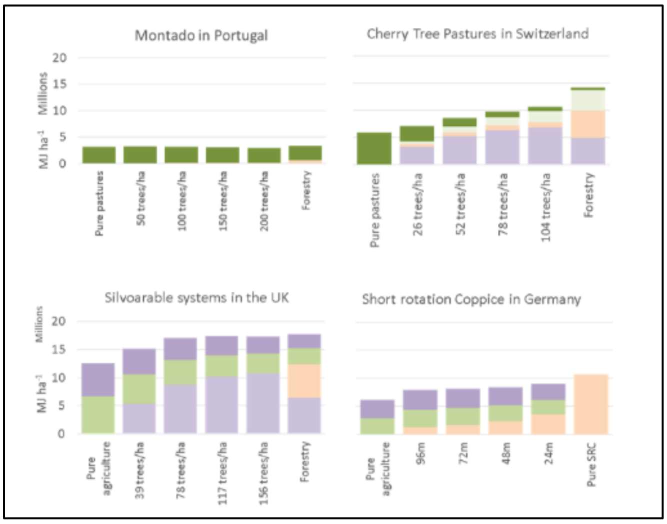
AGFORWARD
Agroforestry for Europe



Modelled agroforestry outputs at field and farm scale to support biophysical and environmental assessments

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1. Context and objectives

The aim of the AGFORWARD project (January 2014-December 2017) is to promote agroforestry practices in Europe that will advance sustainable rural development. Within the project there are four objectives:

1. to understand the context and extent of agroforestry in Europe,
2. to identify, develop and field-test innovations to improve the benefits and viability of agroforestry systems in Europe,
3. to evaluate innovative agroforestry designs and practices for locations where agroforestry is currently not-practiced or is declining, and quantify the opportunities for uptake at a field and farm-scale and at a landscape-scale, and
4. to promote the wider adoption of appropriate agroforestry systems in Europe through policy development and dissemination.

The third objective is addressed partly by work-package 6 which focused on the field- and farm-scale evaluation of innovations. Agroforestry modelling is used to evaluate different scenarios and case studies across Europe. One of the models being used on the project is Yield-SAFE (van der Werf et al. 2007). 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.

In order to assess productivity with Yield-SAFE, the model was calibrated where possible (depending on availability of data) for the species in the systems and innovations identified in the project (See project milestone 27[1]). Several modelling workshops were held to acquire the data and, at the same time, to explain the use of the model to European researchers and students. Data have been collected and questions have been gathered to provide focus for the modelling exercises for future research and extension publications.

Within the AGFORWARD project, the model has also been enhanced to more accurately predict the delivery of ecosystem services provided by agroforestry systems relative to forestry and arable systems. Additional routines where incorporated into the model and are described in Milestone Report 29 (Palma et al. 2016a). The main improvements in the model include: 1) the possibility to model permanent crops (essential for woodland livestock management assessments) with the addition of a maintenance respiration coefficient, 2) the use of vapour pressure deficit data to predict transpiration rates reducing calibration efforts for different environmental regions, 3) new routines to model cork and fruit production, 4) modification of water uptake by trees in relation to the fine root mass, 5) prediction of the effect of trees on temperature and wind speed, 6) routines to predict the turnover of soil organic carbon (integration of RothC), 7) nitrate leaching and 8) the estimation of livestock carrying capacity. Furthermore the model is fully linked to the CliPick tool (http://www.isa.ulisboa.pt/proj/clipick/) (Palma 2015; Palma 2017), reducing the effort regarding the derivation of climate data to be used with the model. Additionally, the model has been

[1]http://agforward.eu/index.php/en/identification-of-agroforestry-systems-and-practices-to-model.html

integrated with Farm-SAFE (Graves et al. 2016a), to allow the biophysical modelling to be used in integrated bio-economic assessments.

Rather than assessing each of the questions that rose during the project, this report explains the basis for a supporting tool capable of addressing those questions and outlines the work undertaken during the workshops that allowed calibration and preparation of the model to simulate agroforestry productivity and complementary ecosystem services in diverse climatic conditions and management scenarios.

This report, comprising deliverable 6.17 in the project, brings together examples of modelled outputs at field and farm scale to support the biophysical, social, and environmental assessment of the innovations selected from work-packages 2 to 5. It also gathers sources of information, about 10 pages of references, mostly dedicated to physiological parameters found in literature to support the use of process based models to further improve the existing calibrations. The calibration and validation process is being integrated, amplified and complemented with a financial and economic analysis in the final deliverable (6.18) of work-package 6.

2. Agroforestry systems in Europe to be modelled

Agroforestry systems can be used in a range of landscapes with complex land use interactions. The AGFORWARD project has categorised agroforestry practices in relation to four key land use sectors: 1) existing agroforestry systems of high nature and cultural value (HNCV) (covered by work-package 2), integrating livestock and crops into high value tree systems (work-package 3), agroforestry for arable systems (work-package 4) and agroforestry for livestock systems (work-package 5).

During 2014, partners within the AGFORWARD project facilitated about 40 stakeholder groups across Europe, each resulting in an initial stakeholder report. These stakeholder reports, and four synthesis reports on the innovations of interest (Hermansen et al. 2015; Mirck et al. 2015; Moreno et al. 2015; Pantera et al. 2015), were used to gather and frame the agroforestry practices being considered across Europe and the research and innovations that needed attention. The stakeholder meetings led to the identification of 46 existing agroforestry systems and about 130 potential innovations raising questions with emphasis on "system design and management" (Palma et al. 2015).

The systems identified during the stakeholders meetings and contextual descriptions were gathered to build a contextual modelling framework, delivering a systems description report (Palma et al. 2015). The descriptions included the basic elements of the systems: tree, crop and animal species; other biophysical attributes such as soil type; an estimation of the area occupied by the system; the main resulting products and other economic interest of the systems and the presence or not of experimental sites for the collection of more information. This provided the basis for the contextual modelling setup envisaging the usage of the model to assess ecosystem services delivery.

Soon it became apparent that the modelling of each system would not be possible given the large number of systems and combinations. Instead, a large effort has been made to develop the model to suit the assessment of the ecosystem services from agroforestry trying to reach stakeholders' needs while interacting as much as possible with partners interested in modelling various agroforestry systems. In this report, an effort has been made in terms of delivering the current calibration parameter datasets that have been derived in collaboration with other participants focused on agroforestry modelling.

High Nature and Cultural Value (HNCV) systems are typically semi-natural agro-silvopastoral systems where cultivation and/or grazing are practised. Prominent examples include the Dehesa and Montado systems in Spain and Portugal (Figure 1), grazed oak woodlands in Sardinia (Italy) and Valonia Oak silvopastoral systems in Greece. Agroforestry systems of high natural and cultural value in Northern and Eastern Europe include parklands in the UK, and wood pastures of Scandinavia, Germany and Romania. Within this group, eleven systems were defined as High Natural Cultural Value systems, including hedgerow agroforestry system of the "bocage" of Brittany in North West France, the "Spreewald" systems in the flood plains in Eastern Germany and the "lameiros" systems located in Portugal.

Figure 1. Example of Montado, a High Natural and Cultural Value system, south Portugal. (More photos under https://www.flickr.com/photos/agforward)

The main questions related to **high nature and cultural value (HNCV) agroforestry** that biophysical modelling could help address are those concerning the biophysical and economic comparison of the ecosystems services provided by these systems compared to conventional agriculture or forestry. The initial surveys also highlighted a need for models to evaluate carrying capacities depending on system design (e.g. tree densities), also considering tree effects that might help to overcome the strong seasonality of natural or semi-natural forage resources. See Milestone 27 (Table 6) for details[2].

[2] http://agforward.eu/index.php/en/identification-of-agroforestry-systems-and-practices-to-model.html

High Value Tree Agroforestry Systems comprise grazed and intercropped apple orchards, olive and citrus groves, and high value walnut, cherry and chestnut trees. Currently, the removal of production-related subsidies threatens the financial sustainability of olive systems and some fruit orchards while innovations identified during the stakeholder meetings include legume intercrops to improve soil nutrition, companion planting to reduce pests and diseases, and using intercrops for grazing. These systems included alley cropping under cherry trees, the "Selva" chestnut system in Switzerland, timber wood trees with cereals, grazed orchards, "Bordure" trees in France, intercropped and grazed orchards in the UK, intercropping and grazing olive orchards in Italy, intercropping of olive orchards, walnut trees and orange groves in Greece, chestnut systems and grazing and intercropping of plantation trees (Olive, almond and carob orchards) in Spain and traditional grazed chestnut tree stands for fruit and/or wood production (Figure 2).

Figure 2. Example of high value tree agroforestry systems: top-left: apple with vegetables, UK; top-right: cherry with vegetables, Switzerland; bottom-left: grazing apple orchards, UK; bottom-right: olive trees and asparagus, Italy (More photos under https://www.flickr.com/photos/agforward)

The main questions related to **high value tree agroforestry systems** that biophysical modelling could help address are those concerning the knowledge and relationships between extensive and intensive systems, the additional income from including livestock into orchards/groves, the assessment of ecosystem services, and profitability from diversification of products. See Milestone 27 (Table 7) for details[3].

[3] http://agforward.eu/index.php/en/identification-of-agroforestry-systems-and-practices-to-model.html

Silvoarable agroforestry combines trees and arable crops in the same land (Figure 3). Arable agriculture provides large quantities of food, but it can be associated with reductions in soil and water quality, reduced biodiversity, and the release of greenhouse gases such as carbon dioxide and nitrous oxide. In some areas, continued arable crop production will be sensitive to climate change. The appropriate integration of trees in arable systems can provide benefits in terms of bioenergy production, improved resource efficiency, and increased biodiversity. Examples are the combination of fruit (e.g. apple, cherry, and walnut) or timber (poplar, walnut, willow, eucalyptus) or short rotation coppice alleys with arable intercropping.

Figure 3. Example silvoarable systems: top-left: short rotation coppice with cereals, DE; top-right: Ploughing hazel alleys, UK; bottom-left: Poplar and wheat, UK; bottom-right: Poplar and Maize, IT. (More photos under https://www.flickr.com/photos/agforward)

The main questions related to **silvoarable systems** that biophysical modelling could help address are those concerning with the design, in particular the number of trees to plant, and to what extent the soil depth is a limiting factor. There is also interest in assessing the land equivalent ratio for efficiency in resource use, and to quantify ecosystem services, for example, carbon storage (above and below ground), water regulation, soil erosion loss. Furthermore, there is a need to understand the profitability of these systems. See Milestone 27 (Table 8) for details[4].

[4] http://agforward.eu/index.php/en/identification-of-agroforestry-systems-and-practices-to-model.html

Agroforestry for livestock farmers considers the application of agroforestry in livestock systems across three sectors: i) poultry; ii) ruminants and iii) pigs (Figure 4). The innovations include improving product quality and profitability whilst enhancing the environment. Examples of these innovative systems include pigs in energy crops in Denmark, wild cherry pastures in Switzerland, woodland eggs and poultry, and woodland cattle in the UK. Traditional agrosilvopastoral systems such as dehesas, montados or streuobst, despite being catergorised as HNCV systems, have common features in terms of modelling and assessment.

Figure 4. Example of silvopastoral systems: top-left: Pigs browsing on montado acorns, Portugal; top-right: woodland chickens, UK; bottom-left: pigs browsing between short rotation coppice plantations, Germany; bottom-right: mixed pigs and beef cattle grazing, Portugal. (More photos under https://www.flickr.com/photos/agforward)

The main questions related to **agroforestry for livestock farmers** that biophysical modelling can address includes design and the combination of species and densities that suit the energetic and mineral needs of livestock. Stakeholder questions also include ecosystem services such as carbon storage, nitrogen usage, and animal welfare. Understanding profitability is a common issue and seasonal aspects are also important in order to match daily livestock energy needs with feed production without the need for external and costly inputs. See Milestone 27 (Table 9) for details[5].

[5] http://agforward.eu/index.php/en/identification-of-agroforestry-systems-and-practices-to-model.html

2.1 Modelling workshops

Most of the content of this report was developed during several workshops held in different contexts, targeting the collection of biophysical, financial and economic data, often in local accessible literature or databases. Workshops were an efficient methodology to boost progress of the modelling work-package (Figure 5).

Figure 5. Modelling workshops held in Portugal, Greece and UK were crucial to boost the collection of data and understand the management dynamics of the systems to be modelled

Participative modelling, while also taking some breaks during the workshops for field visits is essential to understand the characteristics of the systems being modelled. The first workshop was held in Monchique (PT) enabling to synchronize the existing versions of the Yield-SAFE model while planning strategy for the systems to model during the project, focusing on raised questions, problem solving, and model limitations to tackle the challenges. Following workshops focused on high value tree systems, silvoarable systems and silvopastoral systems, having the high natural and cultural systems a transversal scope.

While being a way to boost modelling calibration and validation, targeting to answer questions rose during stakeholders meetings, modelling workshops are an important way to share knowledge regarding working with the model itself. Several (young) researchers are now familiar with the agroforestry models used in these workshops, which is encouraging for the future of the use and analysis these tools can provide, being an important human resource to expand the use of models to tackle the various combinations of the management of agroforestry systems.

3. The Yield-SAFE model

Since the beginning of the AGFORWARD project, an effort has been made to enhance the Yield-SAFE model (van der Werf et al. 2007) to incorporate a livestock component and additional ecosystem services and to integrate the model with Farm-SAFE. Full details can be read in Palma et al (2016a, 2016b) and Graves et al. (2016). However, for clarity the biophysical parameters are also summarised in Annex I to V in terms of the default Yield-SAFE soil, crop, tree and livestock parameters. The parameters for soil are described in Table 18, for trees in Table 19, and the crop in Table 24, and for the livestock in Table 27. Moreover, a prototype of a web-based interface for Yield-SAFE is underway that will try to keep this information updated[6].

3.1 Climate and soil drivers

Daily climate data can be retrieved from the tool CliPick, an online tool[7] developed under the AGFORWARD project to ease the access to climate data for modelling (Palma 2015; Palma 2017). The principal information needed to retrieve the climate data is latitude and longitude. Although this is simulated data there are indications that this artificial climate can be used for calibration purposes with minor loss of quality in comparison to real data (Palma et al. in prep). Furthermore, CliPick has integrated datasets (with daily and monthly data) that consider climate change scenarios and therefore allowing the assessment of climate change impact in several studies comparing land use alternatives (e.g. agroforestry).

Table 1. Main daily weather variables required in Yield-SAFE

ColumnName	Description	Unit / Value
Day	Day of the month	1-31
Month	Month of the year	Jan-Dec
Year	Year	XXXX
Tasmax	Daily maximum temperature	°C
Tasmin	Daily minimum temperature	°C
Hurs	Relative humidity	%
Rsds	Solar radiation	MJ m^{-2}
Pr	Precipitation	mm day^{-1}
sfcWind	Wind speed	m s^{-1}

3.2 Livestock integration

3.2.1 Utilizable metabolizable energy requirements

Livestock assessment is a newly integrated component of Yield-SAFE. The livestock component is now represented in terms of energy requirements using references for livestock unit utilizable metabolizable energy (UME) requirements. The UME requirements of a livestock unit, as suggested by Hodgson (1990), refers to a lactating dairy cow with a liveweight (*W*) of 500 kg and milk yield (*Y*) of 10 kg d^{-1} (Equation 1). Based on this assumption, a livestock unit would need a 103.2 MJ d^{-1}.

[6] Prototype under http://home.isa.utl.pt/~joaopalma/projects/agforward/webyieldsafe/webinterface/
[7] http://www.isa.ulisboa.pt/proj/clipick/

$$UME_{requirement} = 8.3 + 0.091W + 4.94Y \qquad \text{Equation 1}$$

As a reference for Europe the Farm Accountancy Data Network (FADN) is used to assess the energy requirements for the different livestock types based on Equation 1 resulting in Table 2.

