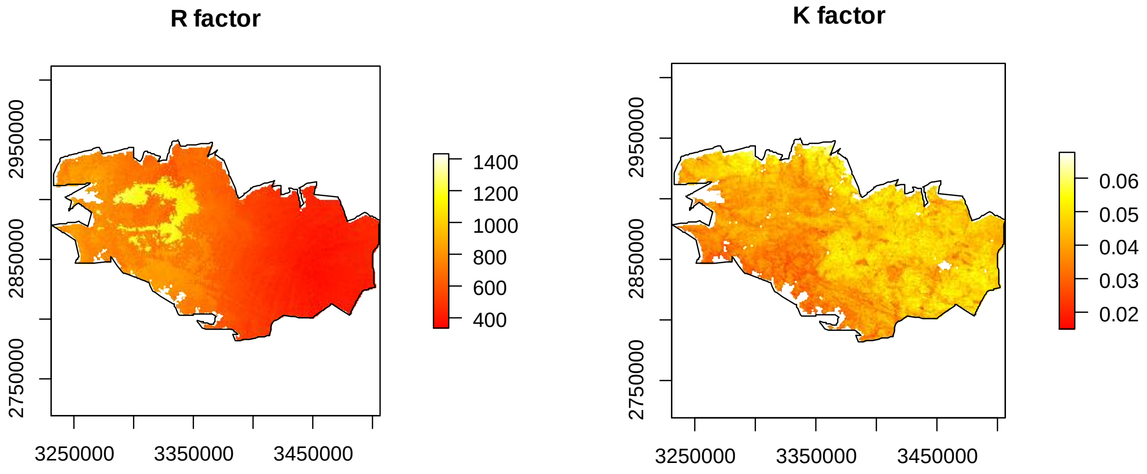


Figure 36. Net margin of farms in Brittany. Source FADN and CORINE land cover.

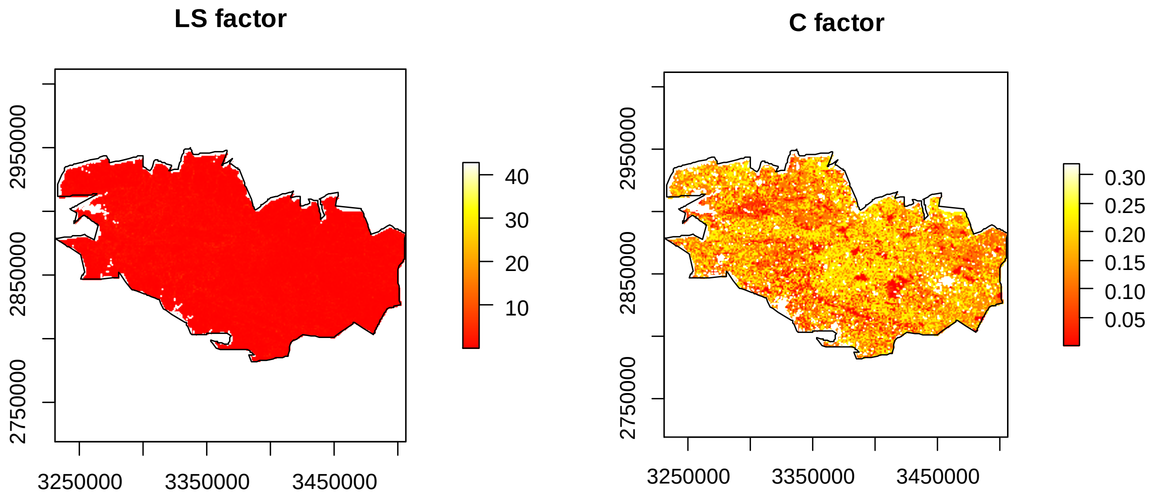
6.3 Calculating soil erosion loss by water at regional scale

The report shows an approach to estimate the effect of increasing tree cover at regional scale. This can be applied to assess multiple ecosystem services. In this report only one regulating ecosystem service (the effect on reducing soil erosion losses by water) is evaluated. Soil erosion loss was assessed using the RUSLE equation (A = *R * K * LS * C * P). A* is the estimated average soil loss in tons per hectare per year; *R* is the rainfall-runoff erosivity factor; *K* is the soil erodibility factor; *L* is the slope length factor; *S* is the slope steepness factor; *C* is the cover-management factor; *P* is the support practice factor. Figure 37 shows the factors used in the RUSLE equation for calculating soil erosion losses by water in Brittany (data taken from the European Soil Data Centre).



Mean R factor in Brittany = 643.343

Mean K factor in Brittany = 0.043



Mean LS factor in Brittany = 0.663

Mean C factor in Brittany = 0.146

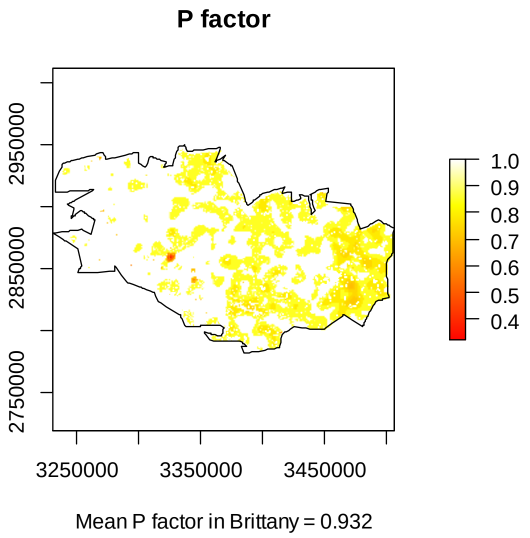


Figure 37. Factors of the RUSLE equation for calculating soil erosion losses by water in Brittany (data taken from the European Soil Data Centre)

Figure 38 shows the estimated current soil erosion losses by water in Brittany. The range of soil erosion losses was between 0 t ha^{-1} year^{-1} and 341 t ha^{-1} year^{-1} with a mean and median value of 2.22 t ha^{-1} year^{-1} and 1.55 t ha^{-1} year^{-1}, respectively.

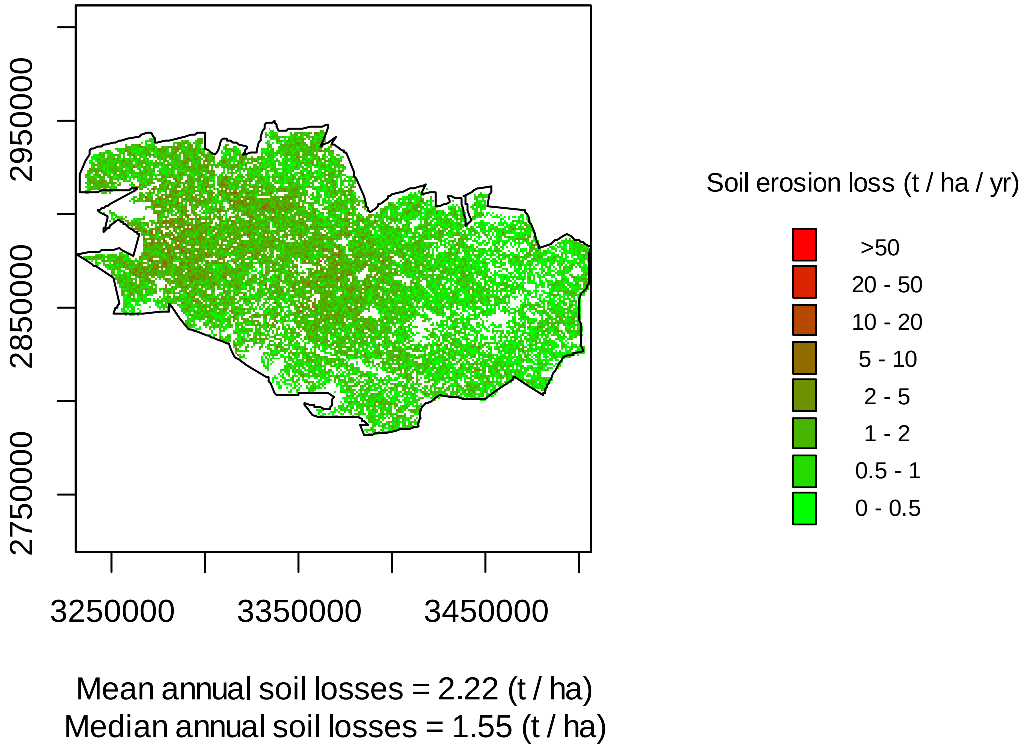


Figure 38. Current soil erosion loss by water in Brittany. Source: Soil European Data Centre.

6.4 Identifying potential areas for adopting agroforestry

The next step in assessing the regional effect of increasing agroforestry in Brittany was to identify potential areas where increasing the tree cover could be more cost-effective. It was assumed that treeless areas would be where the introduction of trees could provide most benefit.

Scenarios for the introduction of trees were developed. Instead of changing current land use, the scenarios considered different tree cover densities whilst maintaining the extent of current land use. This is because it was considered that introducing trees without changing the current land use would be the most likely scenario to occur. Figure 39 shows the frequency of tree cover in arable and pasture land in Brittany (including complex cultivation patterns, non-irrigated arable land, agriculture land, with areas of natural vegetation and pastures). As shown, most arable and pasture land is treeless in Brittany. This treeless area was identified as the area where trees should be planted. Figure 40 shows the geographical location of the tree cover categories in Brittany where the overall tree cover density is 5.87%.

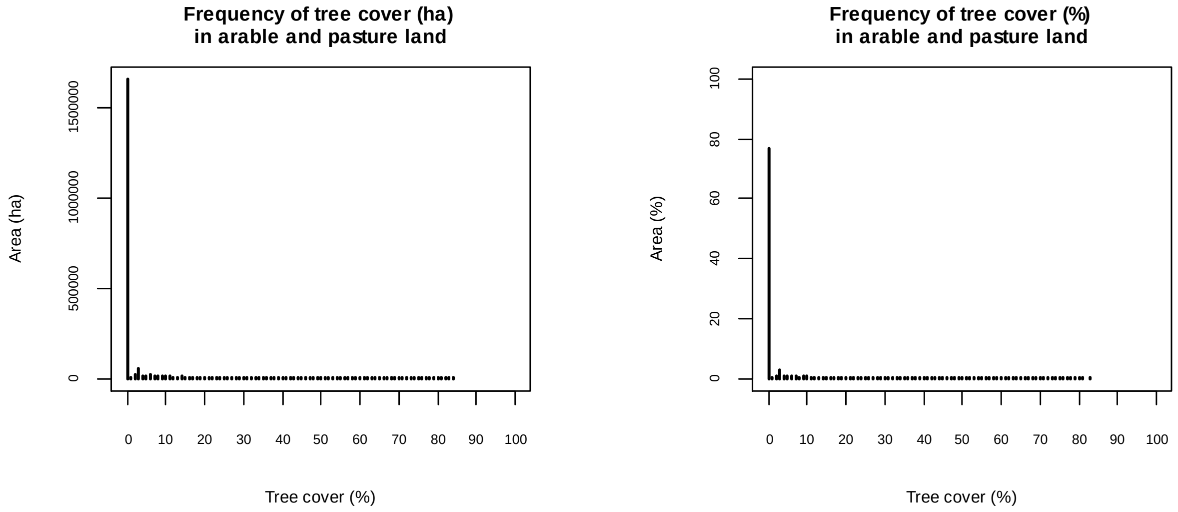


Figure 39. Frequency of tree cover density in arable and pasture land in Brittany.

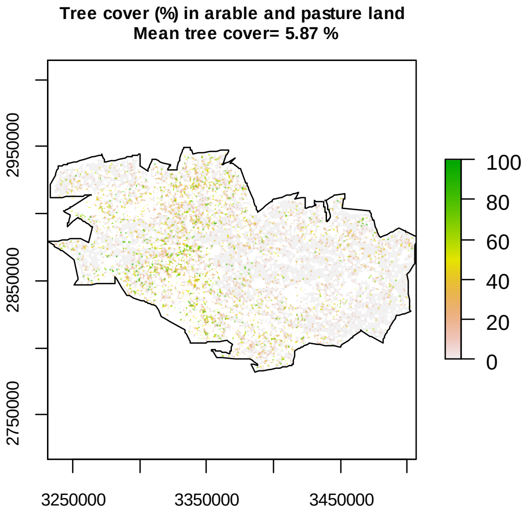


Figure 40. Tree cover in arable and pasture land in Brittany.

6.5 Assessing the effect of increasing tree cover in arable and pasture land

This section shows the effect of increasing tree cover on soil erosion losses at a regional scale. Several scenarios for increasing tree cover in treeless area on the arable and pasture land with 0% tree cover were developed.

6.5.1 Increasing tree cover in arable land

In order to evaluate the effect of increasing tree cover at a regional scale, it is important to assess the effect at the plot level for the whole rotation of the trees. The RUSLE equation was used to dynamically evaluate the effect of introducing trees on soil erosion at the plot scale. When comparing soil loss in arable, forestry and silvoarable systems in the same geographical area, the factors *R*, *K*, *LS* and *P* were considered constant and only changes in the C-factor were used to assess the differences among the systems. Figure 41 shows the effect of introducing trees on the *C* factor, where the tree area was assumed to be 5%. The graph shows how the introduction of trees in arable land reduced the *C* factor from 0.221 to 0.172 (a decrease of 22% in the *C* factor).

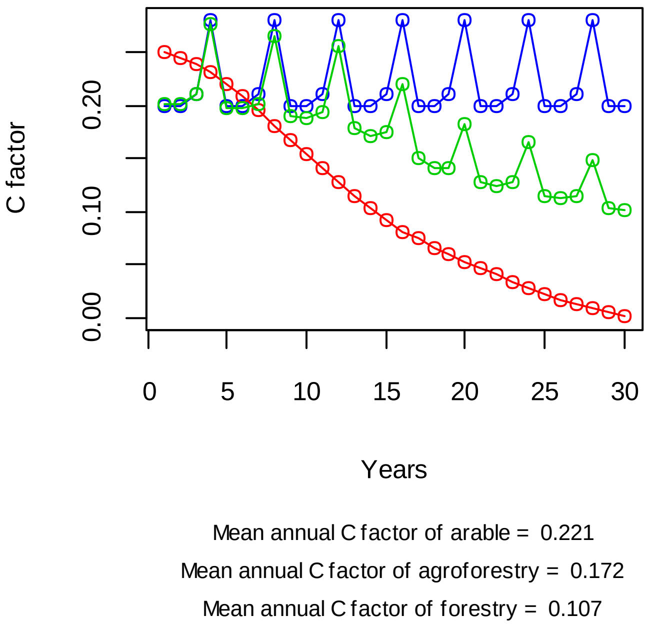
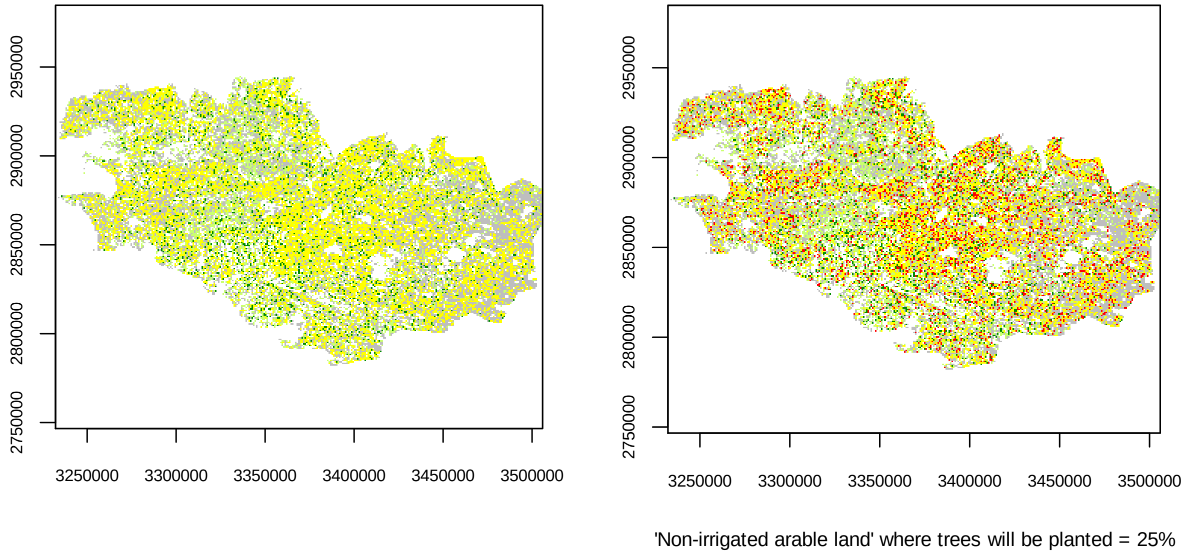


Figure 41. Modelled C factor of the RUSLE equation in arable land (a rotation of wheat, wheat, barley and oilseed rape), forestry (poplar plantation) and agroforestry (alley cropping silvoarable system with poplar and a rotation of wheat, wheat, barley and oilseed rape).

The next step was to up-scale from the plot level to the regional level. In doing so, four different scenarios were evaluated for the arable land in Brittany:

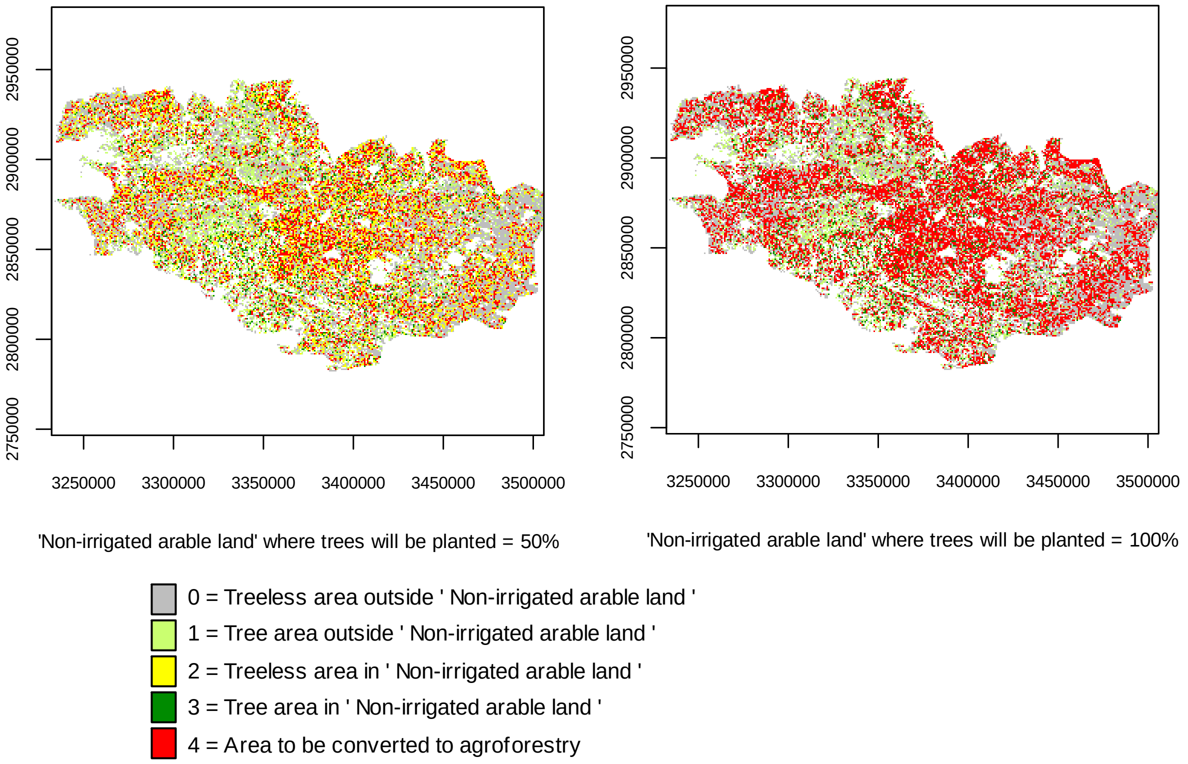
1. Status quo (no changes applied)
2. Increasing tree cover by 5% on 25% of treeless arable land
3. Increasing tree cover by 5% on 50% of treeless arable land
4. Increasing tree cover by 5% on 100% of treeless arable land

The selection of target land, within the treeless arable land area, where the tree cover would increase, was randomly selected through random samples. Figure 42 shows the identified scenarios in arable land in Brittany.



a) Status quo (no changes applied)

b) Increasing tree cover in 25% of treeless arable land

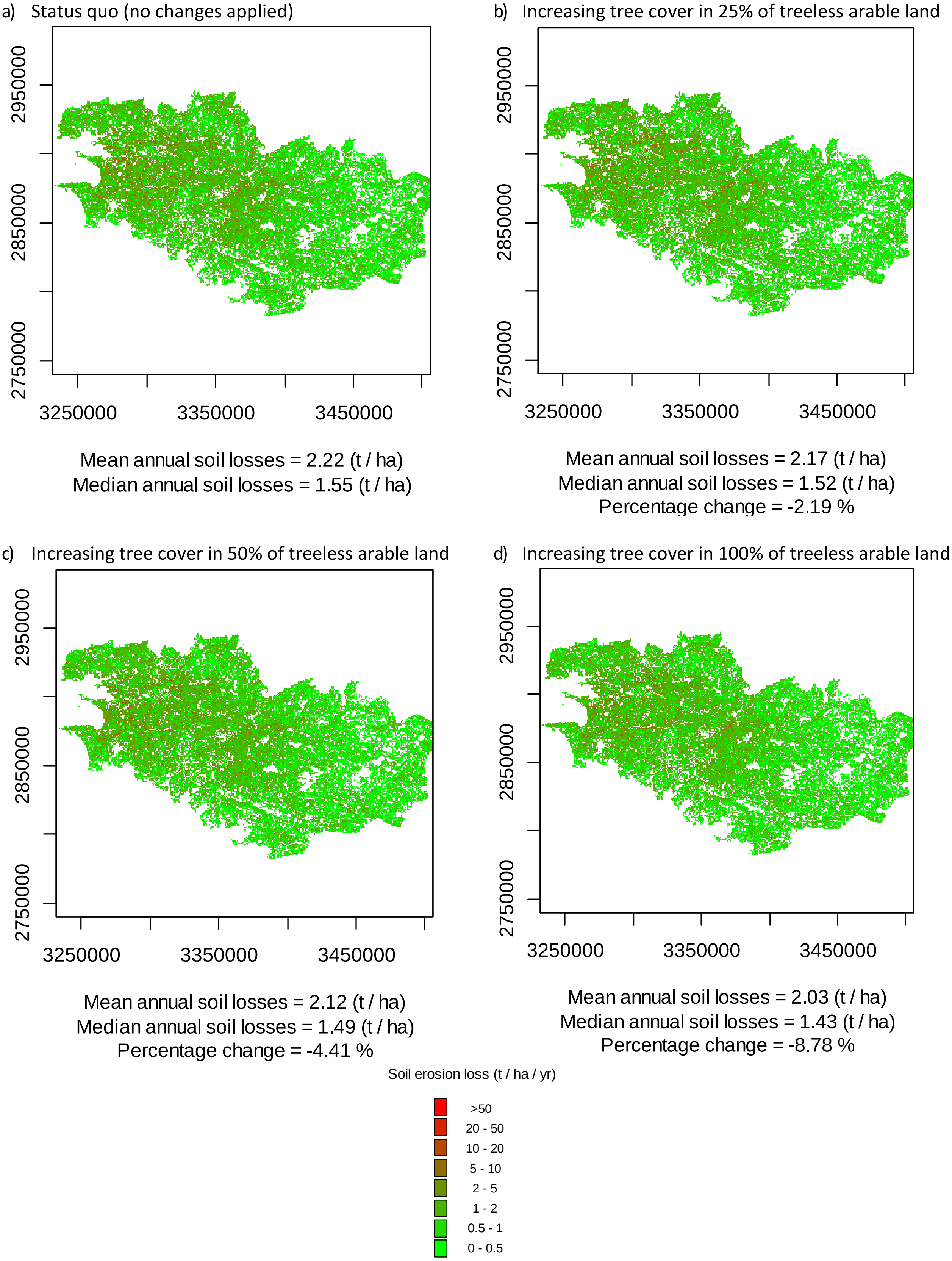


c) Increasing tree cover in 50% of treeless arable land

d) Increasing tree cover in 100% of treeless arable land

Figure 42. Scenarios identifying potential area in ‘Non-irrigated arable land’ to increase tree cover density.

Once the effect of increasing tree cover at the plot scale and the areas where tree cover might be increase were identified, the calculation at the regional level was done using the RUSLE equation. Figure 43 shows the effect of increasing tree cover on reducing soil erosion losses at the regional scale. In the status quo scenario, mean annual soil erosion losses were 2.22 t ha^{-1} year^{-1}. Soil erosion losses were reduced by 2.2%, 4.4% and 8.8% where a 5% increase in tree cover occurred on 25%, 50% and 100% of treeless arable land, respectively.



a) Status quo (no changes applied)

Mean annual soil losses = 2.22 (t / ha)
Median annual soil losses = 1.55 (t / ha)

b) Increasing tree cover in 25% of treeless arable land

Mean annual soil losses = 2.17 (t / ha)
Median annual soil losses = 1.52 (t / ha)
Percentage change = -2.19 %

c) Increasing tree cover in 50% of treeless arable land

Mean annual soil losses = 2.12 (t / ha)
Median annual soil losses = 1.49 (t / ha)
Percentage change = -4.41 %

d) Increasing tree cover in 100% of treeless arable land

Mean annual soil losses = 2.03 (t / ha)
Median annual soil losses = 1.43 (t / ha)
Percentage change = -8.78 %

Figure 43. Scenarios showing the effect of increasing tree cover density by 5% on reducing soil erosion losses by water on 25%, 50% and 100% of non-irrigated arable land in Brittany.