Table 2. Main Livestock Units (LU) values from the Farm Accountancy Data Network and Utilizable Metabolizable Energy Requirements (UMER), based on Equation 1, being used in Yield-SAFE

FADN code	Name - FADN classification	Livestock units	Weight (kg)	Milk production (kg d^{-1})	$UME_{requirement}$ (MJ d^{-1})
D22	Equines	0.8	400		44.7
D23	Calves for fattening	0.4	200		26.5
D24	Other cattle < 1 year	0.4	200		26.5
D25	Male cattle 1-2< years	0.7	350		40.2
D26	Female cattle 1-2< years	0.7	350		40.2
D27	Male cattle >= 2 years	1	500		53.8
D28	Breeding heifers	0.8	400		44.7
D29	Heifers for fattening	0.8	400		44.7
D30	Dairy cows	1	500	10	103.2
D31	Cull dairy cows	1	500	10	103.2
D32	Other cows	0.8	400		44.7
D34	Rabbits (breeding females)	0.02	10		9.2
D38	Goats, breeding females	0.1	50	1	17.79
D39	Other goats	0.1	50		12.9
D40	Ewes	0.1	50		12.9
D41	Other sheep	0.1	50		12.9
D43	Piglets	0.027	13.5		9.5
D44	Breeding sows	0.5	250	5	55.8
D45	Pigs for fattening	0.3	150		22.0
D46	Other pigs	0.3	150		22.0
D47	Table chickens	0.007	3.5		8.6
D48	Laying hens	0.014	7		8.9
D49	Other poultry	0.03	15		9.7
*	Galicia Sheep	0.1			20.8
*	Iberian pig	0.47			48.6

* Units found in literature during modelling workshops

Carrying capacity is then the relation between livestock UME requirements and the UME production of the system. In the case of pasture, UME is a value for the whole biomass but for many other crops, there are different values of UME for the crop (e.g. grain) and the by-product (e.g. straw), and these need to be estimated accordingly. Table 3 lists the UME values for different crops/pastures being used in Yield-SAFE. Furthermore tree components such as leaves from prunings and fruit production (e.g. acorns) are also considered in Yield-SAFE to provide energy to estimate carrying capacity (see Section 3.2.3, page 15).

Table 3. List of crop and pasture utilizable metabolizable energy (UME) content and source

Crop	Metabolizable energy (MJ kg^{-1} DM)	Reference
Cultural and semi-natural grasslands	8.7 - 10.8	(Köster et al. 2004)
Young leafy ryegrass	12	(NRC 2001)
Alpine grass	8.6 - 9.2	(Krautzer et al. 2004)
Lucerne	10.2 - 12	(Slepetys 2004)
Barley	12.4	(Heuzé et al. 2013)
High quality forage (e.g. vegetative legumes and grasses)	6.5 - 7.5	(IPCC 2006)
Moderate quality forage (e.g. mid-season legume and grasses)	5.5 - 6.5	(IPCC 2006)
Low quality forage (e.g. straw, mature grasses)	3.5 – 5.5	(IPCC 2006)
Poor quality grass hay	7	(McDonald et al. 2010)
Oat/barley grain (straw)	12 (7)	(McDonald et al. 2010)
Wheat grain (straw)	13.6 (6.1)	(McDonald et al. 2010)
Maize straw	9	(McDonald et al. 2010, page 528)
Hay: grasses (meadow, mixed grass, orchard grass, Fescue, Ryegrass, Timothy)	8.0 – 8.9	(McDonald et al. 2010, page 524)
Hay: legumes (clover, lucerne, vetches, soybean)	7.8 – 9.1	(McDonald et al. 2010, page 524)
Hay: cereals (barley, oats, wheat)	7.8 – 8.6	(McDonald et al. 2010, page 524)
Roots, root by-products, tubers	11.2 – 13.7	(McDonald et al. 2010, page 534)
Maize, millet, sorghum (Nigeria)	3.3	(Medugu et al. 2010)
Maize (poultry, pig, cattle)	16.2, 16.9, 14	(McDonald et al. 2010, page 254)
Wheat (poultry, cattle)	15.3, 10.6	(McDonald et al. 2010, page 254)
Barley (poultry, pig, sheep, cattle)	13.3, 14.2, 12.9, 12.3	(McDonald et al. 2010, page 254)
Oats (pig)	13.3	(McDonald et al. 2010, page 254)
Dried Ryegrass (young, mature)	13, 9.9	(McDonald et al. 2010, page 254)
Alfalfa hay (young, mature)	9.4, 8.0	(Harlan et al. 1991)
Clover hay (young)	6.4	(Harlan et al. 1991)
Grass hay (young, medium, mature)	8.9, 7.9, 8.2	(Harlan et al. 1991)

Note: Other figures available @ http://www.feedipedia.org/ and under the AGFORWARD developments of the nutritional values database @ http://www.voederbomen.nl/nutritionalvalues/

Figure 4 provides the output of a modelling exercise for a cork oak Montado in south Portugal estimating the daily carrying capacity calculated with the UME provided by the pasture, and the UME required by a livestock unit.

A

B

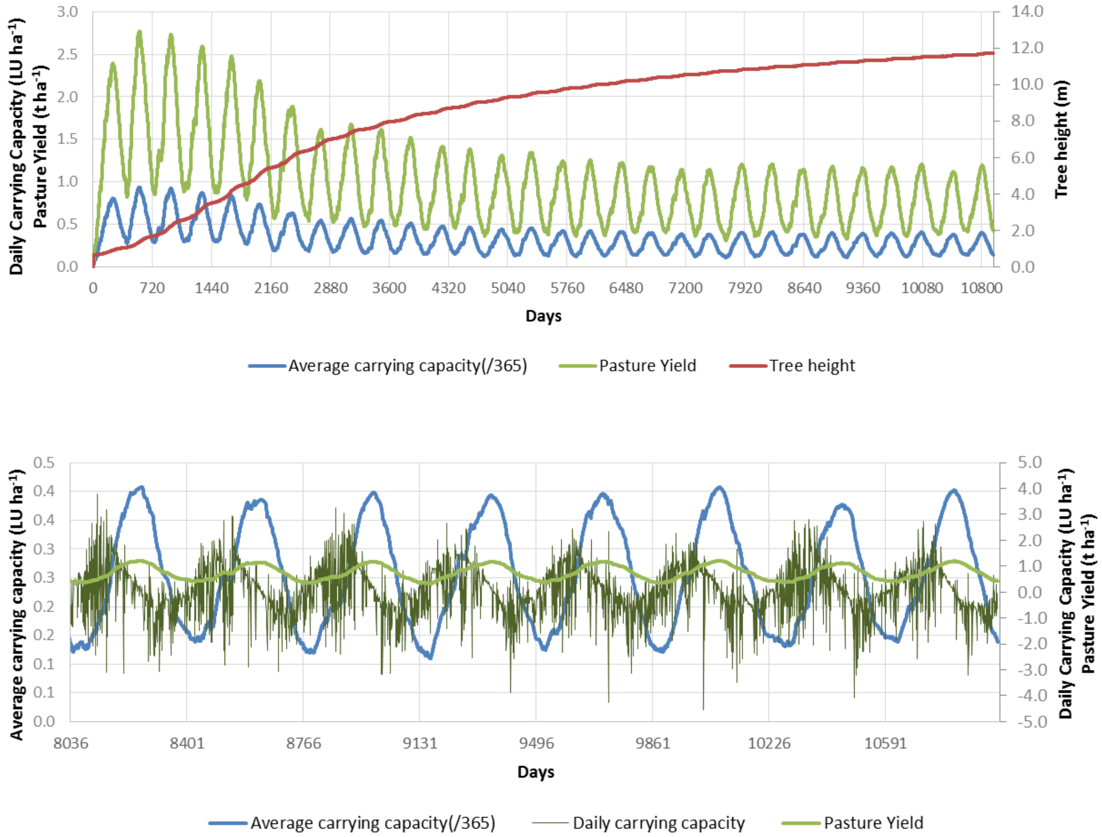


Figure 6. A) Simulation of 30 years of a cork oak silvopastoral system (50 trees ha^{-1}) in south Portugal with the estimation of pasture yield and the carrying capacity as a daily average. B) The last 8 years of a) showing the daily variation of the carrying capacity.

Note that, in this simulation, in later stages of the tree development, the carrying capacity levels are within levels of 0.5 LU/ha or lower. These carrying capacities are in accordance to 1) Potes (2011, page 75) reporting values between 0.32 and 0.74 LU/ha, 2) Goes (1991) reporting a recommended rate of 0.5 pig/ha (0.15 LU/ha) for a 50-60 trees/ha system and 3) an analysis of national statistics reporting 0.4 LU ha^{-1} (Belo et al. 2014).

3.2.2 Shade

Shade is an important service provided by trees. For example, Jacobson (2016) suggests about 2 billion US dollars revenue loss due to the lack of shade in livestock management. To estimate the shade effects in agroforestry systems, the needs per livestock unit were estimated based on existing extension tables by Higgins et al. (1999) - Table 4.

Table 4. Suggested shade requirements (75% of optimum amount) for beef and dairy cattle based on Higgins et al. (1999)

Animal type	Space requirement (m^2 $head^{-1}$)	Average (m^2 $head^{-1}$)
180 kg calves	1.4 – 1.8	1.6
360 kg female cattle	1.8 – 2.3	2.05
Beef cow	2.8 – 3.7	3.25
Dairy cow	3.7 – 4.6	4.15

With the above requirements of shade and with a simple exercise of shade provided by trees in an agroforestry system, it is easy to conclude that the *shade carrying capacity* can hardly be a limiting factor because carrying capacity estimated based on biomass provision have much lower values, sometimes lower than 1 LU ha^{-1} in most extensive systems. Table 5 shows that even with a low tree density (e.g. 20 trees ha^{-1}) with a small canopy width provides a *shade carrying capacity* (shade requirements expressed in LU) of 19 LU ha^{-1}. These shade requirements per LU surpasses largely the carrying capacity in extensive systems, usually below 1 LU ha^{-1} which indicates that even with a very low tree density the shade requirements are met. However there is a limitation on tree height. The current default threshold to provide shade to livestock has been chosen as 4 m.

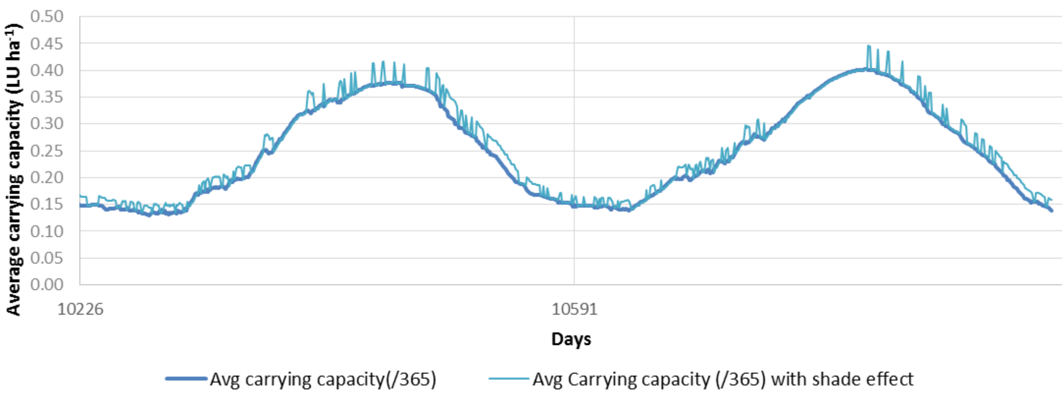
Table 5. Shade carrying capacity of a range of typical density and canopy width, considering a livestock unit needing 3.25 m^2

Tree density (m^2 ha^{-1})	Tree Canopy width (m)	Shade (m^2)	Canopy cover (%)	Shade carrying capacity (LU ha^{-1})
20	2	63	1	19
20	4	251	3	77
20	6	565	6	174
20	8	1005	10	309
50	2	157	2	48
50	4	628	6	193
50	6	1414	14	435
50	8	2513	25	773
100	2	314	3	97
100	4	1257	13	387
100	6	2827	28	870
100	8	5027	50	1547
150	2	471	5	145
150	4	1885	19	580
150	6	4241	42	1305
150	8	7540	75	2320

Numerous authors have reported the effect of **heat stress on livestock** weight loss, milk production, pregnancy rates or semen quality (e.g. Mayer et al. 1999; Mader et al. 2006; Amundson et al. 2006; Coleman et al. 1984). As agroforestry systems can provide shade, an attempt to model this effect is proposed. McDaniel and Roark (1956) and McIlvain and Shoop (1971) studied the effect of shade on liveweight and reported a 5-11% increase due to shade. The gains were most evident on "hot muggy days”, defined as days when temperature + humidity where above 130 (temperature in Fahrenheit, humidity in %). In other words, the daily energy needs of a livestock unit under shade can be 5-11% less than that in a non-shaded field. This effect is now represented in Yield-SAFE, allowing users to assess shade as an ecosystem service provided by agroforestry (see details in Palma et al. 2016a, 2016b).

For example, the activation of the Livestock Metabolizable Energy Requirement (LMER) modifying factor of 0.9 when a heat stress day occurs, triggers a higher carrying capacity in particular day (Figure 7A) because, in that day, the 10% energy that would be spent in reducing livestock body temperature, is not needed, thus leaving the pasture/energy available to feed other livestock. In this example, in south Portugal, a cumulative counting for 30 years yields about 3500 days where heat stress occurs, summing up energy savings of about 40 000 MJ per livestock unit (Figure 7B). Because thousands of megajoules can be an abstract magnitude for many, Figure 7B also shows that the energy savings correspond to roughly 60 000 light bulbs of 7 watts switched on for a whole day.

A



B

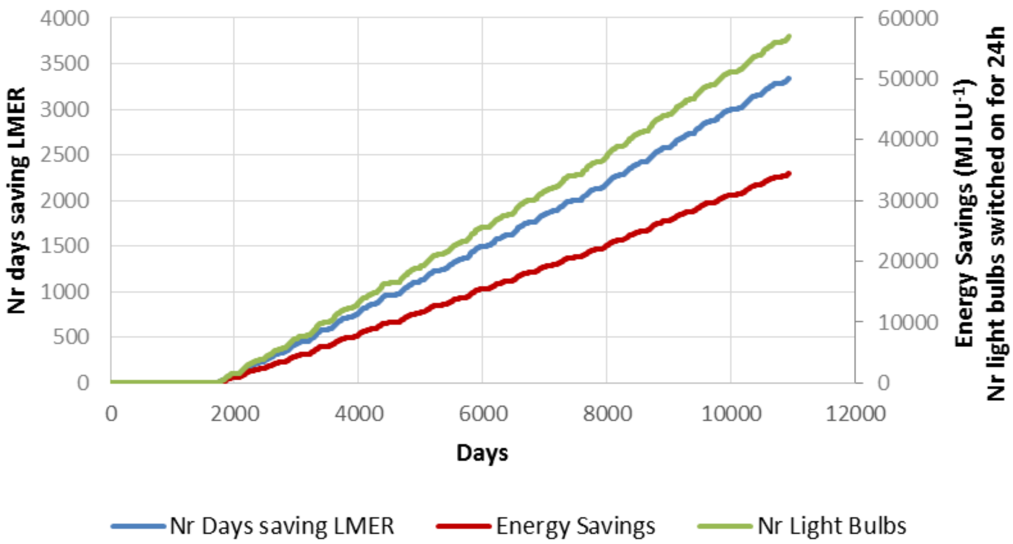


Figure 7. A) Effect of shade modifier on the carrying capacity of an agroforestry system where tree height is higher than 4 m. B) Number of days where the LMER modifier is activated, the accumulated saved energy, and the correspondent energy converted to switch-on a 7 watt bulb for 24 h.