6.5.2 *Increasing tree cover in pasture land*

Figure 44 shows the effect of introducing trees on the C factor. The graph shows at the plot scale how the introduction of trees at 5% cover in pasture land reduced the C factor from 0.1 to 0.079 (a decrease by 21% in the C factor).

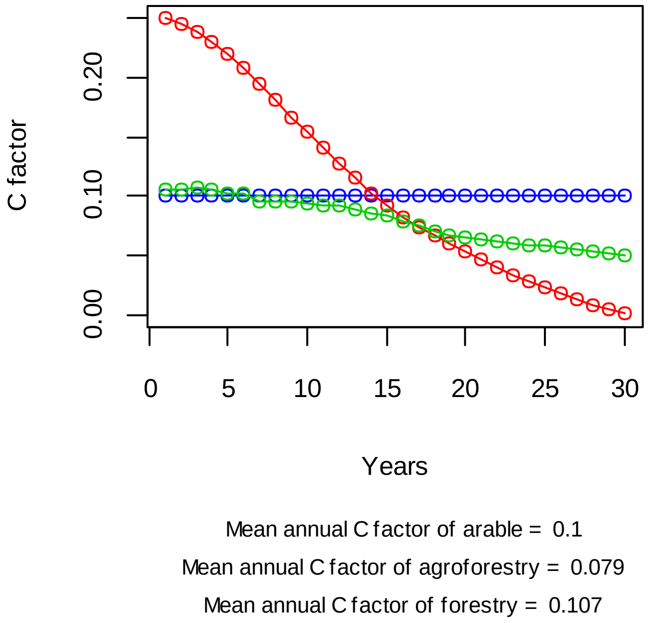


Figure 44. Modelled C factor of the RUSLE equation in pasture land, forestry (poplar plantation) and agroforestry (pasture with trees).

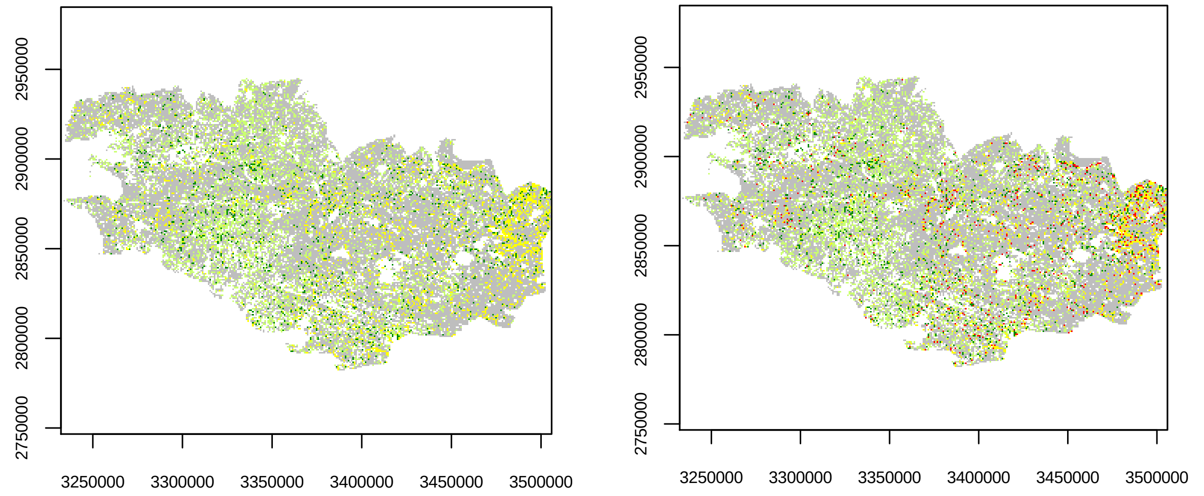
Four different scenarios were evaluated in pasture land in Brittany:

(1) Status quo (no changes applied)
(2) Increasing tree cover by 5% on 25% of treeless pasture land
(3) Increasing tree cover by 5% on 50% of treeless pasture land
(4) Increasing tree cover by 5% on 100% of treeless pasture land

Figure 45 shows the identified scenarios in pasture land in Brittany.

a) Status quo (no changes applied)

b) Increasing tree cover in 25% of treeless arable land



c) Increasing tree cover in 50% of treeless arable land

d) Increasing tree cover in 100% of treeless arable land

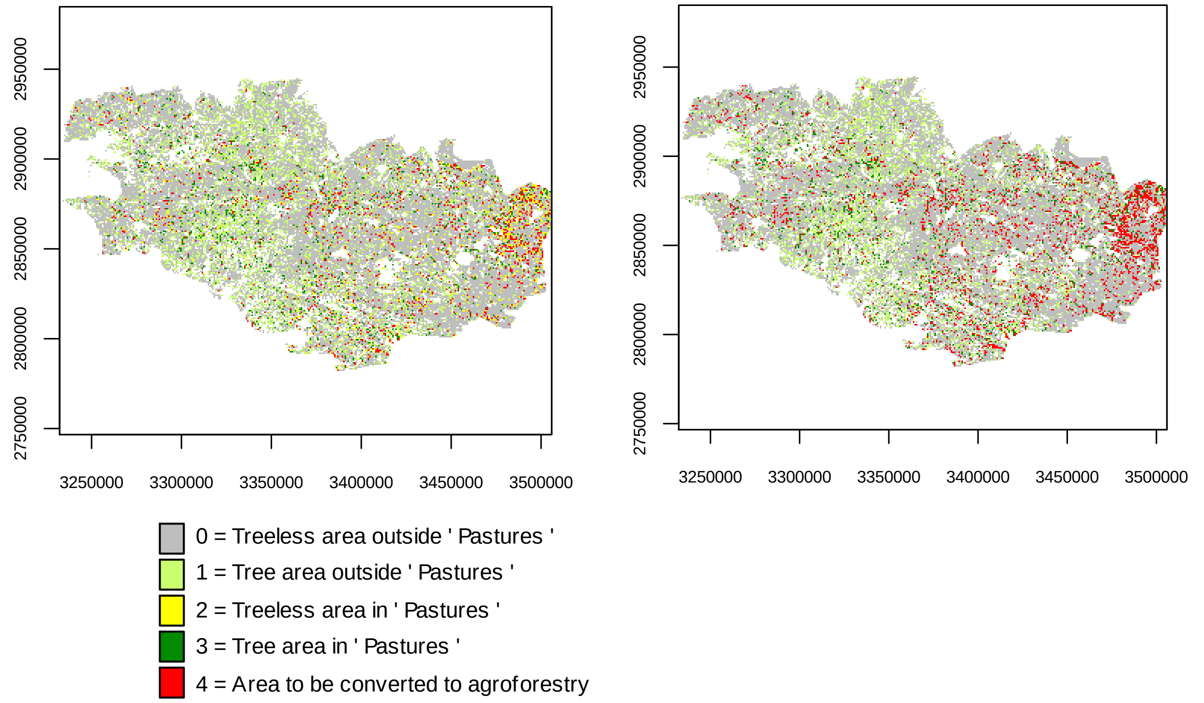


Figure 45. Scenarios identifying potential area in ‘Pastures’ to increase tree cover density.

Figure 46 shows the effect of a 5% increase in tree cover on reducing soil erosion losses at the regional level. In the current status quo scenario, mean annual soil erosion losses were 2.22 t ha^{-1} year^{-1}. The results show that soil erosion losses would be reduced by 0.3%, 0.6% and 1.1% in the scenarios of increasing tree cover in 25%, 50% and 100% of treeless pasture land, respectively.

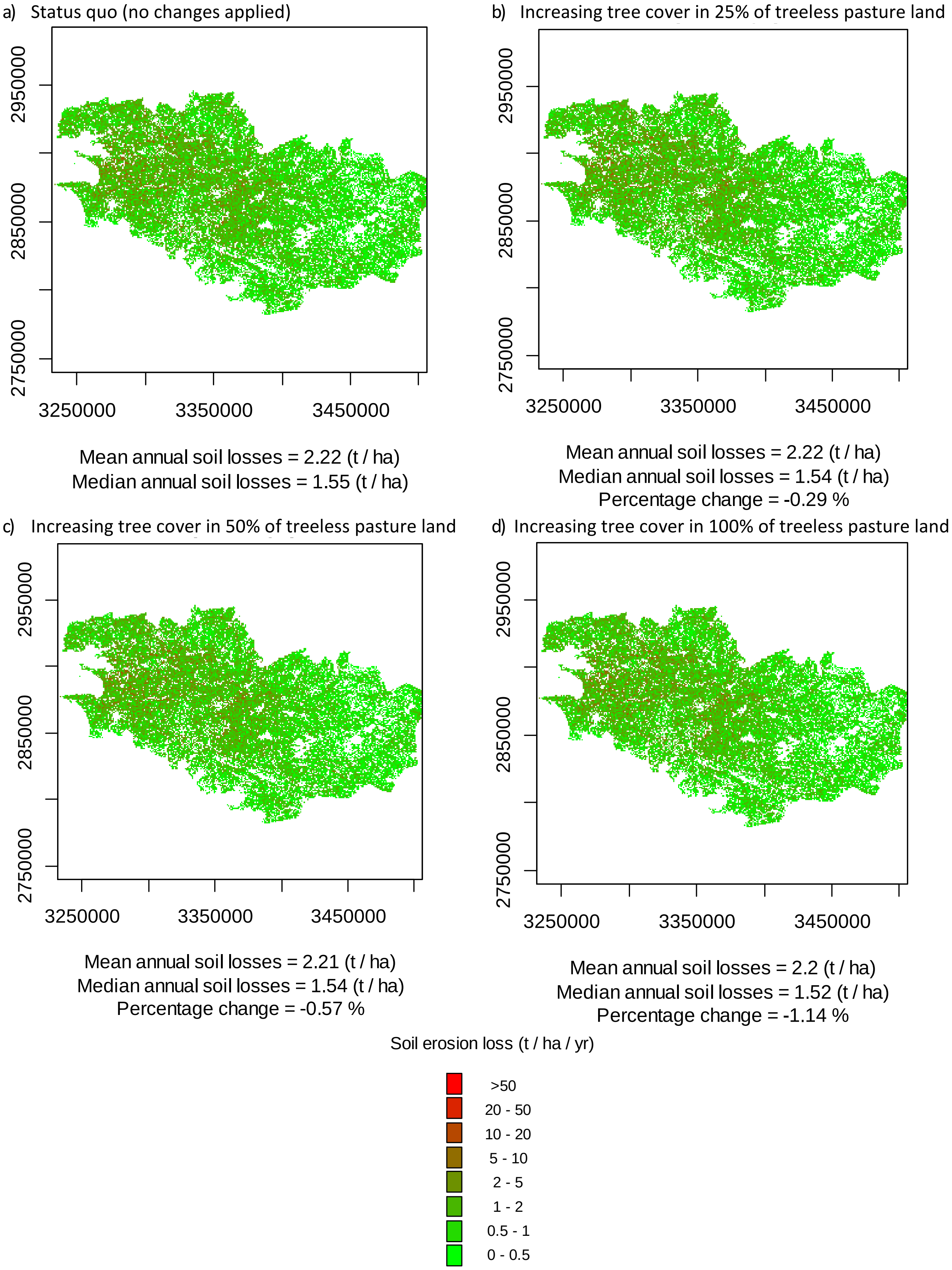


Figure 46. Scenarios showing the effect of increasing tree cover density by 5% on reducing soil erosion losses by water on 25%, 50% and 100% of pasture land in Brittany.

6.6 Estimating the economic effect at regional level

The last step in the methodology was to estimate the economic value of reducing soil erosion losses at the regional level. Thus the estimated soil erosion losses for Brittany were converted into monetary terms.

Since erosion costs could not be identified for Brittany, this study uses soil erosion costs developed for the UK by Graves et al. (2015). Based on Graves et al. (2015) the value of soil erosion losses was based on the annual off-site cost of dredging of water courses. Jacobs (2008) estimated an annual off-site cost of dredging water courses in England and Wales of €12.9 million with an agricultural apportionment of 95%, giving a total cost (adjusted to 2009 prices) of €12.2 million. As Anthony et al. (2009) reported a sediment load of 1.9 million t year^{-1} a unit cost of removal of around €6.41 t^{-1} sediment was estimated.

Table 15 shows the estimated costs of soil erosion losses in Brittany under the different scenarios. As shown, the costs saved by increasing tree cover in the evaluated scenarios in Brittany ranged from 104,000 € year^{-1} when only 25% of treeless pasture land was considered, to 3,538,000 € year^{-1} when 100% of treeless pasture and arable land was considered. The results also show that increasing tree cover density has a greater effect on arable land than on pasture land. This is likely to be because in Brittany the arable area is greater than the pasture area.

Table 15. Estimated saved costs by reducing soil erosion losses as a result of increasing tree cover in Brittany

	a) Status quo (no changes applied)	**b) Increasing tree cover on 25% of treeless land**	**c) Increasing tree cover on 50% of treeless land**	**d) Increasing tree cover on 100% of treeless land**
Increasing tree cover in arable land				
Soil erosion losses (million t soil year^{-1})	5.563	5.441	5.318	5.075
Estimated cost (million € year^{-1})	35.660	34.879	34.087	32.529
Relative reduction (%)	0.00	2.19	4.41	8.78
Saved costs (€ year^{-1})	0.000	781,000	1,573,000	3,131,000
Increasing tree cover in pasture land				
Soil erosion losses (million t soil year^{-1})	5.563	5.547	5.531	5.500
Estimated cost (million € year^{-1})	35.660	35.556	35.456	35.253
Relative reduction (%)	0.00	0.29	0.57	1.14
Saved costs (€ year^{-1})	0.000	104,000	204,000	407,000
Increasing tree cover in arable and pasture land				
Soil erosion losses (million t soil year^{-1})	5.563	5.425	5.286	5.011
Estimated cost (million € year^{-1})	35.660	34.775	33.884	32.122
Relative reduction (%)	0.00	2.48	4.98	9.92
Saved costs (€ year^{-1})	0.000	885,000	1,776,000	3,538,000

7 Conclusions

Financial analyses can quantify the benefits and costs of different land management practices from a farmer's perspective, but this does not necessarily reflect the full benefits and costs to society. Including environmental externalities in the assessment helps highlight the most appropriate land use decisions from a societal perspective.

This report presents results of the financial performance of arable, forestry and agroforestry systems in six case studies in Europe. It also presents some model improvements developed in Farm-SAFE in order to assess key environmental externalities from agricultural, forestry and agroforestry activities. More case studies and model improvements will continue to be being developed within the AGFORWARD project.

In the examples selected from the UK and Switzerland, including carbon sequestration and emission cost tended to reduce the value of conventional arable system relative to agroforestry and forestry. In the UK case study, a part from carbon sequestration and emission cost, the externalities of soil erosion loss by water, and nitrogen and phosphorous surplus were considered. When these externalities are considered in the economic assessment, the relative societal benefit of the agroforestry or forestry system in comparison with the arable system is enhanced. Thus it could be argued that to compensate for this increase in the provision of environmental services in comparison with the arable system, forestry and agroforestry farmers should receive some sort of transfer payments such as subsidies. These transfer payments would represent a redistribution of income that would help internalise the environmental externalities of land-use activities.

This report also presents Forage-SAFE, a bio-economic model that assesses the management and economics of wood pasture systems. The model quantified and compared on a daily time-step, the energy required by livestock and the energy provided by the wood pasture system. It was used to calculate how much additional forage would be needed to satisfy livestock demand, and this had economic impacts on the profitability of the system.

The results for the dehesa case study showed that trees provided revenue that outweighed their costs up to a certain density threshold. Excessive or sparse tree cover was found to lead to unnecessary farm costs and reduced profitability. The results showed that at 0% tree cover the annual pasture production was maximised. However, when pasture, browse and acorns were considered together, the maximum production of metabolisable energy was reached at a tree cover approximately 35%. In terms of profitability, the maximum net margin including unpaid labour was reached at approximately 18%. This estimate increased as the proportion of Iberian pigs was increased. The use of Forage-SAFE has shown that a daily time-step modelling approach based on livestock demand for metabolisable energy and pasture, browse, and acorn production can be used to quantify the buffering effects of trees on the strong seasonality of pasture growth in order to study the economic implications.

Finally, in the case study of Brittany, this report has shown an innovative approach of how plot and farm scale modelling outputs can be up-scaled to larger regional scales. The results show that increasing tree cover in treeless areas in pasture and arable land could provide significant economic benefits when externalities are evaluated at a regional level.

8 Acknowledgements

The AGFORWARD project (Grant Agreement N° 613520) is co-funded by the European Commission, Directorate General for Research & Innovation, within the 7th Framework Programme of RTD, Theme 2 - Biotechnologies, Agriculture & Food. The views and opinions expressed in this report are purely those of the writers and may not in any circumstances be regarded as stating an official position of the European Commission.

9 References

Agro Business Consultants (2013). The Agricultural Budgeting & Costing Book. 80th Edition. Melton Mowbray: Agro Business Consultants. Leicestershire, UK.

Ali I, Cawkwell F, Dwyer E, Barrett B, Green S (2016). Satellite remote sensing of grasslands: from observation to management—a review. Journal of Plant Ecology 9 (6), 649-671.

Anthony S, Duethman D, Gooday R, Harris D, Newell-Price P, Chadwick D, Misselbrook T, (2009) Quantitative Assessment of Scenarios for Managing Trade-Off between the Economic Performance of Agriculture and the Environment and Between Different Environmental Media. Final Report, Defra Project WQ0106 (Module 6), 95 pp.

Barnes P, Wilson BR, Trotter MG, Lamb DW, Reid N, Koen T, Bayerlein L (2011). The patterns of grazed pasture associated with scattered trees across an Australian temperate landscape: an investigation of pasture quantity and quality. The Rangeland Journal 33, 121-130.

Bergmeier E, Petermann J, Schröder E (2010) Geobotanical survey of wood-pasture habitats in Europe: diversity, threats and conservation. Biodiversity and Conservation 19 (11): 2995–3014

Boardman AE, Greenberg DH, Vining AR, Weimer DL (2011). Cost- Benefit Analysis: Concepts and Practice. Fourth Edition. Upper Saddle River, NJ. Pearson Education.

Burgess PJ, Crous-Duran J, den Herder M, Dupraz C, Fagerholm N, Freese D, Garnett K, Graves AR, Hermansen JE, Liagre F, Mirck J, Moreno G, Mosquera-Losada MR, Palma JHN, Pantera A, Plieninger T, Upson M (2015). AGFORWARD Project Periodic Report: January to December 2014. Cranfield University: AGFORWARD. 95 pp.

Burgess PJ, Morris J (2009). Agricultural technology and land use futures. Land Use Policy 26S: S222-S229.

Burgess PJ, Incoll LD, Corry DT, Beaton A, Hart BJ (2005). Poplar growth and crop yields within a silvoarable agroforestry system at three lowland sites in England. Agroforestry Systems 63(2): 157-169.

Camargo GGT, Ryan MR, Richard TL (2013). Energy Use and Greenhouse Gas Emissions from Crop Production Using the Farm Energy Analysis Tool. BioScience 63:263–273.

Campos P, Caparrós A, Beguería S, Carranza J, Díaz-Balteiro L, Díaz M, Ovando P (2014). RECAMAN: Manufactured and environmental total incomes of Andalusian forest. CSIC, Madrid, Spain.

Daza A (1999). Producción de vacuno de carne en la dehesa. Bovis, 87.

DECC (2009). Carbon Valuation in UK Policy Appraisal: A Revised Approach, pp 1–128.

DECC (2012). Updated short-term traded carbon values used for UK public policy appraisal, pp 1–8.

Dupraz C, Burgess P, Gavaland A, Graves A, Herzog F, Incoll LD, Jackson N, Keesman K, Lawson G, Lecomte I, Liagre F, Mantzanas K, Mayus M, Moreno G, Palma J, Papanastasis V, Paris P, Pilbeam DJ, Reisner Y, van Noordwijk M, Vincent G, van der Werf W (2005). SAFE final report- Synthesis of the Silvoarable Agroforestry For Europe project. INRA-UMR System Editions, European Union.

Dupraz C, Vincent G, Lecomte I, Bussière F, Sinoquet H (2004). Above-ground modules in Hi-SAFE (Tree phenology, tree C allocation, tree light interception, microclimate). Deliverable D.4.1 in Silvoarable Agroforestry For Europe (SAFE). European Research contract QLK5-CT-2001-00560).

EMEP (2003). Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe. Available at: www.emep.int. Accessed in January 2017.

Escribano M, Rodríguez de Ledesma A, Mesías FJ, Pulido F (2002). Stocking rate levels in dehesa systems of Extremadura (south-west of Spain). Arch. Zootec. 51: 315-326.

EU (2013). Regulation (EU) No 1305/2013 of the European parliament and of the council of 17 December 2013 on support for rural development by the European Agricultural Fund for Rural Development (EAFRD). Available at: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2013:347:0487:0548:en:PDF

EU (2013). Regulation (EU) No 1306/2013 of the European Parliament and of the Council of 17 December 2013 on the financing, management and monitoring of the common agricultural policy and repealing Council Regulations (EEC) No 352/78, (EC) No 165/94, (EC) No 2799/98, (EC) No 814/2000, (EC) No 1290/2005 and (EC) No 485/2008 (OJ L 347 of 20.12.2013, p. 1.).

Fagerholm N, Oteros-Rozas E, Raymond CM, Torralba M, Moreno G, Plieninger T (2016). Assessing linkages between ecosystem services, land-use and well-being in an agroforestry landscape using public participation GIS. Applied Geography, 74, 30-46.

Farber SC, Costanza R, Wilson MA (2002). Economic and ecological concepts for valuing ecosystem services. Ecological Economics 41:375–392.

Feldwisch N, Frede H, Hecker F, (1998). Verfahren zum Abschätzen der Erosions und Auswaschungsgefahr. In: Frede, H, Dabbert, S. (Eds.), Handbuch zum Gewässerschutz in der Landwirtschaft. Ecomed, Landsberg, pp 22–57.

Gea-Izquierdo G, Montero G, Canellas I (2009). Changes in limiting resources determine spatio-temporal variability in tree–grass interactions. Agroforestry Systems, 76(2), 375-387.

Gifford R (2000a). Carbon Content of Woody Roots: Revised Analysis and a Comparison with Woody Shoot Components. National Carbon Accounting System Technical Report No. 7 (Revision 1), Australian Greenhouse Office, Canberra, 10 pp.

Gifford R (2000b). Carbon Contents of Above-Ground Tissues of Forest and Woodland Trees, National Carbon Accounting System. Technical Report No. 22, Australian Greenhouse Office, Canberra, 24 pp.

Gomez-Limon J, Lucio Fernandez JV (1999). Changes in use and landscape preferences on agricultural-livestock landscapes of the central Iberian Peninsula, Madrid, Spain. Landscape Urban Plan 44:165–175.

Graves AR, Burgess PJ, Liagre F, Terreaux J-P, Borrel T, Dupraz C, Palma J, Herzog F (2011). Farm-SAFE: the process of developing a plot- and farmscale model of arable, forestry, and silvoarable economics. Agroforestry Systems 81: 93–108.

Graves AR, Burgess PJ, Palma JHN, Herzog F, Moreno G, Bertomeu M, Dupraz C, Liagre F, Keesman K, van der Werf W, de Nooy AK, van den Briel JP (2007). Development and application of bioeconomic modelling to compare silvoarable, arable, and forestry systems in three European countries. Ecological Engineering 29(4): 434–449.

Graves AR, Morris J, Deeks L, Rickson J, Kibblewhite M, Harris J, Fairwell T, Truckle I (2015). The cost of soil degradation in England and Wales. Ecological Economics 119: 399–413.

Hanson JD, Baker BB, Bourdon RM, (1994). Documentation and users guide for SPUR2. GPSR Technical Report No. 1. USDA Agricultural Research Service, Great Plains Systems Research Unit, Ft. Collins, CO.

Harmand JM, Njiti C, Bernhard-Reversat F, Olivier R, Feller C (2004). Changes in below ground carbon stocks during rotation “Tree improved fallow—Crops” in the dry tropics of Cameroon. In: Proceedings of the First World Congress of Agroforestry—Book of Abstracts. University of Florida, Institute of Food and Agricultural Sciences, Orlando, pp 1-182.

Hernández Díaz-Ambrona C, Etienne A, Martínez Valderrama J (2008). Producciones potenciales de herbáceas, de bellota y carga ganadera en las dehesas de Extremadura. Pastos, 38 (2), 243 – 258.

Herzog TR, Herbert EJ, Kaplan R, Crooks CL (2000). Cultural and developmental comparisons of landscape perceptions and preferences. Environ Behav 32:323–346.

HM Treasury (2003). The Green Book: Appraisal and Evaluation in Central Government. London: TSO. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/220541/green_book_complete.pdf

Hodgson JG (1990). Grazing management: Science into Practice. Wiley.

Howlett DS, Moreno G, Mosquera-Losada MR, Nair PKR, Nair VD (2011). Soil carbon storage as influenced by tree cover in the Dehesa cork oak silvopasture of central-western Spain. Journal of Environmental Monitoring, 13: 1897–1904.

Iglesias E, Báez K, Diaz-Ambrona CH (2016). Assessing drought risk in Mediterranean Dehesa grazing lands. Agricultural Systems 149, 65-74.

IPCC (1996). Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual.

JACOBS (2008). Environmental accounts for agriculture. Defra Project SFS0601Final report. JACOBS UK Ltd.