These energy savings can be scaled-up. For example over 30 years, an agroforestry system can reduce the heat stress on an annual average of 117 days per days corresponding to about 1333 MJ LU^{-1} $year^{-1}$, the equivalent of 2205 light bulbs operating for one day (6 light bulbs switched on all year), and considering a price of electricity between 0.15 and 0.20€ kWh^{-1}, we could say that each dairy cow under an agroforestry system is saving the farmer between 56€ and 74€ in electricity. Another point of view could consider a reference value of 0.362 kg CO_2 kWh^{-1} for the EU (IPCC/TEAP 2010), suggesting a non-emission of 134 kg CO_2 $year^{-1}$ LU^{-1}. However other methodologies, more appropriate in terms of livestock physiological processes, i.e. involving weight gain with less energy, should be considered when converting energy. The “bulb” exercise is provided *as is* just for reference in terms of energy to frame the magnitudes of energy involved to suggest discussion for future research.

3.2.3 Fruit production module

The fruit production module was implemented in Yield-SAFE based in holm oak acorn production by adding five parameters (Table 6) and supplying an additional eight state variables (see Table 34, page 70). The new parameters offer the possibility to adjust parameter values depending on the observed data on a stand or literature.

Table 6.New parameters from fruit module implemented into Yield-SAFE

Name	Unit	Parameter	Description	*Q.ilex/ Q. suber*	Reference
Fruit name	-	-	Name of the fruit	Acorn	-
Fruit energy content	MJ/t FM	Fru_{UME}	Utilizable metabolisable energy content in fruit	7230	Lopez-Bote et al (2000)
Fruit productivity	g/m^2 LAI	Fru_p	Production related to canopy cover	100	Gea-Izquierdo et al (2006)
Fruit falling days	Days	$Fruit_{FallingDays}$	Number of days when 95% of fruit falls	100	Cañellas et al (2007)
Fruit fall peak day	Julian day	$Fruit_{DOYPeak}$	DOY when peak is occurring	307	Cañellas et al (2007)
Fruit weight	g/piece	$Fruit_{Weight}$	Weight of a single piece of fruit	3.5	Lopez-Bote et al (2000)

Following the suggestion of Gea-Izquierdo et al. (2008), the new module of fruit production depends on the crown cover size. This seems the most reliable way to model productivity and allow comparison between stands, locations and states. Fruit production is considered as a linear relationship between the tree leaf area index (LAI) and a parameter that defines the canopy fruit productivity in terms of fruit yield per unit of LAI. Fruit production is an important energetic asset for some animal species (domestic and wild), so it is defined in terms of energy content within a fruit falling period simulated as a normal distribution (Figure 8). The falling period enables the estimation of livestock carrying capacity and also the number of sequential grazing days considering the fruit energetic availability.

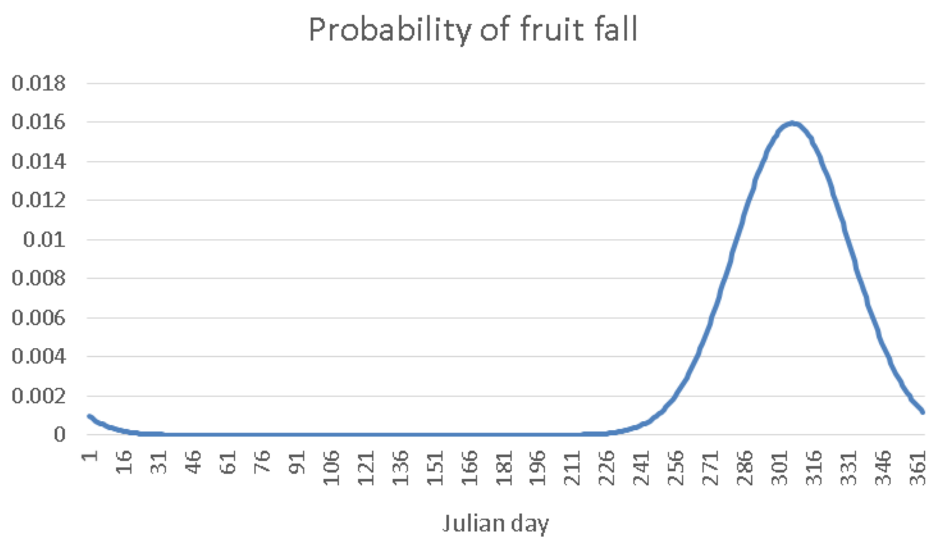


Figure 8. Daily probability used for acorn fall with FF_{Peak} = 307 and FF_{Span} = 100 (based on Cañellas et al. 2007).

Cañellas et al. (2007*)*, assessed two different trials for acorn production on *Quercus suber* and *Quercus ilex* in **Badajoz** province (Extremadura, Spain). The study was carried out on five sites representative of the Spanish dehesa system in the southwest of the province of Badajoz. The mean total annual acorn production for the second year was around 680 kg ha^{-1} while for both years it ranged from 590 to 830 kg ha^{-1}. Yield-SAFE was set up according to the trial setup, an average 32 trees ha^{-1} with weather information from CliPick (Palma 2015; Palma 2017) while the trees were considered to be 70 years old.

Additionally, the fruit/acorn module was compared with the unpublished data provided by the host institution (UEX) from the **Cáceres** province. The study was carried out in Las Majadas del Tiétar and presents 9 different plots where annual acorn production information was collected (Table 7).

Table 7. Average acorn produced in the experimental site of Las Majadas del Tiétar (Spain)

Year	Fruit productivity (g DM / m^2)	Acorn production (kg/ha)
2003	308.5	617.0
2004	108.4	216.8
2005	218.5	437.1
2006	23.7	47.4
2007	187.2	374.4
2008	234.6	469.3
2009	123.1	246.1
2010	223.2	446.4
2011	215.6	431.3
2012	185.6	371.1
Average	182.8	365.7

In Cáceres, data of monthly acorn production of nine plots was collected for ten years. The tree density average was around 20 tree ha^{-1}; the average diameter class, 45 cm and the average biomass per tree associated to that class was 1270 kg tree^{-1}. Following these values and using Yield-SAFE results we associated and average age of the stand of 23 years. At the age of 23 years old in Cáceres, Yield-SAFE estimates a fruit falling distribution with acceptable resemblance to the measures data (Figure 11).

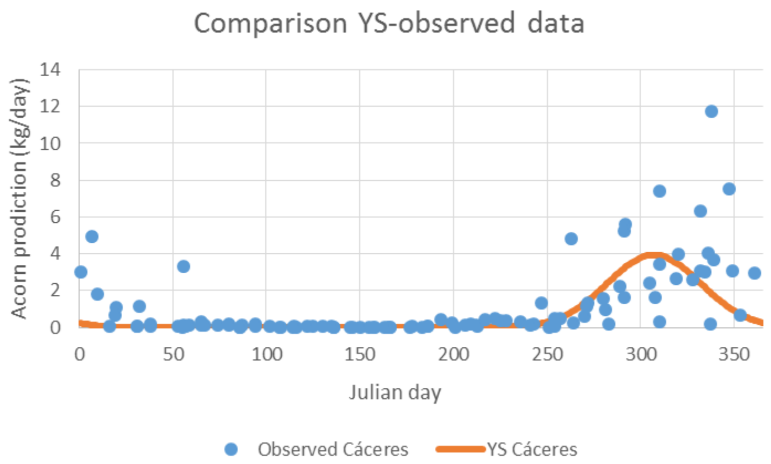


Figure 9. Comparison between Yield-SAFE results and observed data for Cáceres

In Badajoz, in the absence of a stand age in Cañellas et al (2007), a mature stand of 70 years was assumed. Similarly to the Cáceres site, Yield-SAFE estimates of fruit production fall within the observed data from the five plots during the year 1998/1999. Yield-SAFE may seem to slightly underestimate the production, but the conservative approach is optional and can be corrected by adjusting the FF_{Peak} and the FF_{Span} parameters of the distribution according to the regional information available (Figure 10).

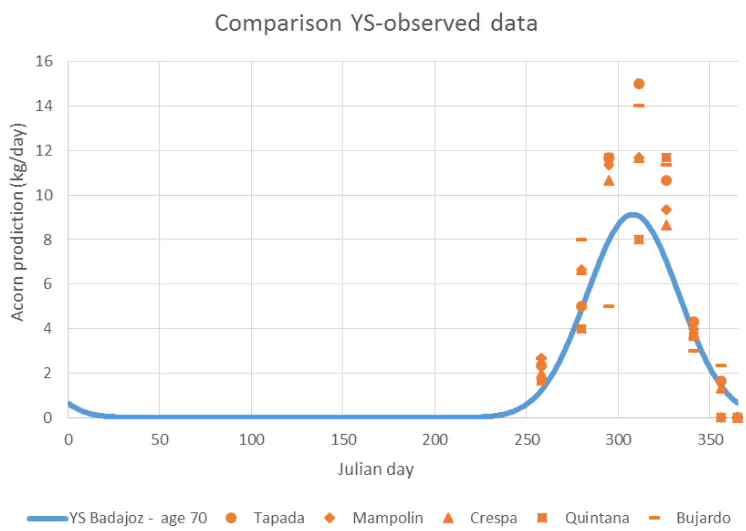


Figure 10. Comparison between Yield-SAFE estimation of acorn production for a tree with 70 years old with observed data from Badajoz

In both cases, Cáceres and Badajoz, the Yield-SAFE fruit module seems to estimate acceptable yields. Furthermore the integration of a small amount of parameters related to the fruit production offers the possibility to adjust productivity for local conditions. For example, in Cáceres, delaying the standard fruit fall peak day (DOY = 307) for 10 days could improve the precision of the model for that site (Figure 11A), while reducing the “fruit falling days” parameter from 100 days to 70 days could also help to fit better the model into the observed data in Badajoz (Figure 11B).

A)

B)

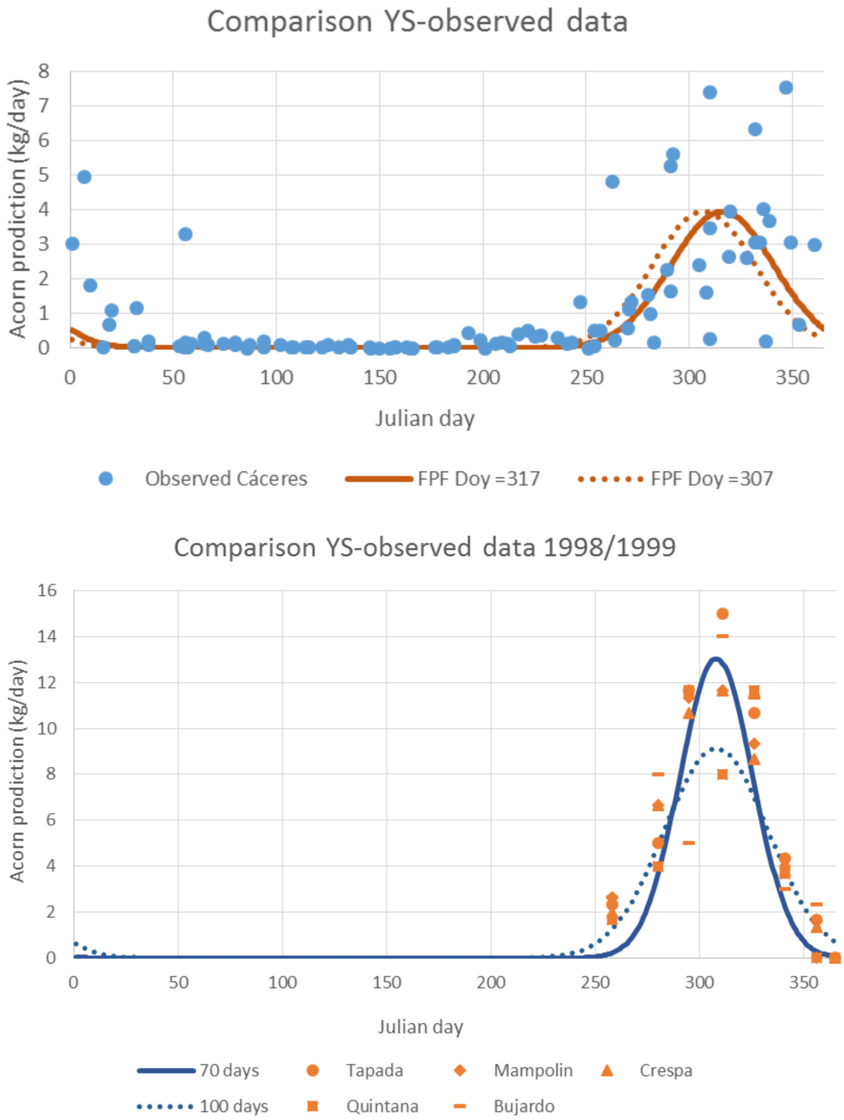


Figure 11. Comparison of the Yield-SAFE predictions by changing A) the Fruit Fall Peak DOY parameter in Cáceres and B) the number of fruit falling days parameter in Badajoz.

Yield-SAFE simulated cork oak stands growth for a period of 100 years for both sites from where data was available (Badajoz and Cáceres). In Figure 13 simulations are consistent in terms of height, tree biomass, diameter at breast height and canopy area (%) with previous studies using Yield-SAFE for cork oak plantations (Palma et al. 2014), while the estimated an annual acorn production per hectare at year 70, of 596 kg ha^{-1} and 406 kg ha^{-1} for Badajoz and Cáceres sites respectively are similar to those of Cañellas et al. (2007) and Table 7 and other previous studies in *dehesa* systems. For example, Gea-Izquierdo (2006), reported productions of around 250-600 kg ha^{-1} in *dehesa* system with 50 trees ha^{-1}, and other authors reported average values around 550 kg ha^{-1} (San

Miguel, 1994; Martín et al, 1998; Cañellas et al, 2007; Fernández-Rebollo and Carbonero-Muñoz, 2007).

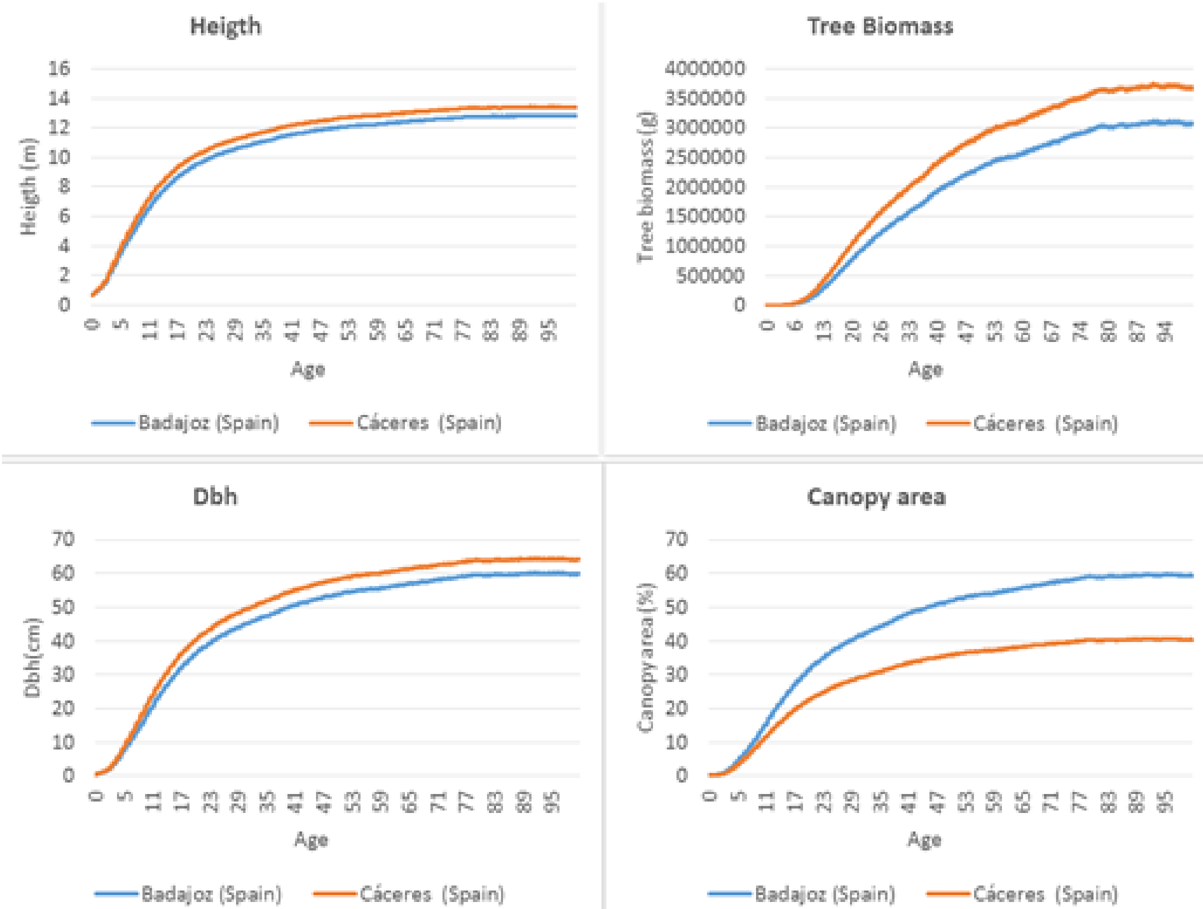


Figure 12. Yield-SAFE estimation for height, tree biomass, diameter at breast height (dbh) and canopy area in Badajoz and Cáceres sites. The latter is used for the tree fruit module.

Estimations obtained at tree level (Figure 13), with values going up to 18 kg tree^{-1} and 20 kg tree^{-1} for the Cáceres and Badajoz respectively are also consistent with results stated in previous studies reporting 15 kg tree^{-1} (Espárrago et al. 1993), 19 kg tree^{-1} Álvarez et al (2002), 20 kg tree^{-1} Medina-Blanco (1963) and 15 to 21 kg tree^{-1} (Gea-Izquierdo et al. 2008).

Considering the energy requirements of an Iberian pig that derives 48.7 MJ day^{-1} (Lopez-Bote et al 2000) from acorns, the dehesa system in Badajoz presents a carrying capacity for Iberian pigs up to 1.4 Iberian pigs ha^{-1} while the system in Cáceres presents just a maximum value of 0.96 Iberian pig ha^{-1} meaning that is needed more than one hectare to support the presence of an animal. The results seem consistent with the average carrying capacity reported for a good fruit productive dehesa of between 1 and 1.5 iberian pigs ha^{-1} (Lopez-Bote et al 2000).

The sequential days of carrying capacity expresses the potential number of following days the system is able to supply the energy requirements for the animal (what in Spanish/Portuguese is called *montanera/montanheira*). As the carrying capacity for Iberian pig of the system is over 1 pig ha^{-1}, the Badajoz system presents a maximum number of sequential days of 41. In Cáceres, however as the carrying capacity for the Iberian pig is below 1 pig ha^{-1}, there were no sequential days of carrying capacity, at least at an 1 ha level (Figure 13).

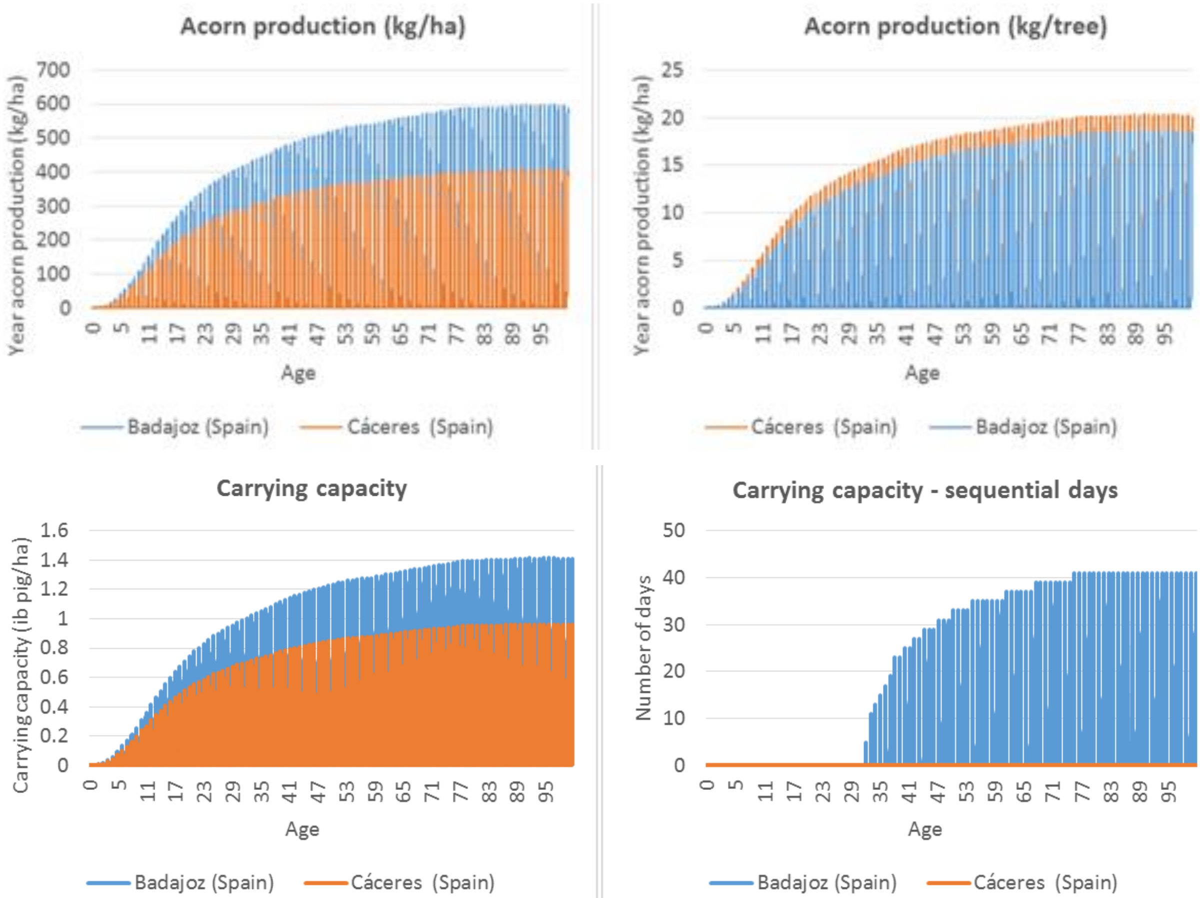


Figure 13. Yield-SAFE estimation of acorn production for Badajoz and Cáceres sites and carrying capacity for Iberian pigs and number of sequential days that the system can support at least one Iberian pig, for Badajoz and Cáceres sites

The section below (3.3) has been partially submitted to Agroforestry Systems (Oliveira et al. 2017) and has updates on the algorithms, in particular the productivity reduction linked to water stress (indirectly with tree density)

3.3 Microclimate and extension of grazing

The effect of trees on microclimate, in particular temperature and windspeed has influence in the evapotranspiration rates, influencing the water availability and dynamics in the system. Such interactions are now integrated in the Yield-SAFE model (see Palma et al. 2016b). Modelling the growth of permanent crops such as grassland has also been improved for the new version of Yield-SAFE (Palma et al. 2016d), although it does not yet capture the autumn yield phase probably due to the parameter simplicity of the model. However, the new algorithms demonstrate the delay of the decrease in yield in the summer period, which is critical when considering livestock grazing (Figure 14). Furthermore, in the example below, by comparing a "bad" and a "good" year (year 52 and 57 respectively), it becomes interesting to see that such "delay-effect" is more prominent, suggesting that trees provide resilience to the system, especially when climatic conditions are less favourable, in particular water scarcity.

A)

B)

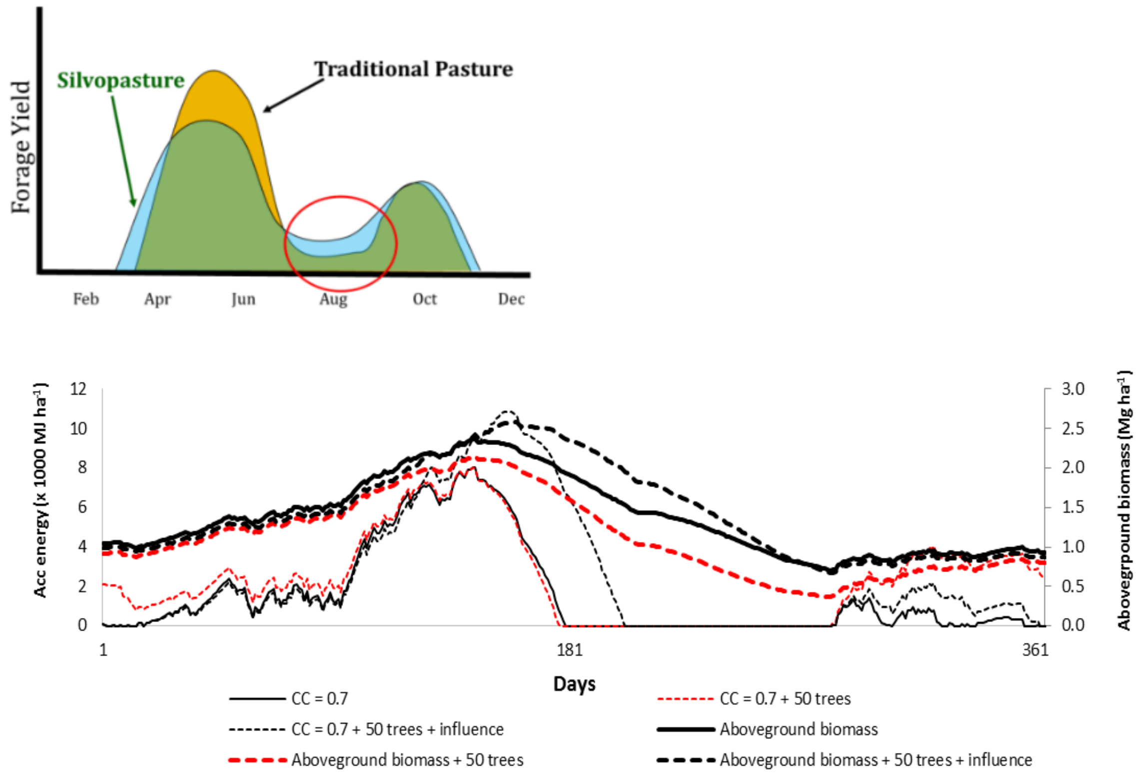


Figure 14. A) Theoretic schema comparing yields of pasture and silvopasture (adapted from Jacobson, 2016) and simulation of Yield-SAFE in a dehesa/montado silvopastoral system, with the effect of tree competition on pasture aboveground biomass and correspondent accumulated energy after reducing energy needs of a carrying capacity of 0.7, considering also the algorithms for influence of trees on wind and temperature

3.4 Soil carbon dynamics - RothC

A paper has been published (Palma et al. 2017b) regarding the RothC integration with Yield-SAFE. This section describes some of the key points.Palma, J.H.N., Crous-Duran, J., Graves, A.R., Garcia de Jalon, S., Upson, M., Oliveira, T.S., Paulo, J.A., Ferreiro-Domínguez, N., Moreno, G., Burgess, P.J. (2017). Integrating belowground carbon dynamics into Yield-SAFE, a parameter sparse agroforestry model. *Agroforestry Systems* DOI 10.1007/s10457-017-0123-4

RothC or the 'The Rothamsted Carbon Model' is a model for the turnover of soil organic carbon (SOC) developed by researchers at the UK agricultural research station Rothamsted Research (Coleman and Jenkinson 2014). The original model uses a monthly time step to calculate total organic carbon (Mg ha^{-1}), microbial biomass (Mg ha^{-1}) and $\Delta^{14}C$ (which allows the calculation of the radiocarbon age of the soil) on an annual to century timescale.

In brief, the model takes incoming organic matter inputs, and splits these into one inert (IOM) and four active soil organic matter pools. Active organic matter is split between two pools: Decomposable Plant Material (DPM) and Resistant Plant Material (RPM) following a ratio depending on the type of plant material. These two fractions are further split into three products of decomposition: CO_2, microbial biomass (BIO), and Humified Organic Matter (HUM). The proportion of SOC that is lost to CO_2 is determined by soil clay content (as this plays a function in the ability of organic matter to be immobilised in organo-mineral complexes). Both the BIO and HUM fraction are split again into subsequent CO_2, BIO, and HUM pools. A proportion of 46% BIO and 54% HUM for the BIO+HUM compartment is considered. BIO and HUM both decompose again to form more CO_2, BIO and HUM. On its turn farmyard manure applied as input material is considered to content 49% of DPM, 49% of RPM and 2% of HUM.

The integration of RothC model into Yield-SAFE excel version was done in several steps:

1. Translation into an Excel sheet of the RothC equations.
2. Transformation of the RothC model from a monthly step to a daily step model.
3. Addition of the translated RothC excel version into the Yield-SAFE excel version.
4. Link Yield-SAFE excel version weather information to RothC excel sheet.
5. Addition of soil data inputs (topsoil depth, clay content and initial carbon content) to the required inputs for Yield-SAFE excel version.
6. Development of an "Input plant material" value to act as input value for RothC as a sum of three different sources: 1) tree leaf fall; 2) root litter stored in soil and 3) carbon residues after harvest in turn computed as the sum of carbon coming from crop roots and from straw residues left on soil after harvest.
7. Calculation of evapotranspiration from Yield-SAFE considering the sum of the actual evapotranspiration, crop water uptake and tree water uptake
8. Development of a "Soil covered" value based on the presence/absence of tree or/and crop identified in Yield-SAFE as Y_{est} and Y_{escp} respectively to act as inputs for RothC sheet.

A scheme of RothC model integration into Yield-SAFE is presented in Figure 15.

As RothC model originally is a monthly-step soil carbon model and Yield-SAFE is a daily-step, basis weather and management inputs of RothC were transformed from monthly to daily values. The transformation was done by considering the total amount per month was equally distributed on 30 days. All months were considered to have 30 days. The complete list of parameters can be found in Annex V (Table 28; page 66) while implementation details on equations can be seen in Palma et al. (2016b).