John Nix Farm Management Pocketbook (2014). John Nix Farm Management Pocketbook. 44th Edition. Melton Mowbray: Agro Business Consultants. Leicestershire, UK.

Johnston RJ, Rolfe J, Rosenberger RS, Brouwer R (2015). Introduction to Benefit Transfer Methods. In: Johnston, R.J, Rolfe, J, Randall, S, Rosenberger, R.S. Brouwer, R. Benefit Transfer of Environmental and Resource Values. A Guide for Researchers and Practitioners. Springer Science+Business Media Dordrecht, pp 1-582.

Kaplan R, Talbot JF (1988). Ethnicity and preference for natural settings: a review and recent findings. Landscape Urban Plan 15: 107–117.

Kaske KJ (2015). Development of an integrated economic model for the assessment of the environmental burden of arable, forestry and silvoarable systems. Master Thesis. School of Energy, Environment and Agrifood, Cranfield University, UK.

Lehman J, Gaunt J (2004). Carbon sequestration in soils under agroforestry. In: Proceedings of the First World Congress of Agroforestry—Book of Abstracts. University of Florida, Institute of Food and Agricultural Sciences, Orlando, pp 1-190.

Liagre F (1997). ARBUSTRA Manuel de l’utilisateur. User manual for ARBUSTRA, Centre Régional de la Propriété Forestiere (CRPF) and l’Institut National de la recherché Agronomique (INRA) Montpellier, France, pp 1-71.

López-Díaz ML, Rolo V, Benítez R, Moreno G (2015). Shrub encroachment of Iberian dehesas: implications on total forage productivity. Agroforestry Systems, 89(4), 587-598.

Manning AD, Fischer J, Lindenmayer DB (2006). Scattered trees are keystone structures – Implications for conservation. Biological Conservation 132(3), 311–321.

MAPA (2008). Ministerio de Agricultura, Pesca y Alimentación. Diagnóstico de las Dehesas Ibéricas Mediterráneas. Tragsatec.

Marañón T, Bartolome JW (1994). Coast live oak (*Quercus agrifolia*) effects on grassland biomass and diversity. Madroño 41, 39–52.

Mazía N, Moyano J, Perez L, Aguiar S, Garibaldi LA, Schlichter T (2016). The sign and magnitude of tree–grass interaction along a global environmental gradient. Global Ecology and Biogeography, 25(12), 1510-1519.

Montoya JM (1989). Encinas y encinares. Mundiprensa. Madrid. 131 pp.

Moreno Marcos G, Obrador JJ, Garcia E, Cubera E, Montero MJ, Pulido F, Dupraz C (2007). Driving competitive and facilitative interactions in oak dehesas through management practices. Agroforest Systems 70, 25-40.

Moreno G, Pulido FJ (2009). The functioning, management and persistence of dehesas. In Agroforestry in Europe (pp. 127-160). Springer Netherlands.

Moreno G, Bartolome JW, Gea-Izquierdo G, Cañellas I (2013). Overstory–Understory Relationships. In Mediterranean Oak Woodland Working Landscapes (pp. 145-179). Springer Netherlands.

Moreno G, Gonzalez-Bornay G, Pulido F, Lopez-Diaz ML, Bertomeu M, Juárez E, Diaz M (2016). Exploring the causes of high biodiversity of Iberian dehesas: the importance of wood pastures and marginal habitats. Agroforestry Systems, 90(1), 87-105.

Moreno G, Obrador JJ, Garcia A (2007). Impact of evergreen oaks on soil fertility and crop production in intercropped dehesas. Agriculture, Ecosystems and Environment 119, 270–280.

Nair PKR (2011). Methodological Challenges in Estimating Carbon Sequestration Potential of Agroforestry Systems. In Kumar, B. M. and Nair, P. K. R. (eds.) Carbon Sequestration Potential of Agroforestry Systems: Opportunities and Challenges. Heidelberg: Springer, pp 3–16.

Noy-Meir I, Harpaz Y (1977). Agro-ecosystems in Israel. In: Harper J, Gruys P (Eds.), Agro-Ecosystems, vol. 4. Elsevier Scientific Publishing, Amsterdam, pp 143–167.

OFWAT (2005). Water Framework Directive - Economic Analysis of Water Industry Costs. Final Report. Water Services Regulation Authority. Oxford.

Olea L, Paredes J, Verdasco MAP (1990). Características y producción de los pastos de las dehesas del S. O. de la Península Ibérica. Pastos 20-21, 131-156.

Olea L, San Miguel-Ayanz A (2006). The Spanish dehesa. A traditional Mediterranean silvopastoral system linking production and nature conservation. Grassland Science in Europe 11, 3-13.

Ovando P, Campos P, Oviedo JL, Caparrós A (2015). Private and public incomes in dehesas and coniferous forests in Andalusia, Spain. In: Standiford, Richard B.; Purcell, Kathryn L., tech. cords. Proceedings of the seventh California oak symposium: managing oak woodlands in a dynamic world. Gen. Tech. Rep. PSW-GTR-251. Berkeley, CA, U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station: 241-250.

Ovington JD, Madgwick HAI (1958). The sodium, potassium and phosphorus contents of tree species grown in close stands. New Phytologist. Version of record online 2 May 2006 57(3). DOI: 10.1111/j.1469-8137.1958.tb05316.x,

OXERA (2006). What is the cost of reducing ammonia, nitrates and BOD in sewage treatment works effluent? Prepared for Ofwat. Oxford. Available at: http://www.ofwat.gov.uk/wp-content/uploads/2015/11/rpt_com_oxera080107.pdf

Palma JHN (2015). CliPick: Project Database of Pan-European Climate Data for Default Model Use. Milestone Report 26 (6.1) for EU FP7 Research Project: AGFORWARD 613520. 10 October 2015. 22 pp. http://www.agforward.eu/index.php/en/clipick-project-database-of-pan-european-simulated-climate-data-for-default-model-use.html

Palma JHN, Graves AR, Bunce RGH, Burgess PJ, de Filippi R, Keesman KJ, van Keulen H, Liagre F, Mayus M, Moreno G, Reisner Y, Herzog F (2007). Modeling environmental benefits of silvoarable agroforestry in Europe. Agriculture, Ecosystems & Environment 119(3-4): 320–334.

Palma JHN, Oliveira T, Crous-Duran J, Graves AR, Garcia de Jalon S, Upson M, Giannitsopoulos M, Burgess PJ, Paulo JA, Tomé M, Ferreiro-Dominguéz N, Mosquera-Losada MR, Gonzalez-Hernández P, Kay S, Mirk J, Kanzler M, Smith J, Moreno G, Pantera A, Mantovani D, Rosati A, Luske B, Hermansen J (2017). Deliverable 6.17 (6.2): Modelled agroforestry outputs at field and farm scale to support biophysical and environmental assessments. AGFORWARD project. 18 October 2017. 162 pp.

Panagos P, Ballabio C, Borrelli P, Meusburger K, Klik A, Rousseva S, Tadic MP, Michaelides S, Hrabalíková M, Olsen P, Aalto J, Lakatos M, Rymszewicz A, Dumitrescu A, Beguería S, Alewell C (2015a). Rainfall erosivity in Europe. Science of Total Environment 511:801-814. DOI: 10.1016/j.scitotenv.2015.01.008

Panagos P, Borrelli P, Meusburger C, Alewell C, Lugato E, Montanarella L (2015b). Estimating the soil erosion cover-management factor at European scale. Land Use Policy 48, 38-50.

Panagos P, Borrelli P, Meusburger K (2015c). A New European Slope Length and Steepness Factor (LS-Factor) for Modeling Soil Erosion by Water. Geosciences 5, 117-126.

Panagos P, Borrelli P, Meusburger K, van der Zanden EH, Poesen J, Alewell C (2015d). Modelling the effect of support practices (P-factor) on the reduction of soil erosion by water at European Scale. Environmental Science & Policy 51, 23-34.

Panagos P, Meusburger K, Ballabio C, Borrelli P, Alewell C (2014). Soil erodibility in Europe: A high-resolution dataset based on LUCAS. Science of Total Environment 479–480, 189–200.

Pardini A, Mori S, Rigueiro-Rodríguez A, Mosquera-Losada MR (2010). Efecto del arbolado en la producción de pasto y trigo (*Triticum aestivum* L.) ecológicos en la maremma Toscana (Italia central). Pastos 40(2), 211-223.

Pérez-Corona ME, Vázquez de Aldana BR, Garcia Criado B, García Ciudad A (1998). Variations in nutritional quality and biomass production of semiarid grasslands. J. Range Manage. 51, 570-576.

Plieninger T, Hartel T, Martín-López B, Beaufoy G, Bergmeier E, Kirby K, Montero MJ, Moreno G, Oteros-Rozas E Van Uytvanck J (2015). Wood-pastures of Europe: Geographic coverage, social–ecological values, conservation management, and policy implications. Biological Conservation 190, 70–79.

Rhoades CC (1997). Single-tree influences on soil properties in agroforestry: lessons from natural forest and savanna ecosystems. Agroforestry Systems 35, 71–94.

Rigueiro-Rodríguez A, Rois-Díaz M, Mosquera-Losada MR (2010). Integrating silvopastoralism and biodiversity conservation. In Biodiversity, Biofuels, Agroforestry and Conservation Agriculture. Springer Netherlands 359-373.

Rivest D, Paquette A, Moreno G, Messier C (2013). A meta-analysis reveals mostly neutral influence of scattered trees on pasture yield along with some contrasted effects depending on functional groups and rainfall conditions. Agriculture, Ecosystems & Environment 165, 74-79.

Rodríguez-Estévez V, García A, Gómez-Castro AG (2009). Intrinsic factors of acorns that influence the efficiency of their consumption by Iberian pigs. Livestock Science 122(2), 281-285.

Rodríguez-Estévez V, García A, Perea J, Mata C, Gómez AG (2007). Acorn production at the dehesa: influential factors. Arch. Zootec. 56 (R), 25-43.

San Miguel A (1994). La Dehesa Española. Origen, tipología, características y gestión. Fundación Conde del Valle de Salazar. Escuela Técnica Superior de Ingenieros de Montes. Madrid.

Sandaña P, Pinochet D (2014). Grain yield and phosphorus use efficiency of wheat and pea in a high yielding environment. Journal of Soil Science and Plant Nutrition 14 (4), 973-986.

Silva-Pando FJ, González-Hernández MP, Rozados-Lorenzo MJ (2002). Pasture production in a silvopastoral system in relation with microclimate variables in the Atlantic coast of Spain. Agroforestry Systems 56, 203–211.

Sing L, Ray D, Watts K (2015). Ecosystem services and forest management. Research Note. UK Forestry Commission. Available at: http://www.forestry.gov.uk/pdf/FCRN020.pdf/$FILE/FCRN020.pdf

Thomas TH (1991). A spreadsheet approach to the economic modelling of agroforestry systems. Forest Ecology and Management 45, 207-235.

Tipping E, Benham S, Boyle JF, Crow P, Davies J, Fischer U, Guyatt H, Helliwell R, Jackson-Blake L, Lawlor AJ, Monteith DT, Roweg EC, Toberman H (2014). Atmospheric deposition of phosphorus to land and freshwater. Environmental Science: Processes and Impacts 16, 1608-1617.

Tscharntke T, Klein AM, Kruess A, lfSteffan-Dewenter I, Thies C (2005). Landscape perspectives on agricultural intensification and biodiversity - Ecosystem service management. Ecology Letters 8(8), 857–874.

UK Forestry Commission (2015). UK Woodland Carbon Code. Available at: www.forestry.gov.uk/carboncode

van der Werf W, Keesman K, Burgess P, Graves A, Pilbeam D, Incoll LD, Metselaar K, Mayus M, Stappers R, van Keulen H, Palma J, Dupraz C (2007). 'Yield-SAFE: A parameter-sparse, process-based dynamic model for predicting resource capture, growth, and production in agroforestry systems'. Ecological Engineering 29(4), 419–433.

van Keulen H, Aarts H, Habekotte B, van der Meer H, Spiertz J (2000). Soil–plant–animal relations in nutrient cycling: the case of dairy farming system 'De Marke'. Eur J Agron 13 (2/3), 245–261.

van Noordwijk M, Lusiana B (1999). WaNuLCAS, a Model of Water, Nutrient and Light Capture in Agroforestry Systems. Agroforestry Systems 43, 217-242.

Vlek P, Fillery I, Burford J (1981). Accession, transformation, and loss of nitrogen in soils of the arid region. Plant Soil 58, 133–175.

Wild A (1993). Soils and the Environment: An Introduction. Cambridge University Press, Cambridge.

Williams AG, Audsley E, Sandars DL (2010). Environmental burdens of producing bread wheat, oilseed rape and potatoes in England and Wales using simulation and system modelling. International Journal of Life Cycle Assessment 15(8), 855–868.