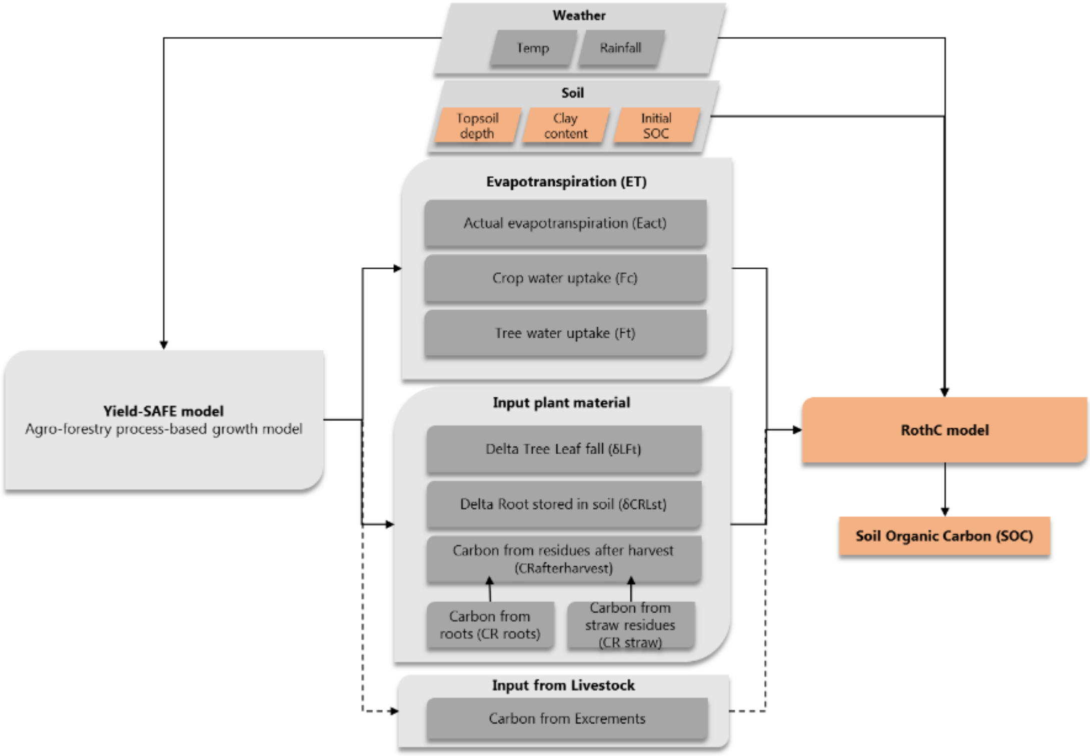


Figure 15. Schema of RothC model using Yield-SAFE outputs to feed the estimation of soil organic carbon. The livestock component is still under development.

For testing the model integration, both models were set up with the same soil and weather data, while the input plant material was estimated by Yield-SAFE. This input plant material was introduced manually in the RothC model. The observed datapoints considered are as suggested in Coleman and Jenkinson (2014) for the unmanured management plan. Input values related to soil information are presented in Table 8 whilst Table 9 presents the inputs related to weather and management.

Table 8. Inputs required for RothC model as proposed in Coleman and Jenkinson (2014)

Input	Unit	Value
Clay content of the soil	%	23.4
Topsoil depth	cm	23
An estimate of the decomposability of the incoming plant material - the DPM/RPM ratio[a]	None	1.44
Initial Carbon soil content	tC/ha	33.86

[a] DPM/RPM ratios are proposed in Coleman and Jenkinson (2014) for Agricultural crops and improved grasslands (1.44; 59% DPM and 41% is RPM), Unimproved grasslands and scrub (0.67; 40% DPM and 60% RPM); Deciduous or tropical woodland (0.25; 20% DPM and 80% RPM) and Farmyard manure (1; DPM 49%, RPM 49% and HUM 2%).

Yield-SAFE was then calibrated for barley (Hordeum vulgare) in Rothamsted (UK), resulting in the parameter set used in Yield-SAFE. The simulation of the integrated RothC into Yield-SAFE shows an interesting approximation to the observed data points from the Hoosfield experiment (Figure 15), for the three treatments (Manured, unmanured and partially manured).

Table 9. Weather and land management for the unmanured treatment as suggested values in Coleman and Jenkinson (2014)

Month	Average temperature	Monthly rainfall	Monthly evapotranspiration	Input plant material	Farmyard manure applied	Soil covered
Unit	°C	mm	mm	tC ha^{-1}	tC ha^{-1}	1 present, 0 absent
January	3.4	74.0	8.0	0	0	0
February	3.6	59.0	10.0	0	0	0
March	5.1	62.0	27.0	0	0	0
April	7.3	51.0	49.0	0.16	0	1
May	11.0	52.0	83.0	0.32	0	1
June	13.9	57.0	99.0	0.48	0	1
July	16.0	34.0	103.0	0.64	0	1
August	16.0	55.0	91.0	0	0	0
September	13.5	58.0	69.0	0	0	0
October	10.2	56.0	34.0	0	0	0
November	6.1	75.0	18.0	0	0	0
December	4.6	71.0	8.0	0	0	0

A)

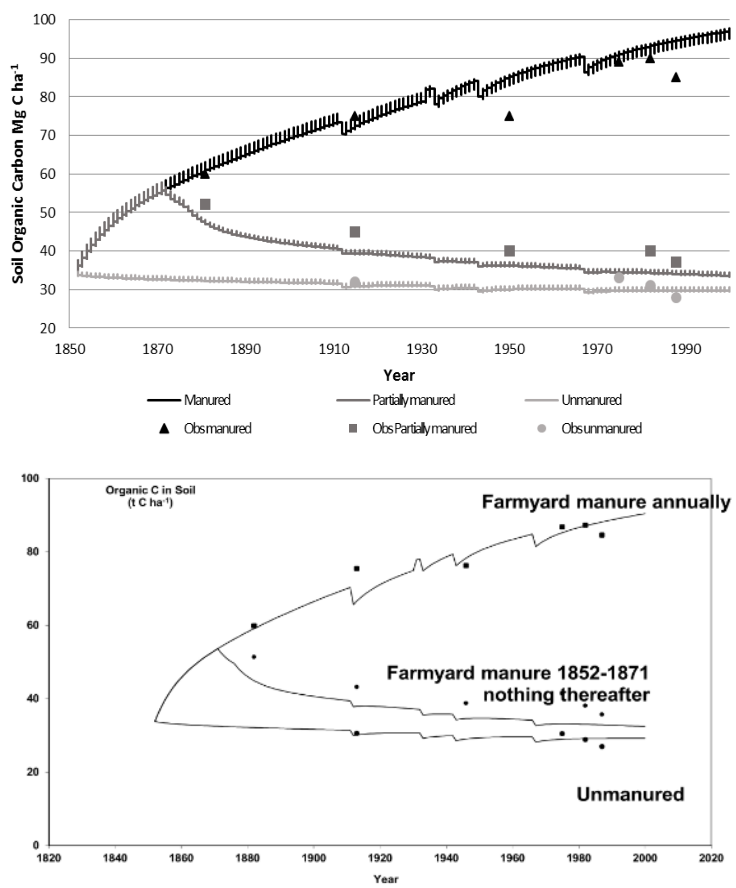


Figure 16. Observed datapoints from Hoosfield experiment (Rothamsted) and the predicted soil organic carbon with A) RothC integrated into Yield-SAFE and B) original simulation of RothC (Adapted from Coleman and Jenkinson, 2014).

The daily timestep integration of RothC into Yield-SAFE and the development of an “Input plant material” variable to act as input value for RothC based on the daily changes in tree leaf fall (δLFt), Root litter stored in soil (δCRLs) and carbon residues after harvest ($CR_{afterharvest}$) provides a daily dynamic for the different components. Figure 17A describes the daily soil incorporation of carbon while Figure 17B shows the annual accumulation in comparison with RothC results. Figure 17C shows the annual input of plant material estimated from Yield-SAFE-RothC (assuming barley) compared to the unmanured scenario of the Hoosfield experiment (annual input of plant material of 1.6 t C/ha).

A)

B)

C)

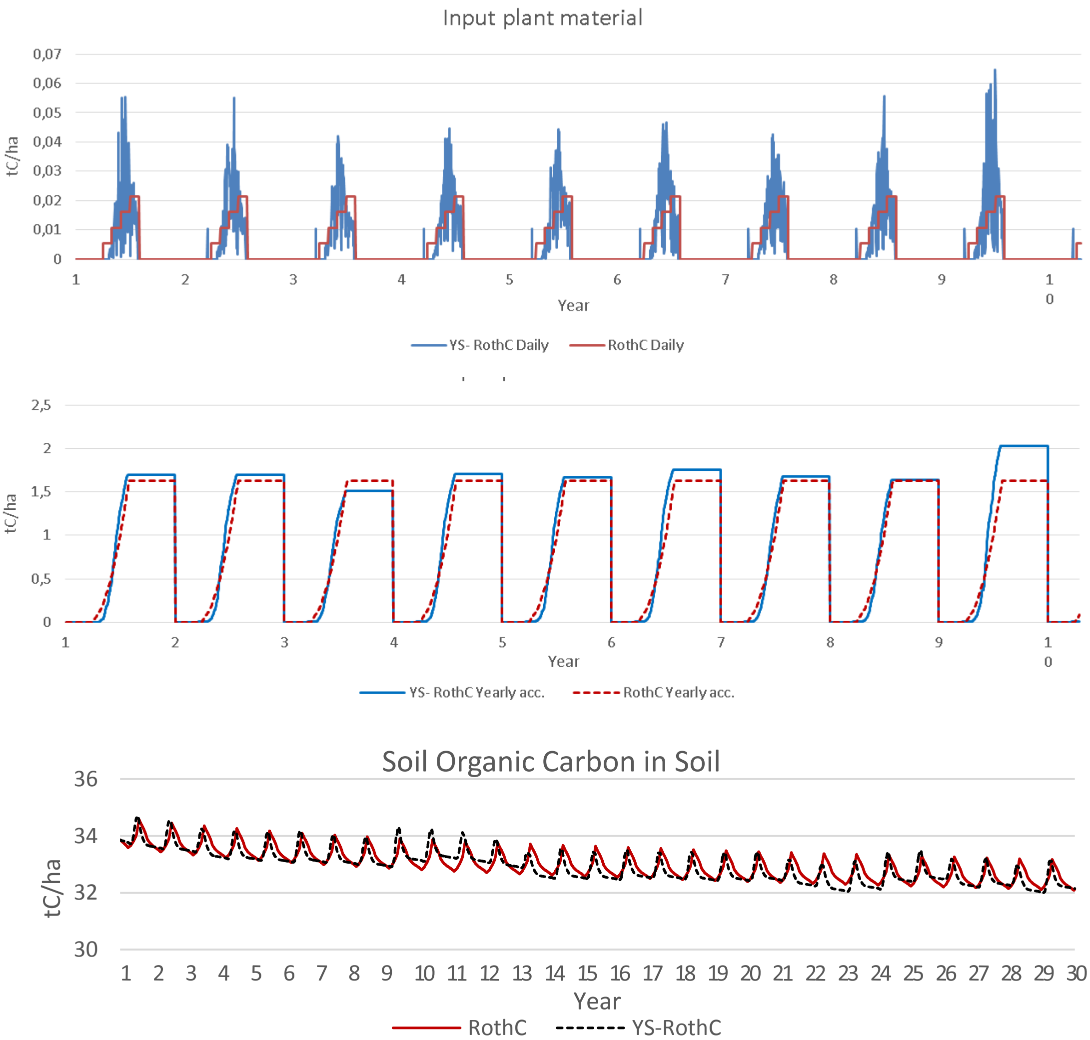


Figure 17. Comparison between the Yield-SAFE-RothC and the stand-alone RothC models, for the dynamics of the input plant material at A) daily and B) annual sum for the unmanaged scenario (1.6 Mg C ha^{-1}) while C) provides a comparison of soil organic carbon estimation between Yield-SAFE-RothC and RothC models for a period of simulation of 30 years.

A comparison of the soil organic carbon estimated using the integrated version of Yield-SAFE-RothC and the stand alone version of RothC, following the unmanaged scenario (Coleman and Jenkinson, 2014), shows that the new implementation of the model captures the essential components of the soil organic carbon dynamics demonstrated by RothC, which should allow the capacity to assess management practices under agroforestry. Improvements are undergoing to consider tree prunings and livestock excrements as source of additional carbon in the soil.

4. Steps to calibrate new species

An important process in using the model is the calibration of new species. During the modelling workshops of the AGFORWARD project, a recurrent question was "what are the steps to calibrate new species?" This section resumes the steps for users to calibrate new species for their own needs.

The main steps to calibrate new species in Yield-SAFE are:

- If you have an experiment with measurements, briefly **describe your data**
- Have **latitude and longitude** from your site (e.g. http://www.latlong.net/)
- **Soil depth** and **texture** (based on five classes from FAO)
- Set your management. Define:
  - **Thinning** (remember: mortality can be set as a thinning). Provide year and residual density
  - **Pruning** (when (year and DOY), how much (ratio of total above ground biomass is removed per pruning))
- **Review** tree/crop **parameters** from literature (see page 60 for tree parameters, page 63 for crop parameters)
- Check with the list of **Yield-SAFE outputs** (page 67) which data (and units) can be used for calibration, i.e. to compare with your observed data
- Set your tabular **measured data** prepared for **days of simulation** (count days since the January 1^{st})
- **Run** the model against your observed data
- Plot the **observed vs model predicted**
- **Calibrate/adjust the parameters** according to the physiological range of parameters from literature as much as possible. This can be done manually or automatically (the latter requires somehow advanced programming skills).

Typical examples of these steps can be seen in Annex VII (page 74).

4.1 Note on latitude and longitude

Longitude and latitude are needed for acquiring daily climate data. The coordinates will be used to retrieve data from CliPick, an online tool[8] developed under AGFORWARD project to ease the access to climate data for modelling (Palma 2015; Palma 2017). There are indications that the simulated climate can be used for calibration purposes with minor loss of quality in comparison to real data (Palma et al. 2017a). However, with CliPick, the user can check if the simulated data is providing an acceptable climate dataset for the given location. When doing this, it is recommendable to compare at 20 or 30 year averages.

4.2 Calibration procedure

First, the potential growth is calibrated using only irrigated data and "switching-off" the water module of the model. Secondly, other data from control plots are used with the water model turned on to calibrate the water related parameters.

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[8] http://home.isa.utl.pt/~joaopalma/projects/agforward/clipick/

For most of the calibration processes, a Python implementation of the model could be used for initial verification and parameter fitting optimization. This Python version of the Yield-SAFE model was prepared to use an optimization module with the L-BFGS-B algorithm (Byrd et al. 1995). In this technique, lower and upper bounds are set for each parameter value found in literature, and a minimization procedure is performed on the likelihood between observed vs modelled, providing the optimal set of parameters that best fit the observed measurements.

A Microsoft Excel© implementation of the model can also be used to edit the parameters manually, and provide a corroboration of the calibration results, including a more graphic interpretation of the results (Graves et al. 2010).

Since tree volume, height and diameter are all dependent of tree biomass values, for the first stage, only biomass and leaf area were used for the calibration procedure. The parameters for which there were values in the literature are set and the other ones are allowed to vary between biologically relevant values.

On a second stage, volume, height and diameter values are also considered and a manual calibration is made changing each parameter value at a time.

When the potential growth is calibrated, the control measurements are used to calibrate the water related variables (water use efficiency, and soil pF critical for initiating water stress), while fine-tuning the other parameters as a whole.

5. Ecosystem services at plot and farm scale using Yield-SAFE

This section has been accepted as a paper for Agroforesry Systems (Crous-Duran et al. 2017).

After the Convention on Climate Change in Rio de Janeiro, in 1992, the concept of Ecosystem Services (ES) was discussed and several definitions proposed (Daily 1997; Millennium Ecosystem Assessment 2005). In Fisher et al. (2009), ES are seen as aspects of ecosystems (actively or passively) used to provide human well-being. After several attempts of classification (Wallace 2007), ES were divided into three main categories that directly affect people: 1) Provisioning ES (PES) which considers food, materials, or energy outputs from ecosystems; 2) Regulating ES (RES) which include services where ecosystems act as regulators on water, soil, or air quality; and 3) Cultural ES (CES) including aspects related to the recreation and subjective services offered by ecosystems. A fourth category is also typically considered: Supporting services which include those which facilitate the other three categories (Millennium Ecosystem Assessment 2005).

A consensus is also growing on classifying these contributions as intermediate or final services. Intermediate services are ecosystem characteristics measured as ecosystem structure, processes, and functions that support final services. Final services are components of nature possessing an explicit connection to human well-being, meaning that they have direct value to society (Boyd and Banzhaf 2007). Therefore, the amount of human welfare provided depends on the ecological conditions of the respective ecosystems which, in turn, are affected on how they are managed.

In order for land-managers and other decision-makers to practically use this ES concept, credible and legitimate measurements are needed to estimate the potential existing trade-offs between ES (Maes et al. 2012). In ecology, biophysical models (empirically- or process-based) are usually used to estimate how specific ecosystem indicators evolve at different spatial and temporal scales. One of the best ways of determining the impacts of management decisions is through the use of process-based models (Cuddington et al. 2013; Wong et al. 2014).

During the project, the Yield-SAFE model was calibrated for several agroforestry systems in Europe and was improved with algorithms to estimate Provisioning Ecosystem Services (PES) i.e. the food, material and energy produced. These algorithms were then tested in four different agroforestry systems and applied to variations of each system differing in tree densities and crop area. The Yield-SAFE model offers the possibility to analyse how the supply of PES is related to tree density and how this supply varies from monoculture systems (no trees), through agroforestry, to forestry (with high tree density). Considering there can be three main components (trees, crops and livestock) and each can provide three main types of PES (food, material and energy) there are potentially nine combinations of PES (Table 10).

Table 10. Potential combinations of provisioning ecosystem services (PES) supplied by the components of an agroforestry system

		Agroforestry component		
		Tree	Crop	Livestock
PES	Food	Food-tree	Food –crop	Food-livestock
	Materials	Materials-tree	Materials-crop	Materials-livestock
	Energy	Energy-tree	Energy-crop	Energy-livestock

Examples of the types of PES are shown in Table 11. For a better comparison, all PES are translated into an energetic unit per unit of area and per unit of time (MJ ha^{-1} d^{-1}).

Table 11. Examples of Provisioning Ecosystem Services (PES) provided by agroforestry

		Agroforestry component		
		Tree	Crop	Livestock
PES	Food	Fruits	Grain	Meat, dairy products
	Materials	Timber, cork	Straw	Leather, wool
	Energy	Fuelwood	Bioethanol	Excrement, manure

5.1 Case studies

The Provisioning Ecosystem Services and how they are affected by tree densities were analysed in four different agroforestry systems. The four systems selected were: 1) The Iberian wood pastures (Dehesas in Spain or Montados in Portugal); 2) the Swiss cherry tree pastures; 3) a silvoarable system in England and 4) an alley-cropping system with fast-growing tree plantations for energy purposes in Germany. These four systems were chosen for three main reasons: 1) they represent different climate conditions; 2) the different agroforestry components that conform it; and 3) the availability of information of long-term experimental trials among the partners in the project.

5.1.1 Montado in Portugal

For this assessment the *Montado* is assumed to be a pure holm oak plantation providing acorns between September and January and grass during all the year for feeding livestock. Regular light prunings occur every 12 years removing 10% of total biomass (Olea and Miguel-Ayanz 2006). The typical dehesa presents low tree densities (20-50 trees ha^{-1}). For this assessment we considered agroforestry densities of 50, 100, 150 and 200 trees ha^{-1} with 99% of pasture area respectively. The monoculture land use alternatives are represented as a “pure pastures” (0 trees ha^{-1}, 100% crop area) and a forest alternative, a holm oak plantation with a starting planting tree density of 505 trees ha^{-1} with successive thinning until a tree density of 100 trees ha^{-1} at year 100.

The final services provided by the system include food provided by livestock (meat) and energy from trees, i.e. wood for heating from tree prunings and thinnings (Table 12). Livestock is considered to be fed by acorns (when present) and pasture. Livestock food is quantified in Livestock Units (LU). Each LU represents a reference animal (dairy cow) with energy requirements of 103.2 MJ d^{-1} (McDonald et al. 2010). Acorns and pastures ingested are converted into energetic units by considering the UME contained (See Section 3.2, page 9). UME values used for acorns and grass are 17600 MJ Mg^{-1} and 10270 MJ Mg^{-1} respectively (Rodríguez-Estévez et al. 2010). For estimating energy provided by wood from thinnings and prunings the calorific value was used. For holm oak wood this values is 14000 MJ Mg^{-1} (Imflorestal 2014) .

Table 12. Considered provisioning ecosystem services provided by Montados

		Agroforestry component		
		Tree	Crop	Livestock
PES	Food	Acorns*	Natural grasslands*	Meat
	Materials	-	-	-
	Energy	Fuelwood	-	-

*Acorns and pastures are considered for feeding livestock.

5.1.2 *Cherry tree pastures in Switzerland*

Cherry tree orchards, or also known as *Streuobst* or *Pré-verger* are traditional agroforestry systems widely spread in Central Europe (Nerlich et al. 2013). These systems consist of tall fruit trees mixed in tree species, variety and age managed on grassland or cropland (Herzog 1998a). Tree densities varies from 20 to 100 trees per hectare, with the most common fruit tree species being apples (*Malus* spp.), pears (*Pyrus* spp.), plums (*Prunus domestica*) and/or cherry trees (*Prunus avium*) that were planted to primarily provide fruits but also to obtain timber. The grassland was traditionally used as meadow or pasture for feeding animals. Despite a steady decline over the last years, these systems currently cover around 0.4 million ha of agricultural land (Herzog 1998b; Eichhorn et al. 2006).

Cherry orchards are of great significance in Switzerland (Schüpbach et al. 2009; Sereke et al. 2015). The system consists of around 80 cherry trees per hectare of different ages on grassland where livestock grazes freely. The system provides cherries during summer (June-July) and grass as fodder for cattle or sheep for the whole vegetation period (Schmid 2006; Sutter and Albrecht 2016). The cherries are mainly used for liquor, canned or used for direct consumption. Overall the system provides fruits and grass every year and prunings every third year. It is considered that 1% of the total biomass is pruned to ensure a constant fruit production. Timber is mainly used for furniture and is obtained in year 80 with the final cut of the tree.

The provisioning ecosystem services (PES) provided by cherry tree pastures are indicated in Table 13. These include cherries, timber and wood for heating from trees and meat from livestock estimated indirectly depending only on pasture production. The variations of the system considered include a "pure pastures" alternative (0 trees ha^{-1} and 100% of crop area), four agroforestry alternatives with different tree densities 26, 52, 78 and 104 trees ha^{-1}) and a forestry alternative willing to simulate a cherry tree plantation with a starting planting tree density of 690 trees ha^{-1} and a final tree density of 110 trees ha^{-1} at year 60. It is considered pastures occupy the 99% of the area in agroforestry and forestry alternatives. The UME provided by cherry fruits and Swiss pastures is 7000 MJ Mg^{-1} and 10500 MJ Mg^{-1} respectively (Biertümpfel et al. 2009). Cherry tree wood has an energy value of 18260 MJ Mg^{-1} (Telmo and Lousada 2011). In the "forestry" alternative the wood from thinnings were considered to be used as a source of energy.

Table 14. Considered provisioning ecosystem services provided by cherry pastures in Switzerland

		Agroforestry component		
		Tree	Crop	Livestock
PES	Food	Cherries	Natural grasslands*	Meat**
	Materials	Timber	-	-
	Energy	Fuelwood	-	-

*Pastures are used for feeding livestock. ** Meat is quantified in Livestock Units (LU)

5.1.3 *Silvoarable systems in the UK*

Some of the silvoarable systems in the UK are experimental sites of trees lines planted with arable crops in the alleys (Beaton et al. 1999; Burgess et al. 2005). The tree component consists either of top fruit or timber trees species such as poplar (*Populus* spp). The arable crops in the alleys are mainly cereals such as wheat (*Triticum* spp), barley (*Hordeum vulgare*), oats (*Avena sativa*) or oilseed rape (*Brassica napus*) (Smith 2015; Smith and Venot 2015).

Silvoarable agroforestry integrating poplar trees for timber with cereal crops is a traditional way of managing poplar trees for matchstick production in the UK. In 1992 four poplar hybrids for timber (Beaupré, Trichobel, Gibecq, and Robusta) were planted at three sites in England, including Silsoe in Bedfordshire, with uncropped and cropped plots including wheat, barley and winter beans. The crops in the alleys were managed in the same was as in a control arable treatment. The trees were planted at a spacing of 10 m × 6.4 m offering a tree density of 156 trees ha^{-1} with rows oriented north-south (Burgess et al. 2005). The combination of poplar trees for timber and cereals intercropped offers the supply of materials (timber) and food (grain from cereals). For the modelling exercise, cereal straw was considered as a material product. The simulation period includes four rotations of 20 years each with trees being replanted at the end of each rotation. The tree densities analysed were of 39, 78, 117 and 156 trees ha^{-1}. The “forestry” alternative followed a thinning regime as proposed in Burgess et al. (2003) with a starting density of 1250 trees ha^{-1} reduced to 158 trees ha^{-1} at year 12. During tree growth wood from formation pruning are considered to be left on the ground. For the modelling it was assumed that the trees are located in a 2 m wide line each line separated by 10 m so machinery can work during field operations. In agroforestry alternatives, tree density is increased by reducing distance between trees in the tree line. Therefore for all the alternatives with tree presence crop area remains constant (80% of the total area). The UME provided by wheat, barley and oilseed are 16630 MJ Mg^{-1}, 16960 MJ Mg^{-1} and 19450 MJ Mg^{-1} (Rymer and Short 2003; Cervantes-Pahm et al. 2014). Poplar wood is mostly used for the manufacture of paper or as low quality hardwood timber for fruit/vegetables wood boxes, pallets and cheap plywood. In order to consider energetic content of materials (firewood and straw) these are considered to be burnt. Calorific value used for poplar is 19380 MJ Mg^{-1} (Sannigrahi and Ragauskas 2010) and of 17300 MJ Mg^{-1} for wheat, 16100 MJ Mg^{-1} for barley and 14000 MJ Mg^{-1} for oilseed straw (McKendry 2002). The PES provided by poplar silvoarable can be resumed in Table 15.

Table 15. Considered provisioning ecosystem services provided by silvoarable systems in UK

		Agroforestry component		
		Tree	Crop	Livestock
PES	Food	-	Wheat, barley, oilseed	-
	Materials	Timber	Wheat, barley, oilseed, straw	-
	Energy	Wood from pruning and thinning.		-

5.1.4 *Short rotation coppice in Germany*

Short-rotation coppice (SRC) with poplar or other fast-growing species for the production of bioenergy is currently gaining interest within the framework of global energy supply. In temperate zones these systems offer an approach for the production of a sustainable biomass feedstock, thus matching the increasing demand for a self-sufficient energy supply in rural decentralized areas (Gruenewald et al. 2007). Currently in Germany alley cropping systems combining rows of fast growing trees of poplar (*Poplar* spp) and black locust (*Robinia pseudoacacia*) with agricultural crops only exists as experimental fields in Mariensee, Wendhausen, Dornburg, Welzow-Sued and Forst (Mirck et al. 2016).

In Forst (north-eastern Germany) during years 2010 and 2011 an alley cropping agroforestry trial was established. The system included 11 m wide hedgerows with crop alleys ranging in widths from 24 to 96 m. The tree hedgerows consisted of poplar varieties Max 1 (*Populus nigra* L. × *Poplar maximowiczii*) and Fritzi-Pauley (*Poplar trichocarpa*) and black locust (*Robinia pseudoacacia*). The trial area occupied around 40 ha and tree densities were between 8715 tree ha^{-1} and 9804 tree ha^{-1} depending on whether a single or double row design was used. Currently these alley cropping systems occupy around 175 ha in Germany.

The combination analyzed for this study includes a poplar Max 1 variety (*Populus nigra* L. × *Poplar maximowiczii*) short rotation coppice system (SRC) with double winter wheat (*Triticum durum*) and fallow crop rotation. The tree coppicing rotation considered is every four years and therefore 20 rotations are considered for the 80 years of the period simulated. Every three rotations trees are replanted. Alternatives considered include a “pure agriculture” and a “pure SRC” and four agroforestry alternatives. The agroforestry alternatives differ in their crop alley width while SRC lines remain 11 m wide and consist of four double rows of poplar. Four different crop alleys widths are considered: 24, 48, 72 and 96 m. For the agroforestry alternatives, within the SRC lines, it is considered that the 2 double rows located in the middle act as pure SRC while the 2 double rows located on the sides are considered to interact with the crop. The Provisioning ES supplied are shown in Table 16 and include the supply of the food from cereal grain; materials from wheat straw and the energy provided by the tree component. The UME provided by wheat is 12000 MJ Mg^{-1} (Cervantes-Pahm et al. 2014); the heating value of wheat straw is 17300 MJ Mg^{-1} (McKendry 2002) and the heating value considered for hybrid poplar wood is 19380 MJ Mg^{-1} (Sannigrahi and Ragauskas 2010).

Table 16. Considered provisioning ecosystem services provided by short rotation coppice in Germany

		Agroforestry component		
		Tree	Crop	Livestock
PES	Food	-	Wheat grain	-
	Materials		Wheat straw	-
	Energy	Wood		-

*It is considered that pastures are used for feeding livestock. ** Meat is quantified in Livestock Units (LU)

Table 17 summarises the set up of the management alternatives for the four land use systems analysed. In terms of tree spatial distribution, the Montado system is considered to have equidistant trees, while in the other three systems, trees are in tree lines in order to offer enough space for machinery working. For "forestry" alternatives, the initial tree densities are shown.

Table 17. Details of the system alternatives analysed in the study

System	Alternative	Tree density (trees ha^{-1})	Crop area (%)	Livestock	Period of simulation (years)	Notes
Holm oak *Montado*	MONTPT-Pure pasture	0	100	LU	80	Trees remain in stand after the simulation period
	MONTPT-AF1	50	99	LU	80	
	MONTPT-AF2	100	99	LU	80	
	MONTP-AF3	150	99	LU	80	
	MONTPT-AF4	200	99	LU	80	
	MONTPT-Forestry	505	99	LU	80	
Cherry Tree Pastures	CTCH-Pure pasture	0	100	LU	80	Trees are cut down at the end of the period
	CTCH-AF1	26	99	LU	80	
	CTCH-AF2	52	99	LU	80	
	CTCH-AF3	78	99	LU	80	
	CTCH-AF4	104	99	LU	80	
	CTCH-Forestry	690	99	LU	80	
Silvoarable system	SAFUK-Pure agriculture	0	100	-	4 x 20	Trees are replanted after 20 years
	SAFUK-AF1	39	80	-	4 x 20	
	SAFUK-AF2	78	80	-	4 x 20	
	SAFUK-AF3	117	80	-	4 x 20	
	SAFUK-AF4	156	80	-	4 x 20	
	SAFUK-Forestry	1250	80	-	4 x 20	
Short Rotation Coppice	SRCDE-Pure agriculture	0	100	-	20 x 4	Trees are replaced after third rotations
	SRCDE-AF1 (96m)	497	94	-	20 x 4	
	SRCDE-AF2 (72m)	691	93	-	20 x 4	
	SRCDE-AF3 (48m)	905	90	-	20 x 4	
	SRCDE-AF4 (24m)	1516	81	-	20 x 4	
	SRCDE-Pure SRC	9672	0	-	20 x 4	

** Dairy cows are used as reference livestock units (LU) for energy requirements. ** A thinning regime was applied for the forest alternative reducing the initial tree identity.*

5.2 Estimation of food

The definition of food includes all the products intended for human consumption. In terms of food production, Yield-SAFE is now able to estimate food provided by tree and crop or, indirectly by livestock if the crop is used as feedstock. From trees, Yield-SAFE is able to estimate fruit production considering canopy cover and leaf area index (LAI) following the methodology presented in Section 3.2.3. The model also offers the possibility to consider if the fruits are eaten by livestock or picked up for other uses (not eaten) as for example: for direct human consumption or transformation in liquor or marmalade. This management option is important for some of the systems analysed such as the Portuguese Montado or the Spanish Dehesa where livestock, usually cows or Iberian pigs, require energy from acorns for a better growth and for obtaining a certified quality stamp.