Young A, Menz K, Muraya P, Smith C (1998). SCUAF Version 4: a model to estimate soil changes under agriculture, agroforestry and forestry. ACIAR Technical Report Series no. 41, ACIAR, Canberra, Australia, pp 1-49.

10 Appendix

10.1 Arable data

Table A.1. Arable financial data in Bedfordshire, UK

D1. Metadata	Country and region Crop name	None	Bedfordshire UK Wheat	Bedfordshire UK Wheat	Bedfordshire UK Barley	Bedfordshire UK Oilseed	Bedfordshire UK Fallow
D2. Revenue	Grain price	(€/t)	173.6111	173.6111	159.7222	361.1111	0
	By-product 1	(€/t)	37.5	37.5	55	0	0
	Area payment	(€/ha)	235.2	235.2	235.2	235.2	235.2
D3. Variable costs	Seed price	(€/kg)	0.444444	0.638889	0.472222	10.11111	0
	Seed rate	(kg/ha)	150	170	155	5	0
	Fertiliser price	(€/kg N)	1.138889	1.138889	1.138889	1.138889	0
		(€/kg P)	0.902778	0.902778	0.902778	0.902778	0
		(€/kg K)	0.625	0.625	0.625	0.625	0
		(€/kg Manure)	0	0	0	0	0
		(€/kg Limestone)	0	0	0	0	0
	Fertiliser rate	(kg N/ha)	175	195	145	200	0
		(kg P/ha)	60	65	55	55	0
		(kg K/ha)	90	105	80	45	0
		(€/kg Manure)	0	0	0	0	0
		(kg Limestone/ha)	0	0	0	0	0
	Spray price	(€/application)	298.6111	326.3889	222.2222	277.7778	0
	Spray rate	(app/ha)	1	1	1	1	0
	Other price	(€/unit)	0	0	0	0	0
	Other rate	(units/ha)	0	0	0	0	0
	Aggregate variable cost if no breakdown	(€/ha)	0	0	0	0	20
	Total variable costs	(€/ha)	675	781.3889	560.2083	633.8889	20
D3. Fixed costs	Fuel and repairs	(€/ha)	78.9412	78.9412	78.9412	78.9412	78.9412
	Machinery	(€/ha)	0	0	0	0	0
	Interests on working capital	(€/ha)	0	0	0	0	0
	General costs	(€/ha)	0	0	0	0	0
	Installation costs	(€/ha)	0	0	0	0	0
	Rent	(€/ha)	0	0	0	0	0
	Other 1	(€/ha)	0	0	0	0	0
	Other 2	(€/ha)	34.72222	30.55556	27.77778	25	0
	Labour -Cultivation	(hr/ha)	2.58419	2.58419	2.58419	2.58419	4.356899
	Labour -Spraying	(hr/ha)	0.136503	0.136503	0.136503	0.136503	0
	Labour -Fertilizing	(hr/ha)	0.136503	0.136503	0.136503	0.136503	0
	Labour - Harvesting	(hr/ha)	1.805317	1.805317	1.805317	1.805317	0
	Labour - Straw baling	(hr/ha)	0.555369	0.555369	0.555369	0.555369	0
	Labour input farm operations	(hr/ha)	0	0	0	0	0
	Labour Yield dependant	(h/t)	0.5706	0.5706	0.5706	0.5706	0
	Labour Straw dependant	(h/t)	0.190476	0.190476	0.190476	0.190476	0
	Total Labour Time	(hr/ha)	5.978958	5.978958	5.978958	5.978958	4.356899
	Labour cost farm operations	(€/h)	14.6	14.6	14.6	14.6	14.6
	Labour cost expert	(€/h)	0	0	0	0	0
	Labour cost other	(€/h)	0	0	0	0	0
	Total Labour Cost	Total (€/ha)	37.72917	37.72917	37.72917	37.72917	63.61073
	Aggregate fixed cost if no breakdown (excluding labour)	(€/ha)	444.4444	444.4444	444.4444	444.4444	0
	Total fixed costs (excluding labour)	(€/ha)	444.4444	444.4444	444.4444	444.4444	78.9412
	Net margin (no production)	(€/ha)	-884.244	-990.633	-769.453	-843.133	136.2588

Table A.2. Arable financial data in Schwarzbubenland and Zurich, Switzerland

Country and region	None	Switzerland	Switzerland	Switzerland	Zurich Switzerland	Zurich Switzerland	Zurich Switzerand	Zurich Switzerland	Zurich Switzerland
Crop name		Establishment grass	Maintenance grass - Harvest	Maintenance grass - No Harvest	Fallow	Wheat	Oilseed	Grassland-ext	Grassland
Grain price	(€/t)	52.9	52.9	52.9	0	590	800	0	354.1667
By-product 1	(€/t)	0	0	0	0	116	0	0	0
Area payment	(€/ha)	372.6	372.6	372.6	1040	1804	3201	1040	1040
Seed price	(€/kg)	10.58	0	0	0	0	0	0	0
Seed rate	(kg/ha)	32.5	0	0	0	0	0	0	0
Fertiliser price	(€/kg N)	0	0	0	0	0	0	0	0
	(€/kg P)	0	0	0	0	0	0	0	0
	(€/kg K)	0	0	0	0	0	0	0	0
	(€/kg Manure)	0	0	0	0	0	0	0	0
	(€/kg Limestone)	0	0	0	0	0	0	0	0
Fertiliser rate	(kg N/ha)	0	0	0	0	175	200	0	0
	(kg P/ha)	0	0	0	0	60	55	0	0
	(kg K/ha)	0	0	0	0	90	45	0	0
	(€/kg Manure)	36000	36000	36000	0	0	0	0	0
	(kg Limestone/ha)	0	0	0	0	0	0	0	0
Spray price	(€/application)	0	0	0	0	298.6111	277.7778	0	0
Spray rate	(app/ha)	0	0	0	0	1	1	0	0
Other price	(€/unit)	0	0	0	0	0	0	0	0
Other rate	(units/ha)	0	0	0	0	0	0	0	0
Aggregate variable cost if no breakdown	(€/ha)	0	0	0	0	1182	1462	0	0
Total variable costs	(€/ha)	343.85	0	0	0	1182	1462	0	0
Fuel and repairs	(€/ha)	0	0	0	125	1591	1366	371.4286	2677.815
Machinery	(€/ha)	0	0	0	0	0	0	0	0
Interests on working capital	(€/ha)	0	0	0	0	0	0	0	0
General costs	(€/ha)	0	0	0	0	0	0	0	0
Installation costs	(€/ha)	0	0	0	0	0	0	0	0
Rent	(€/ha)	0	0	0	0	0	0	0	0
Other 1	(€/ha)	116.012	116.012	29.44	718	718	718	718	718
Other 2	(€/ha)	143.52	143.52	143.52	795	791	784	795	795
Labour -Cultivation	(hr/ha)	5.170372	2.688982	0.204364	2.313263	2.58419	2.58419	2.58419	2.917523
Labour -Spraying	(hr/ha)	0	0	0	0	0.136503	0.136503	0.136503	0.136503

Labour -Fertilizing	(hr/ha)	0.13437	0.13437	0	0	0.136503	0.136503	0.136503	0.136503
Labour - Harvesting	(hr/ha)	0	1.805317	0	0	1.805317	1.805317	1.805317	1.805317
Labour - Straw baling	(hr/ha)	0	0	0	0	0.555369	0.555369	0.555369	0.555369
Labour input farm operations	(hr/ha)	0	0	0	0	0	0	0	0
Labour Yield dependant	(h/t)	0	0.5706	0	0	0.5706	0.5706	0.5706	0.5706
Labour Straw dependant	(h/t)	0	0	0	0	0.190476	0.190476	0.190476	0.190476
Total Labour Time	(hr/ha)	5.304743	5.199269	0.204364	1.19	34	29	14.29	22.26
Labour cost farm operations	(€/h)	25.76	25.76	25.76	25.76	25.76	25.76	25.76	25.76
Labour cost expert	(€/h)	25.76	25.76	25.76	0	0	0	0	0
Labour cost other	(€/h)	25.76	25.76	25.76	0	0	0	0	0
Total Labour Cost	Total (€/ha)	133.1888	83.96683	5.264407	59.58966	66.56873	66.56873	66.56873	75.1554
Aggregate fixed cost if no breakdown (excluding labour)	(€/ha)	0	0	0	0	0	0	0	0
Total fixed costs (excluding labour)	(€/ha)	259.532	259.532	172.96	1638	3100	2868	1884.429	4190.815
Net margin (no production)	(€/ha)	-230.782	113.068	199.64	-598	-2478	-1129	-844.429	-3150.82

Table A.3. Arable financial data in Neu Sacro, Germany

	Country and region	None	Neu Sacro Germany arable	Neu Sacro Germany arable	Neu Sacro Germany agroforestry	Neu Sacro Germany agroforestry
	Crop name		Sugar beet	Wheat	Sugar beet	Wheat
D2. Revenue	Grain price	(€/t)	38.5	260	38.5	260
	By-product 1	(€/t)	0	0	0	0
	Area payment	(€/ha)	160	160	142.4	142.4
D3. Variable costs	Seed price	(€/kg)	208	0.55	208	0.55
	Seed rate	(kg/ha)	1	110	1	110
	Fertiliser price	(€/kg N)	1.34	1.34	1.34	1.34
		(€/kg P)	1.1	1.1	1.1	1.1
		(€/kg K)	0.94	0.94	0.94	0.94
		(€/kg Manure)	0	0	0	0
		(€/kg Limestone)	0.0535	0.0535	0.0535	0.0535
	Fertiliser rate	(kg N/ha)	67.5	114	67.5	114
		(kg P/ha)	80	65	80	65
		(kg K/ha)	160	115	160	115
		(€/kg Manure)	0	0	0	0
		(kg Limestone/ha)	700	400	700	400
	Spray price	(€/application)	227.25	312.5	227.25	312.5
	Spray rate	(app/ha)	1	1	1	1
	Other price	(€/unit)	0	0	0	0
	Other rate	(units/ha)	0	0	0	0
	Aggregate variable cost if no breakdown	(€/ha)	0	0	0	0
	Total variable costs	(€/ha)	801.55	726.76	801.55	726.76
D3. Fixed costs	Fuel and repairs	(€/ha)	30	30	30	30
	Machinery	(€/ha)	430	163	430	163
	Interests on working capital	(€/ha)	75	75	75	75
	General costs	(€/ha)	0	0	0	0
	Installation costs	(€/ha)	0	0	0	0
	Rent	(€/ha)	350	350	350	350
	Other 1	(€/ha)	0	20	0	20
	Other 2	(€/ha)	0	0	0	0
	Labour -Cultivation	(hr/ha)	2.741192	2.741192	2.741192	2.741192
	Labour -Spraying	(hr/ha)	0.136503	0.136503	0.136503	0.136503
	Labour -Fertilizing	(hr/ha)	0.136503	0.136503	0.136503	0.136503
	Labour - Harvesting	(hr/ha)	7	1.805317	7	1.805317
	Labour - Straw baling	(hr/ha)	0	0	0	0
	Labour input farm operations	(hr/ha)	0	0	0	0
	Labour Yield dependant	(h/t)	0	0.5706	0	0.59913
	Labour Straw dependant	(h/t)	0	0	0	0
	Total Labour Time	(hr/ha)	10.0142	5.390116	10.51491	5.689578
	Labour cost farm operations	(€/h)	17.5	17.5	17.5	17.5
	Labour cost expert	(€/h)	0	0	0	0
	Labour cost other	(€/h)	0	0	0	0
	Total Labour Cost	Total (€/ha)	47.97086	47.97086	47.97086	47.97086
	Aggregate fixed cost if no breakdown (excluding labour)	(€/ha)	0	0	0	0
	Total fixed costs (excluding labour)	(€/ha)	885	638	885	638
	Net margin (no production)	(€/ha)	-1526.55	-1204.76	-1544.15	-1222.36

Table A.4. Arable financial data in Cambridgeshire, UK

	Country and region	None	Cambridgeshire UK organic
	Crop name		Wheat
D2. Revenue	Grain price	(€/t)	226
	By-product 1	(€/t)	0
	Area payment	(€/ha)	185.6731
D3. Variable costs	Seed price	(€/kg)	0.513636
	Seed rate	(kg/ha)	220
	Fertiliser price	(€/kg N)	0
		(€/kg P)	0
		(€/kg K)	0
		(€/kg Manure)	26
		(€/kg Limestone)	0
	Fertiliser rate	(kg N/ha)	0
		(kg P/ha)	0
		(kg K/ha)	0
		(€/kg Manure)	1
		(kg Limestone/ha)	0
	Spray price	(€/application)	163
	Spray rate	(app/ha)	1
	Other price	(€/unit)	0
	Other rate	(units/ha)	0
	Aggregate variable cost if no breakdown	(€/ha)	0
	Total variable costs	(€/ha)	302
D3. Fixed costs	Fuel and repairs	(€/ha)	213
	Machinery	(€/ha)	0
	Interests on working capital	(€/ha)	0
	General costs	(€/ha)	0
	Installation costs	(€/ha)	0
	Rent	(€/ha)	0
	Other 1	(€/ha)	31
	Other 2	(€/ha)	14
	Labour -Cultivation	(hr/ha)	0
	Labour -Spraying	(hr/ha)	0
	Labour -Fertilizing	(hr/ha)	0
	Labour - Harvesting	(hr/ha)	0
	Labour - Straw baling	(hr/ha)	0
	Labour input farm operations	(hr/ha)	0
	Labour Yield dependant	(h/t)	0
	Labour Straw dependant	(h/t)	0
	Total Labour Time	(hr/ha)	0
	Labour cost farm operations	(€/h)	0
	Labour cost expert	(€/h)	0
	Labour cost other	(€/h)	0
	Total Labour Cost	Total (€/ha)	0
	Aggregate fixed cost if no breakdown (excluding labour)	(€/ha)	0
	Total fixed costs (excluding labour)	(€/ha)	258
	Net margin (no production)	(€/ha)	-374.327