Most of the crops calibrated for Yield-SAFE can be categorised in two big groups: 1) cereals, including grasses cultivated for grain (e.g. winter wheat, oats, rye, barley or maize) and 2) pastures: grasses with a mix of species including leguminous species that are mainly sown for grazing, or, natural grasslands. Also, other root-yielded species like sugar beet (*Beta vulgaris*) or shrub-type crops such as asparagus (*Asparagus officinalis*) were calibrated with some parameter adjustments of Yield-SAFE.

For cereals, the original version of Yield-SAFE (2007 version, van der Werf et al. 2007b) was already able to differentiate between grain and straw by using harvest index from the crop total biomass. In this case just grain is considered to be used directly as food and the available energy is derived by using the grain Utilizable Metabolic Energy (UME in MJ Mg^{-1}).

As mentioned before, livestock production (meat) is estimated using the carrying capacity methodology implemented into Yield-SAFE and explained in detail in Section 3.2. The methodology depends on the combination between the UME provided by the tree and/or crop and the Livestock Unit Energy Requirements (LUER). The reference LUER used is 103.2 MJ d^{-1} as suggested by Hodgson (1990). In the case of fruits and pasture, UME is a value for the whole biomass but for cereals, there are different values of UME for the grain and the by-product (e.g. straw). The possibility of using grain to feed livestock could be considered in Yield-SAFE but by default Yield-SAFE considers that is used for other uses.

5.3 Estimation of materials

Raw materials are considered all the material outputs supplied by the systems that are neither used for human nutrition nor for obtaining energy. These products are mostly used to be part of other structures or are transformed into other products. Examples of raw materials are timber for building wood structures, wood boxes or furniture; bark from cork oak can be transformed into cork stoppers or isolating panels; wool from sheep; or livestock manure that can be used as fertilizer.

In this assessment silvoarable systems in the UK and the cherry tree pasture systems in Switzerland provide materials from trees. In the UK system the tree element (poplar tree) is managed to obtain timber. Poplar wood is soft and therefore the primary use of poplar wood is as biomass boiler fuel but is also well-suited for the manufacture of quality paper or can be sawn into lumber as low quality wood for use in pallets or wood boxes for fruit or vegetables. In the Swiss cherry wood pasture system, after 80 years, the cherry tree is cut down to obtain timber for furniture manufacturing. Also straw from crops in the UK and from short rotation coppice in Germany are considered to be materials and its energetic value is estimated using their heating value. There is no direct method to quantify the energy accumulated in materials. For this assessment, the higher heating value (MJ Mg^{-1}) of timber and crop straw as the energy accumulated in these materials is considered. For all the systems, wood from thinning regimes is considered to be dedicated to energy as the required size may not be attained for other purposes.

5.4 Estimation of energy

The energy supplied by the systems is assumed to come directly (e.g. bioenergy dedicated plantations) or indirectly (e.g. prunings) from the tree component. The use of straw as an energy source is not considered as it was assumed to be harvested as a material. The direct source of energy implies that a key objective of the system is, for example, to maximize wood supply for bioenergy electric-plants as is the case for the SRC system in Germany. The indirect source of energy considers that the main management objective is not the production of wood for energy but it is available due to some management operations related to the main objective of the system. For example wood from formation pruning or thinning that are required for the Portuguese and Swiss silvo-pastoral pastures are considered as a source of energy although fruit and timber quality are the main management objectives. It is assumed that the operations of pruning and thinning increase fruit production and improve the quality of the timber. The wood harvested from these field operations is usually used by local people for firewood.

5.5 Results

The use of an energetic unit allowed at a first instance the standardization of the produced PES into a common "currency" so the total food, materials and energy could be related together. Furthermore the results could be compared with other management alternatives and other agroforestry systems. For validation, the systems were simulated in areas where they are present and where experimental data is available, making possible to compare the predicted results with existing measurements.

Generally, all the systems increase their energy accumulated until the end of the period with the increase of tree density except in the Montado system, where the "agroforestry" alternatives present a slight decline at the end of the simulation period. The "forestry" alternatives assumed common management practices related to pure tree plantations to optimise tree growth. The forestry plantation usually starts with a higher tree density that is reduced over time following a thinning regime. The thinning regime provides the benefit of increased growing space to the remaining trees and improves the quality of the stand by removing defective trees while also providing intermediate financial returns (Jobling 1990). For "agroforestry" alternatives it is considered that the final tree density is plantation density. The wood from thinnings, considered to be used as fuelwood, increases significantly the amount of energy accumulated by the systems meaning that at the end of the simulation period the "forestry" alternatives accumulate more energy compared to other alternatives.

The first results of the energy accumulated by the systems at year 80, provides an idea of the intensity in which systems are managed or could be managed. In Figure 18, a traditional agroforestry system such as *Montado*, where the tree is the main component and remains in stands for hundreds of years, while usually located in dry areas with grass yields to between 1 and 2 Mg ha^{-1}, offer lower levels of energy accumulated for the simulated period compared to cherry tree pastures in Switzerland, a similar system where also the tree is the main component, where fruits are used for human consumption but, due to a more favourable climatic condition, trees grow faster and grass offers higher levels of yields, between 4 and 12 Mg ha^{-1} (Sereke et al. 2015). One of the differences is that holm oaks need around 80 years to be considered mature while cherry trees need less than half of that time. Both systems are usually managed for extensive meat production as the main activity consists in extensive livestock grazing in natural grasslands and the presence of scattered trees provide additional output products, such as fruits, cork or simply shelter for animals under heat or cold weather.

On the other hand, modern agroforestry systems such as the silvoarable systems in the UK or the short rotation coppice for energy are specifically designed to maximise production by, for example, using improved clones or more efficient tree varieties. Even though, the differences between both systems are evident as the "pure agriculture" alternatives in the silvoarable systems in UK present double the yield of a similar rotation in the short rotation coppice in Germany.

Materials tend to be more significant depending on the use that is considered. The calorific value of the wood or straw for energy or for materials considered tends to be superior to the energy available if the products are for human or livestock consumption (UME).

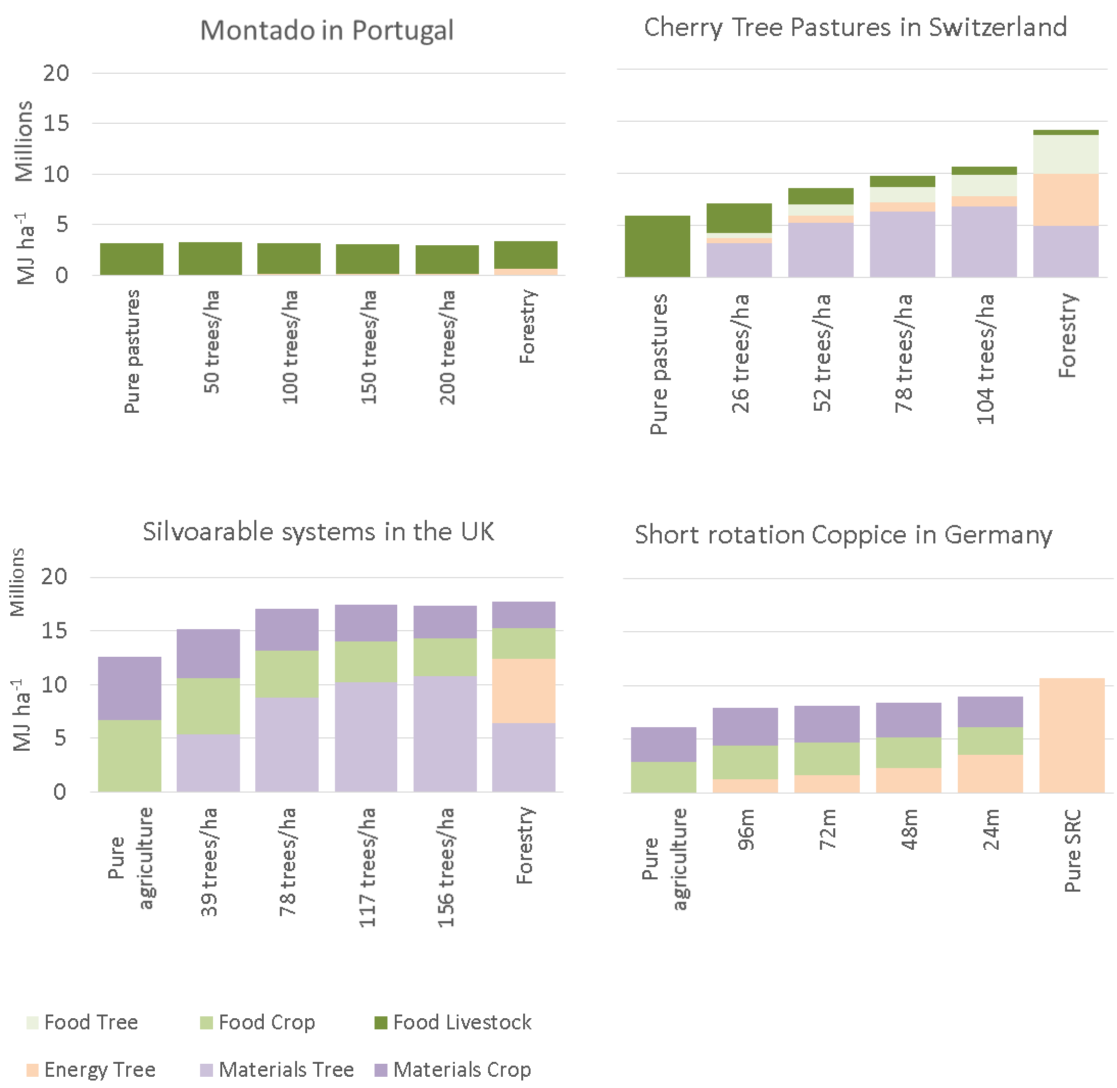

Figure 18. Modelled accumulated energy provided over 80 years by provisioning ecosystem services for six management alternatives in four agroforestry systems across Europe.

5.5.1 Montado in Portugal

Montado is an example of an extensive silvopastoral system and livestock are fed on natural grassland while acorns provide an additional energy source. Modelling suggests that, regarding PES, there is a decrease in the provisioning of food provided by livestock as tree density increases or when trees grow along the simulation period (Figure 19). In the Forestry alternative there is some energy compensation provided by thinnings and prunings but for all the other agroforestry alternatives the simulations suggest there is a lower amount of daily energy supplied for livestock. This decrease is associated to the loss of pasture due to competition for water and light which is not compensated by the amount of acorns produced by trees and therefore, a decrease of the amount of energy available for livestock.

Furthermore, in Montado systems, trees remain in stands for more than 200 years. Therefore at the end of the simulation period, the trees are neither cut down for energy purposes nor for timber. Hence the Montado have the lower levels of energy when compared to the other systems analysed.

Figure 19. Modelled comparison of the daily food energy provided by livestock (MJ ha^{-1}) for six *Montado* alternatives.

Figure 20 shows the evolution of the average yearly value of the food provided by the livestock component (Food: livestock) of the six management alternatives proposed for Montado. Only the simulation of “pure pasture” maintains a consistent value over the energy threshold of one livestock unit of 103 MJ d^{-1}. All of the other alternatives result in a decrease, with the largest decreases occurring at high tree densities. Interestingly, the model estimates a slightly higher initial energetic content in the systems where trees are present, either agroforestry or forestry. This is due to the new algorithms where the presence of tree affects the microclimate and particularly the wind speed, decreasing evapotranspiration and therefore increasing soil water content and consequently leading to an increase in pasture yield. However, at later stages, the tree growth imposes water and light competition leading to lower pasture yield compared to a treeless pasture.

Livestock carrying capacity units are estimated by directly converting resources into livestock energy needs. However conversion losses can occur due to damage caused by cattle trampling, manure covering the ground (daily livestock excrements are about 10% of their weight (USDA 2013)), and inaccessibility (e.g. steep slopes). These negative interactions, could explain the value of 0.9 LU ha^{-1} obtained for the 50 trees per hectare alternative which is higher than an optimal montado carrying capacity for livestock grazing in current ecological conditions for southern Portugal suggested by

Godinho et al. (2014) of 0.6 LU ha^{-1} (61.92 MJ day^{-1}) and higher than the average value observed in the year 2000 in Dehesas of Spain of around 0.45 LU ha^{-1} (Palomo 2017).

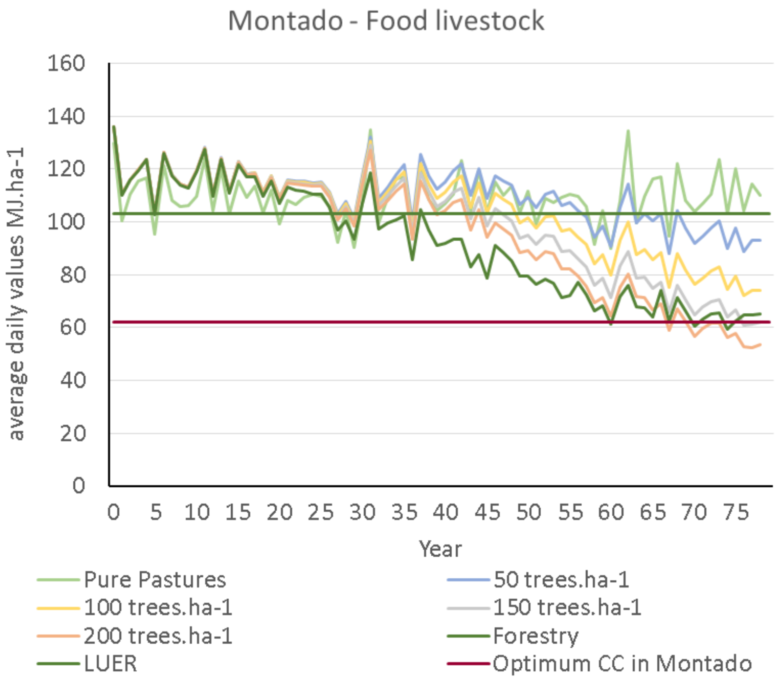

Figure 20. Modelled comparison of food provided for livestock (MJ ha^{-1} d^{-1}) for the six *Montado* management alternatives with reference thresholds for 103.2 MJ d^{-1} (one livestock unit energy requirement) and 61.92 MJ d^{-1} (0.6 LUER), the Montado carrying capacity suggested by Godinho et al. (2014).

5.5.2 Cherry tree pastures in Switzerland

The cherry tree pastures was the analysed system that offers the greatest diversity of PES while, at the same time, offers the highest accumulated energy. The cherry tree offers fruits for human consumption, timber for materials, and energy from tree thinnings. Cherry trees allow the presence of natural pastures where livestock can graze freely during the initial years but pasture yield decreases with tree growth and carrying capacity is reduced.

Figure 22 suggest that as tree density increases more energy is generated by the system with the "forestry" system accumulating most energy in total. The presence of trees, supplying fruits, wood, prunings and thinnings compensates for the loss of energy from the reduced productivity of the pastures. At the end of the simulation period most of the energy accumulated comes from timber when the stems are cut to obtain wood for furniture.

In terms of timber production, the obtained results are in line with previous studies. For example, Sereke et al. (2015) presents values of 1.34 m^3 tree^{-1}, 1.14 m^3 tree^{-1} and 1.07 m^3 tree^{-1} of wild cherry timber in Switzerland for 40 and 70 trees ha^{-1} agroforestry systems and a "forestry" system with a starting tree density of 816 trees ha^{-1} that declines to 100 trees ha^{-1} in year 60. These values are slightly lower than those obtained in our simulation in year 60 between 1.3 and 1.5 m^3 tree^{-1} for 26 trees ha^{-1} and 52 trees ha^{-1}; respectively while 1.4 m^3 tree^{-1} for 78 trees ha^{-1} could be explained by the fact that the initial and final tree density are equal and therefore no differences in tree competition is occurring. In the "forestry" alternative with a tree density of 110 trees ha^{-1} in year 60, the corresponding value was 0.8 m^3 tree^{-1}. Regarding fruit production, the results seem to be slightly lower than those suggested by Sereke et al. (2015) of 41 kg tree^{-1} as the simulated fruit production in year 60 ranges from 27 kg tree^{-1} for a "forestry" tree to 35 kg tree^{-1} at a density of 26 trees per hectare.