Table A.5. Arable financial data in Extremadura Spain

D1. Metadata	Country and region Crop name		Extremadura Spain Oats mono (+grazing)	Extremadura Spain Pasture mono	Extremadura Spain Pasture mono dehesa
D2. Revenue	Grain price	(€/t)	159.1707	159.1707	159.1707
	By-product 1	(€/t)	92.84955	92.84955	92.84955
	Area payment	(€/ha)	186.7555	107	0
D3 Variable costs	Seed price	(€/kg)	0	0	0
	Seed rate	(kg/ha)	0	0	0
	Fertiliser price	(€/kg N)	0	0	0
		(€/kg P)	0	0	0
		(€/kg K)	0	0	0
		(€/kg Manure)	0	0	0
		(€/kg Limestone)	0	0	0
	Fertiliser rate	(kg N/ha)	0	0	0
		(kg P/ha)	0	0	0
		(kg K/ha)	0	0	0
		(€/kg Manure)	0	0	0
		(kg Limestone/ha)	0	0	0
	Spray price	(€/application)	0	0	0
	Spray rate	(app/ha)	0	0	0
	Other price	(€/unit)	0	0	0
	Other rate	(units/ha)	0	0	0
	Aggregate variable cost if no breakdown	(€/ha)	200.7416	47.7	47.7
	Total variable costs	(€/ha)	200.7416	47.7	47.7
D3. Fixed costs	Fuel and repairs	(€/ha)	78.9412	78.9412	78.9412
	Machinery	(€/ha)	0	0	0
	Interests on working capital	(€/ha)	0	0	0
	General costs	(€/ha)	0	0	0
	Installation costs	(€/ha)	0	0	0
	Rent	(€/ha)	0	0	0
	Other 1	(€/ha)	0	0	0
	Other 2	(€/ha)	34.72222	34.72222	34.72222
	Labour -Cultivation	(hr/ha)	2.509866	2.509866	2.509866
	Labour -Spraying	(hr/ha)	0.136503	0.136503	0.136503
	Labour -Fertilizing	(hr/ha)	0.136503	0.136503	0.136503
	Labour - Harvesting	(hr/ha)	1.805317	1.805317	1.805317
	Labour - Straw baling	(hr/ha)	0	0	0
	Labour input farm operations	(hr/ha)	0	0	0
	Labour Yield dependant	(h/t)	0.5706	0.5706	0.5706
	Labour Straw dependant	(h/t)	0	0	0
	Total Labour Time	(hr/ha)	5.158789	5.158789	5.158789
	Labour cost farm operations	(€/h)	0	0	0
	Labour cost expert	(€/h)	0	0	0
	Labour cost other	(€/h)	0	0	0
	Total Labour Cost	Total (€/ha)	0	0	0
	Aggregate fixed cost if no breakdown (excluding labour)	(€/ha)	0	0	0
	Total fixed costs (excluding labour)	(€/ha)	113.6634	113.6634	113.6634
	Net margin (no production)	(€/ha)	-127.65	-54.3634	-161.363

Table A.6. Arable financial data in Restinclières, France

	Country and region	None	Restinclières France	Restinclières France	Restinclières France	Restinclières France	Restinclières France
	Crop name		Wheat	Oilseed	Setaside	Sunflower	Fallow
D2. Revenue	Grain price	(€/t)	110	220	0	280	0
	By-product 1	(€/t)	30	0	0	0	0
	Area payment	(€/ha)	340	360	337	360	0
D3. Variable costs	Seed price	(€/kg)	0.265	10.6	5	1.36	0
	Seed rate	(kg/ha)	200	5	3	70	0
	Fertiliser price	(€/kg N)	0.2	0.2	0	0.2	0
		(€/kg P)	0	0	0	0	0
		(€/kg K)	0	0	0	0	0
		(€/kg Manure)	0	0	0	0	0
		(€/kg Limestone)	0	0	0	0	0
	Fertiliser rate	(kg N/ha)	680	645	0	110	0
		(kg P/ha)	0	0	0	0	0
		(kg K/ha)	0	0	0	0	0
		(€/kg Manure)	0	0	0	0	0
		(kg Limestone/ha)	0	0	0	0	0
	Spray price	(€/application)	36	34	0	24	0
	Spray rate	(app/ha)	3	4	0	2	0
	Other price	(€/unit)	0	0	0	0	0
	Other rate	(units/ha)	0	0	0	0	0
	Aggregate variable cost if no breakdown	(€/ha)	0	0	0	0	0
	Total variable costs	(€/ha)	297	318	15	165.2	0
D3. Fixed costs	Fuel and repairs	(€/ha)	90	90	90	90	0
	Machinery	(€/ha)	0	0	0	0	0
	Interests on working capital	(€/ha)	0	0	0	0	0
	General costs	(€/ha)	0	0	0	0	0
	Installation costs	(€/ha)	0	0	0	0	0
	Rent	(€/ha)	0	0	0	0	0
	Other 1	(€/ha)	55	55	55	55	0
	Other 2	(€/ha)	78	78	78	78	0
	Labour -Cultivation	(hr/ha)	2.58419	2.58419	0	2.58419	2.313263
	Labour -Spraying	(hr/ha)	0.136503	0.136503	0	0.136503	0
	Labour -Fertilizing	(hr/ha)	0.136503	0.136503	0	0.136503	0
	Labour - Harvesting	(hr/ha)	1.805317	1.805317	0	1.805317	0
	Labour - Straw baling	(hr/ha)	0.555369	0.555369	0	0.555369	0
	Labour input farm operations	(hr/ha)	0	0	0	0	0
	Labour Yield dependant	(h/t)	0.5706	0.5706	0	0.5706	0
	Labour Straw dependant	(h/t)	0.190476	0.190476	0	0.190476	0
	Total Labour Time	(hr/ha)	5.978958	5.978958	0	5.978958	2.313263
	Labour cost farm operations	(€/h)	0	0	0	0	0
	Labour cost expert	(€/h)	0	0	0	0	0
	Labour cost other	(€/h)	0	0	0	0	0
	Total Labour Cost	Total (€/ha)	0	0	0	0	0
	Aggregate fixed cost if no breakdown (excluding labour)	(€/ha)	0	0	0	0	0
	Total fixed costs (excluding labour)	(€/ha)	223	223	223	223	0
	Net margin (no production)	(€/ha)	-180	-181	99	-28.2	0

10.2 Tree data:

Table A.7. Tree cost data

E1. Metadata (from Treesystem)	Pricing system	None	UK Poplar Agroforestry	UK Poplar Forestry	Switzerland Cherry fruit Agroforestry	Switzerland Cherry timber Forestry	Germany Poplar SRC 96m alley Agroforestry	Germany Poplar SRC Forestry
E2. Establishment costs	Cost of plant	(€/tree)	0	0	55.2	0.8	0.332159	0.335977
	Cost of individual tree protection	(€/tree)	0.93	0.93	12.328	0.8	0	0
	Labour for ground preparation	(hr/ha)	0.41	0.41	0	6.5	0.41	0.41
	Labour for full weeding	(hr/ha)	1.4	1.4	0	1.5	1.4	1.4
	Labour for marking out	(hr/ha)	0	0	0	4	0	0
	Labour for planting trees	(min/tree)	2	2	100	2	0.009193	0.009195
	Labour for tree protection	(min/tree)	2.1	2.1	12	1	0	0
	Labour for localised weeding	(min/tree)	0.5	0.5	0	0.525	0	0
	Labour for fertiliser	(min/tree)	0	0	1	0	0	0
	(€/kg N)	(€/kg N)	0	0	1.138889	0	0	0
	(€/kg P)	(€/kg P)	0	0	0.902778	0	0	0
	(€/kg K)	(€/kg K)	0	0	0.625	0	0	0
	(€/kg Manure)	(€/kg Manure)	0	0	0	0	0	0
	(€/kg Limestone)	(€/kg Limestone)	0	0	0	0	0	0
	(kg N/ha)	(kg N/ha)	0	0	30	0	0	0
	(kg P/ha)	(kg P/ha)	0	0	20	0	0	0
	(kg K/ha)	(kg K/ha)	0	0	20	0	0	0
	(€/kg Manure)	(€/kg Manure)	0	0	0	0	0	0
	(kg Limestone/ha)	(kg Limestone/ha)	0	0	0	0	0	0
	Cost of fertiliser	(€/tree)	0	0	0	0	0	0
E3. Maintenance costs	Year of first weeding	(year)	1	1	1	1	0	0
	Year of last weeding	(years)	3	3	60	3	0	0
	Annual labour for weeding	(min/tree)	0.5	0.5	12	0.5	0	0
	Annual cost of herbicide for weeding	(€/tree)	0.18	0.18	22.54	0.22	0	0
	Application rate of herbicide	(l/tree)	0.005	0.005	0	0	0	0
	Establishment of grass sward	(year)	1	1	0	0	0	0
	Labour for grass sward establishment	(hr/ha grass)	1.787131	1.787131	0	0	0	0
	Materials for grass sward establishment	(€/ha grass)	0	0	0	0	0	0
	Final year of grass sward	(year)	6	6	0	12	0	0
	Labour for grass sward maintenance	(hr/ha grass)	1.249578	1.249578	0	4	0	0
	Materials for annual grass sward maintenance	(€/ha grass)	30	90	0	144	0	0
	Year of first removal of epicormics	(year)	15	15	0	0	0	0
	Year of last removal of epicormics	(years)	30	30	0	0	0	0
	Labour for removal of epicormics	(min/tree)	1.15	1.15	0	0	0	0
E4. Pruning	Height at first prune	(m)	1	1	1	1	0	0

E1. Metadata (from Treesystem)	Pricing system	None	UK Poplar Agroforestry	UK Poplar Forestry	Switzerland Cherry fruit Agroforestry	Switzerland Cherry timber Forestry	Germany Poplar SRC 96m alley Agroforestry	Germany Poplar SRC Forestry
	Minutes per tree at first prune	(min/tree)	1	1	15	0.183333	0	0
	Height at last prune	(m)	4.5	4.5	8	6	0	0
	Minutes per tree at last prune	(min/tree)	19	19	48	6.4	0	0
	Removal of pruning	(min/tree)	4	4	0	4	0	0
E5. Administration	Administrative cost of forestry	(€/ha)	0	0	0	0	0	0
	Insurance management	(€/ha)	9	9	159.068	32	0	0
E6. Thinning	Marking up & thinning	(min/tree)	7	7	0	7	0	0
	Removal of tree thinning	(min/tree)	5	5	0	5	0	0
E7. Clear felling	Clear fell	(min/tree)	4	4	25	4	0	0
	Removal of tree	(min/tree)	2	2	2	2	0	0
E8. Fruit harvest costs	First year of harvest	(years)	0	0	2	0	0	0
	Last year of harvest	(years)	0	0	60	0	0	0
	Fruit harvest labour	(h/t)	0	0	50	0	0	0
	Harvest Amount	(€/t)	0	0	1288	0	0	0
Harvest for SRC	Harvest labour for SRC	(h/ha)	0	0	0	0	0.22	2
	Removal of stumps for SRC	(h/ha)	0	0	0	0	0.33	3
	Harvest cost per ton for SRC	(€/t)	0	0	0	0	45.1	45.1
E8. Other costs	First year of cost	(years)	0	0	1	51	28	28
	Last year of cost	(years)	0	0	60	60	28	28
	Amount	(€/ha)	0	0	1200	62.4	165	1500
E9. Establishment	Establishment (Ground preparation)	(€/h)	14.6	14.6	25.76	25.76	0	0
	Establishment (Full weeding)	(€/h)	14.6	14.6	25.76	25.76	0	0
	Establishment (Marking out)	(€/h)	14.6	14.6	25.76	0	0	0
	Establishment (Planting)	(€/h)	14.6	14.6	25.76	25.76	0	0
	Establishment (Protection)	(€/h)	14.6	14.6	25.76	25.76	0	0
	Establishment (Fertiliser)	(€/h)	14.6	14.6	25.76	0	0	0
	Establishment (Localised weeding)	(€/h)	14.6	14.6	25.76	25.76	0	0
E10. Maintenance	Maintenance (Weeding)	(€/h)	14.6	14.6	25.76	25.76	0	0
	Maintenance (Pruning)	(€/h)	14.6	14.6	25.76	25.76	0	0
	Maintenance (Removal of prunings)	(€/h)	14.6	14.6	25.76	25.76	0	0
	Maintenance (Sward establishment)	(€/h)	14.6	14.6	25.76	25.76	0	0
	Maintenance (Sward maintenance)	(€/h)	14.6	14.6	25.76	25.76	0	0
	Maintenance (Epicormics)	(€/h)	14.6	14.6	25.76	25.76	0	0
	Maintenance (Marking-up and thinning)	(€/h)	14.6	14.6	25.76	25.76	0	0
	Maintenance (Removal of thinned trees)	(€/h)	14.6	14.6	25.76	25.76	0	0
E11. Clear fell	Clear felling (Labour)	(€/h)	14.6	14.6	25.76	25.76	0	0
	Clear felling (Removal of clear felled trees)	(€/h)	14.6	14.6	25.76	25.76	0	0

Table A.8. Tree cost data continued

E1. Metadata (from Treesystem)	Pricing system	None	Apple UK agroforestry organic	Apple UK forestry organic	Extremadura Spain forestry (800)	Extremadura Spain agroforestry (50)	Walnut France agroforestry	Walnut France forestry
E2. Establishment costs	Cost of plant	(€/tree)	6.5	6.5	0.36	0.36	6	6
	Cost of individual tree protection	(€/tree)	3.2	3.2	0.5	0.5	1.5	0.5
	Labour for ground preparation	(hr/ha)	0	0	6.95	1.23	4	6.5
	Labour for full weeding	(hr/ha)	0	0	0	0	0.5	1.5
	Labour for marking out	(hr/ha)	0	0	0	0	7	4
	Labour for planting trees	(min/tree)	10	10	2.7	2.7	2	2
	Labour for tree protection	(min/tree)	5	5	2.7	2.7	2	1
	Labour for localised weeding	(min/tree)	0	0	0	0	0.5	0.5
	Labour for fertiliser	(min/tree)	0	0	0	0	0	0
	(€/kg N)	(€/kg N)	0	0	0	0	0	0
	(€/kg P)	(€/kg P)	0	0	0	0	0	0
	(€/kg K)	(€/kg K)	0	0	0	0	0	0
	(€/kg Manure)	(€/kg Manure)	0	0	0	0	0	0
	(€/kg Limestone)	(€/kg Limestone)	0	0	0	0	0	0
	(kg N/ha)	(kg N/ha)	0	0	0	0	0	0
	(kg P/ha)	(kg P/ha)	0	0	0	0	0	0
	(kg K/ha)	(kg K/ha)	0	0	0	0	0	0
	(€/kg manure)	(€/kg Manure)	0	0	0	0	0	0
	(kg Limestone/ha)	(kg Limestone/ha)	0	0	0	0	0	0
	Cost of fertiliser	(€/tree)	0	0	0	0	0	0
E3. Maintenance costs	Year of first weeding	(year)	1	1	1	1	1	1
	Year of last weeding	(years)	15	15	3	5	3	3
	Annual labour for weeding	(min/tree)	1.6	1.6	0.06225	0.53	0.5	0.5
	Annual cost of herbicide for weeding	(€/tree)	0	0	0	0.14	0.14	0.14
	Application rate of herbicide	(l/tree)	0	0	0	0	0	0
	Establishment of grass sward	(year)	1	1	12	0	1	1
	Labour for grass sward establishment	(hr/ha grass)	6	54.05405	3.88	0	8	8
	Materials for grass sward establishment	(€/ha grass)	10.5	94.59459	0	0	0	0
	Final year of grass sward	(year)	1.125	1.125	0	0	0	15
	Labour for grass sward maintenance	(hr/ha grass)	0	0	0	0	2	4
	Materials for annual grass sward maintenance	(€/ha grass)	6.9615	62.71622	0	0	30	90
	Year of first removal of epicormics	(year)	0	0	0	0	15	15
	Year of last removal of epicormics	(years)	0	0	0	0	30	30
	Labour for removal of epicormics	(min/tree)	0	0	0	0	1.15	1.15
E4. Pruning	Height at first prune	(m)	1	1	2.64	2.64	1	1
	Minutes per tree at first prune	(min/tree)	0.7	0.7	5.425868	0	1	0.2
	Height at last prune	(m)	1	1	8.06	8.06	4.5	4.5

E1. Metadata (from Treesystem)	Pricing system	None	Apple UK agroforestry organic	Apple UK forestry organic	Extremadura Spain forestry (800)	Extremadura Spain agroforestry (50)	Walnut France agroforestry	Walnut France forestry
	Minutes per tree at last prune	(min/tree)	0.7	0.7	46.94006	0	7	7
	Removal of pruning	(min/tree)	0	0	0	0	4	4
E5. Administration	Administrative cost of forestry	(€/ha)	0	0	0	0	0	0
	Insurance management	(€/ha)	0	0	0	0	20	20
E6. Thinning	Marking up & thinning	(min/tree)	0	0	2	0	7	7
	Removal of tree thinning	(min/tree)	0	0	0	0	5	5
E7. Clear felling	Clear fell	(min/tree)	0	0	23	23	4	4
	Removal of tree	(min/tree)	0	0	0	0	2	2
E8. Fruit harvest costs	First year of harvest	(years)	4	4	0	0	1	51
	Last year of harvest	(years)	15	15	0	0	60	60
	Fruit harvest labour	(h/t)	6.857	6.857	0	0	0	0
	Harvest Amount	(€/t)	54.856	54.856	0	0	44	30
Harvest for SRC	Harvest labour for SRC	(h/ha)	0	0	0	0	0	0
	Removal of stumps for SRC	(h/ha)	0	0	0	0	0	0
	Harvest cost per ton for SRC	(€/t)	0	0	0	0	0	0
E8. Other costs	First year of cost	(years)	0	0	0	0	1	51
	Last year of cost	(years)	0	0	0	0	60	60
	Amount	(€/ha)	0	0	0	0	44	30
E9. Establishment	Establishment (Ground preparation)	(€/h)	10	10	30.86	30.86	14.6	14.6
	Establishment (Full weeding)	(€/h)	10	10	0	0	14.6	14.6
	Establishment (Marking out)	(€/h)	10	10	0	0	14.6	14.6
	Establishment (Planting)	(€/h)	12	12	7.83	7.83	14.6	14.6
	Establishment (Protection)	(€/h)	6	6	7.83	7.83	14.6	14.6
	Establishment (Fertiliser)	(€/h)	0	0	0	0	14.6	14.6
	Establishment (Localised weeding)	(€/h)	9.3	9.3	0	0	14.6	14.6
E10. Maintenance	Maintenance (Weeding)	(€/h)	10	10	30.9	0	14.6	14.6
	Maintenance (Pruning)	(€/h)	13	13	9.51	9.51	14.6	14.6
	Maintenance (Removal of prunings)	(€/h)	10	10	0	0	14.6	14.6
	Maintenance (Sward establishment)	(€/h)	10	10	30.86	0	14.6	14.6
	Maintenance (Sward maintenance)	(€/h)	10	10	0	0	14.6	14.6
	Maintenance (Epicormics)	(€/h)	10	10	0	0	14.6	14.6
	Maintenance (Marking-up and thinning)	(€/h)	7.2	7.2	9.51	0	14.6	14.6
	Maintenance (Removal of thinned trees)	(€/h)	10	10	0	0	14.6	14.6
E11. Clear fell	Clear felling (Labour)	(€/h)	10	10	9.51	0	14.6	14.6
	Clear felling (Removal of clear felled trees)	(€/h)	10	10	0	0	14.6	14.6

Table A.9. Tree values

Location Species		UK poplar	Switzerland Cherry fruit	Switzerland Wild Cherry Timber	Germany Poplar SRC 96m alley	Germany Poplar SRC forestry	UK Apple forestry	UK Apple agroforestry	Extremadura Oak	France Walnut
Firewood value	(€ m^{-3})	10	48.3	44				0		10
By-product 1 value	(€/t)	0	2760	0	70	70	655	118	164.4763	0
Timber value	Average tree size	Standing value	Standing value	Standing value	Standing value	Standing value	Standing value	Standing value	Standing value	Standing value
	(m3)	(€/m3)	(€/m3)	(€/m3)	(€/m3)	(€/m3)	(€/m3)	(€/m3)	(€/m3)	(€/m3)
	0	0	0	0						0
	0.01	3.339703	0	0						0
	0.02	4.497489	0	0						0
	0.03	5.352833	0	0						0
	0.04	6.056649	0	10						10
	0.05	6.665697	0	10						10
	0.06	7.208518	0	10						10
	0.07	7.701812	0	20						20
	0.08	8.156328	0	20						20
	0.09	8.579452	0	30						30
	0.1	8.976516	0	40						40
	0.11	9.351512	0	60						60
	0.12	9.707519	0	80						80
	0.13	10.04697	0	100						100
	0.14	10.37183	0	126						126
	0.15	10.68369	0	135						135
	0.16	10.98391	0	144						144
	0.17	11.2736	0	153						153
	0.18	11.55372	0	162						162
	0.19	11.82509	0	171						171
	0.2	12.08844	0	180						180
	0.3	14.38745	0	270						270
	0.4	16.27917	0	360						360
	0.5	17.91619	0	450						450
	0.6	19.37519	0	540						540
	0.7	20.70108	0	630						630
	0.8	21.92273	0	800						720
	0.9	23.06001	0	800						810
	1	24.12725	0	800						900
	1.1	25.13517	0	800						925
	1.2	26.09205	0	800						950
	1.3	27.00444	0	800						1000
	1.4	27.87759	0	800						1000
	1.5	28.71583	0	800						1000
	1.6	29.52276	0	800						1000
	1.7	30.30139	0	800						1000
	1.8	31.05431	0	1000						1000
	1.9	31.78371	0	1000						1000
	2	32.49153	0	1100						1100
	3	38.67085	0	1200						1200
	4	43.75547	0	1300						1300
	5	48.15546	0	1400						1400
	6	52.077	0	1500						1500
	7	55.64074	0	1500						1500
	8	58.92433	0	1500						1500
	9	61.98114	0	1500						1500

Table A.10. Tree grants.

G1. Metadata	Grant system	None	UK poplar	UK poplar agroforestry	Switzerland Cherry fruit Schwarzbubenland Agroforestry	Grants (timber cherry Switzerland)	Germany Agroforestry SRC	Germany Forestry SRC
G2. Establishment payment	Year of first planting grant	(year)	1	1				
	Value of first planting grant	(€/ha)	1888.889	1888.889				
	Year of planting grant supplement	(year)	5	5				
	Value of planting grant supplement	(€/ha)	472.2222	472.2222				
	Year of second planting grant	(year)						
	Value of second planting grant	(€/ha)						
	Percentage total cost payments	For percentage payments based on costs, use inputs in "Options and results"	none	none		none		
G3. Compensation payment	Initial year of receipt	(year)	1	1	10	1	1	1
	Final year of receipt	(year)	15	15	60	60	28	28
	Amount	(€/ha)			3680	1040	17.6	160
G3. Maintenance payment period 1	Initial year of receipt	(year)	1	1		1		
	Final year of receipt	(year)	5	5		1		
	Amount	(€/ha)	0	0		0		
G3. Maintenance payment period 2	Initial year of receipt	(year)						
	Final year of receipt	(year)						
	Amount	(€/ha)						

Table A.11. Tree grants

G1. Metadata	Grant system	None	UK apple agroforestry	UK apple forestry	Extremadura Spain agroforestry	Extremadura Spain forestry holm oak	Walnut France agroforestry	Walnut France agroforestry
G2. Establishment payment	Year of first planting grant	(year)				1	1	
	Value of first planting grant	(€/ha)				2013.39	100	
	Year of planting grant supplement	(year)					2	
	Value of planting grant supplement	(€/ha)					500	
	Year of second planting grant	(year)					5	
	Value of second planting grant	(€/ha)					1000	
	Percentage total cost payments	For percentage payments based on costs, use inputs in "Options and results"					From years 1-4 in years 1-4, planting grant = 50% of total costs	From years 1-4 in years 1-4, planting grant = 50% of total costs
G3. Compensation payment	Initial year of receipt	(year)	1	1	1		1	1
	Final year of receipt	(year)	15	15	60		10	10
	Amount	(€/ha)	452.85	452.85	18.4		240	240
G3. Maintenance payment period 1	Initial year of receipt	(year)					1	1
	Final year of receipt	(year)					5	5
	Amount	(€/ha)					100	288
G3. Maintenance payment period 2	Initial year of receipt	(year)					1	6
	Final year of receipt	(year)					15	10
	Amount	(€/ha)					50	122