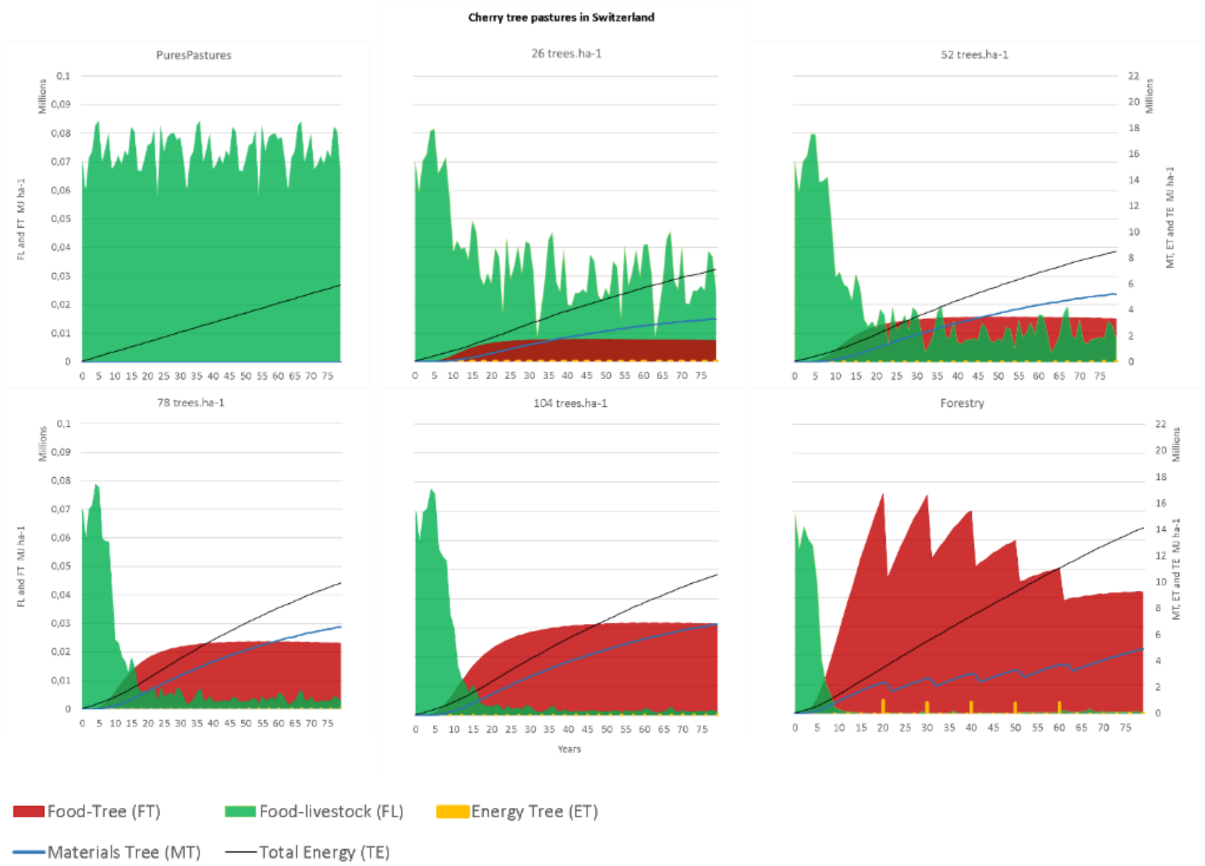

Figure 21. Modelled comparison of the total energy accumulated in 80 years for the six management alternatives with cherry tree pastures system in Switzerland.

The energy derived from tree source increases with time and tree density (Figure 22A). However, in agroforestry systems, there is a steady-state process after year 25. The "forestry" alternative at maturity presents similar energy levels than agroforestry at 156 trees ha^{-1}, although having an earlier phase with higher productivity. However, the higher productivity leads to a heavier impact on pasture production (Figure 22B) while agroforestry systems provide additional yield for longer periods. The "pure pastures" alternative maintains energetic values at levels that are able to support almost 2 LU, while agroforestry systems with 26 trees ha^{-1} is the only "agroforestry" alternative able to maintain at least 1 LU until year 80.

A **B**

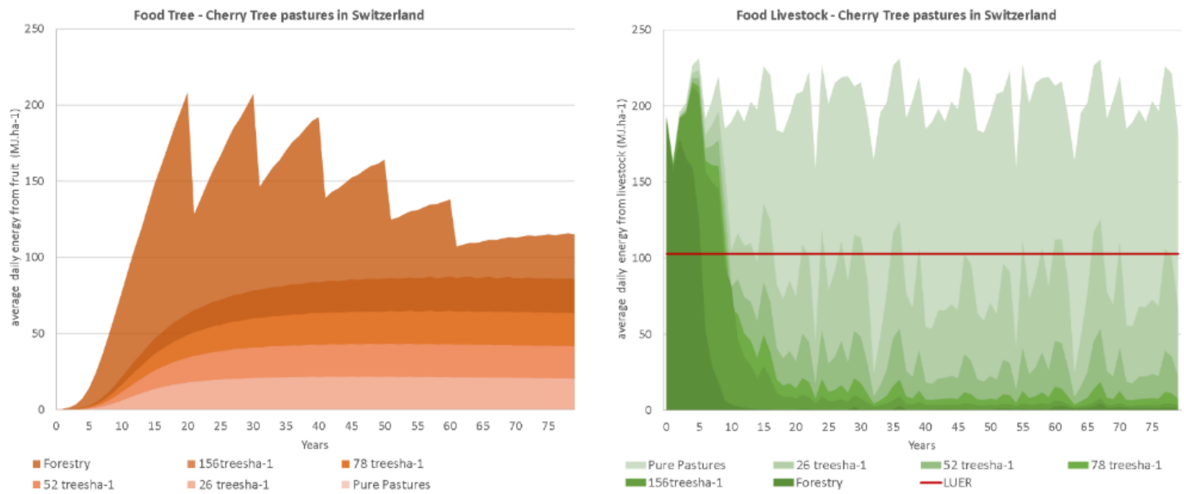

Figure 22. Modelled average energy values obtained from fruit and livestock from the six alternatives analysed for the cherry tree pasture system

Through the year, there is a seasonal variation in the food energy available from the livestock and from the trees. For example, at year 40 of the previous simulation, energy from trees and from livestock (pastures production) is mostly generated between May and September (Figure 23).

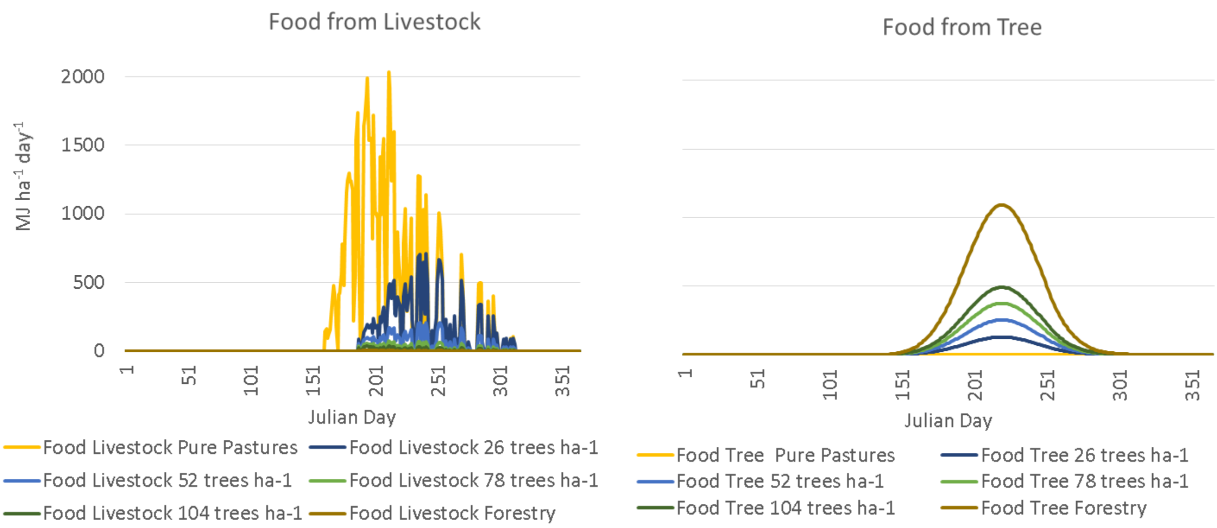

Figure 23. Food from Livestock (FL) and Food from Tree (FT) at year 40 for the six management alternatives analysed for cherry tree pastures in Switzerland

5.5.3 Silvoarable systems in the UK

The simulation results seem to be coherent with the results obtained in experimental sites in the UK. Graves et al (2010) reported modelled crop yields of 8.23 Mg ha^{-1}, 6.83 Mg ha^{-1} and 3.44 Mg ha^{-1} for winter wheat, barley and oilseed rape in the same area at earlier stages for an agroforestry alternative of 156 trees ha^{-1}. The simulated results for the same tree density obtained similar average yields for barley and oilseed, 6.4 Mg ha^{-1} and 3.5 Mg ha^{-1} respectively, while winter wheat was slightly lower (6.0 Mg ha^{-1}). In terms of tree growth, Graves et al. (2010) reported tree volumes of 0.35 m^3 $tree^{-1}$ and 0.25 m^3 $tree^{-1}$ for the forestry and agroforestry alternatives respectively and predicted timber volumes of 2.41 m^3 $tree^{-1}$ for the forestry and 1.85 m^3 $tree^{-1}$ for the agroforestry stand at year 30 respectively. In order to compare the results with the reference values, simulations were extended up to 30 years. The specific 30-year simulations offered values at year 30 of 2.5 m^3 $tree^{-1}$ and 1.9 m^3 $tree^{-1}$ for the “forestry” and for 156 trees ha^{-1} “agroforestry” alternatives respectively.

Regarding accumulated energy, the presence of trees in “agroforestry” and “forestry” alternatives reduces crop area, leading to a reduction in crop production and consequently there is decrease of energy output as food from crop (cereal grain) and materials from crop straw (Figure 24). As tree density in the agroforestry alternatives increases, the total energy accumulated in the system also increases. The energy accumulated by the tree stems largely matches the energy lost by the reduction of the crop due to the higher competition with trees. The thinning regime for the “forestry” alternative simulates a higher energy output from the trees and hence this system accumulates the most energy.

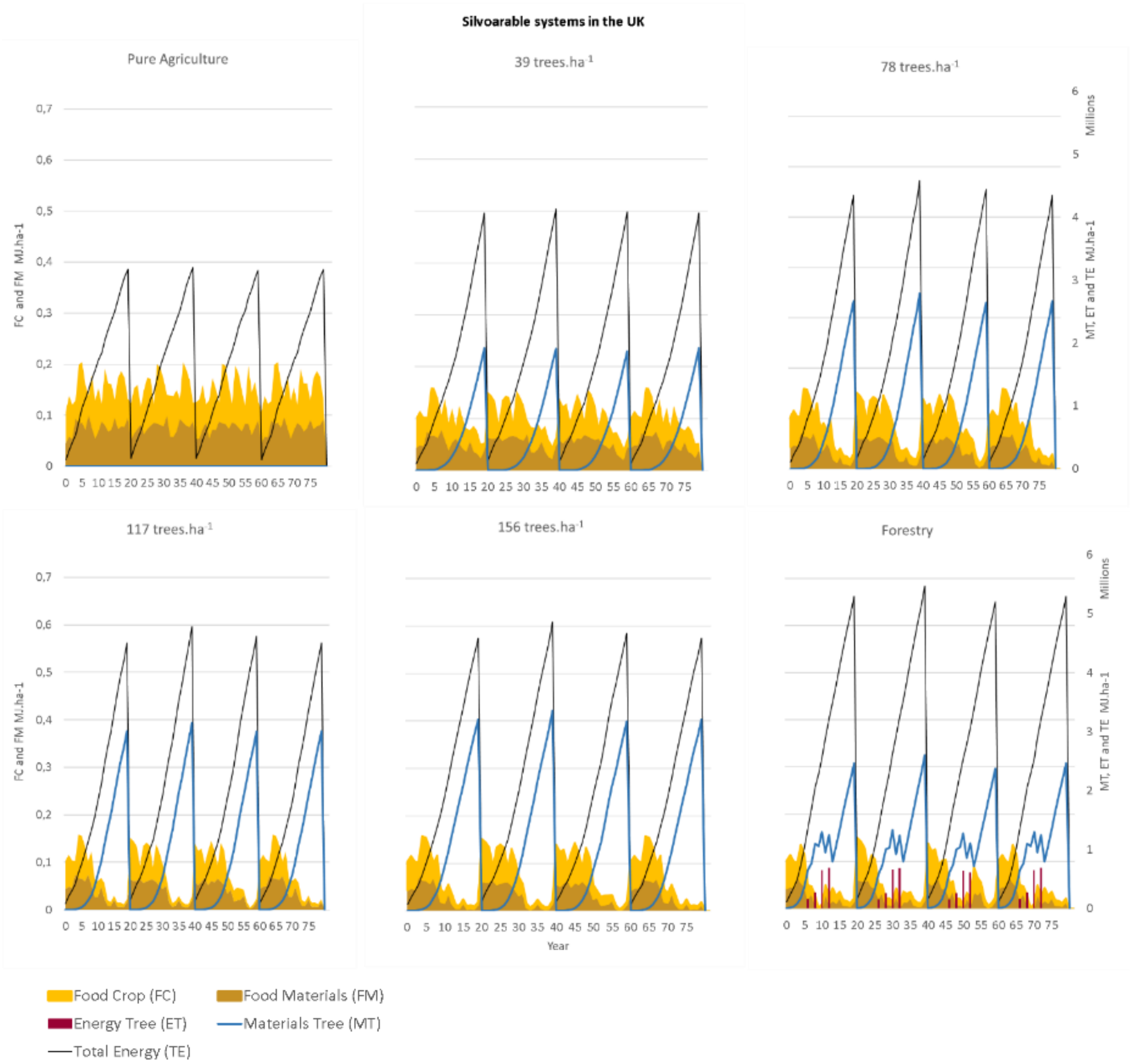

Figure 24 . Comparison of the total energy provided in 80 years by the poplar silvoarable systems in the UK from to the provisioning ecosystem services for six different management alternatives

5.5.4 Short rotation coppice in Germany

The simulated monocropping yields of 4-4.5 Mg ha^{-1} match observed reference wheat yields for the Forst site of 4.9 Mg ha^{-1}. In terms of tree biomass, the observed values for the experimental site are in the order of 22 Mg ha^{-1} for a “pure SRC” alternative considering tree densities of 9804 tree ha^{-1} for the double row system. The modelled results are higher - 36 Mg ha^{-1} - but are considerably reduced to 27 Mg ha^{-1} if a tree mortality of 25% is considered as seen in the experimental site.

In terms of energy accumulated, the introduction of SRC lines (trees), increases the total amount of energy accumulated by the system for the simulation period not only because of the introduction of trees itself but also due to the improvement of crop yields (Figure 25). Comparing the four “agroforestry” alternatives the total accumulated energy is very similar. This means that the energy provided by wheat as food and materials in four years is similar to the energy provided by the poplar SRC for the same period. Even though the presence of more lines of SRC increases competition between the tree and the crop the model simulates a small reduction in the energy accumulated by the crops.

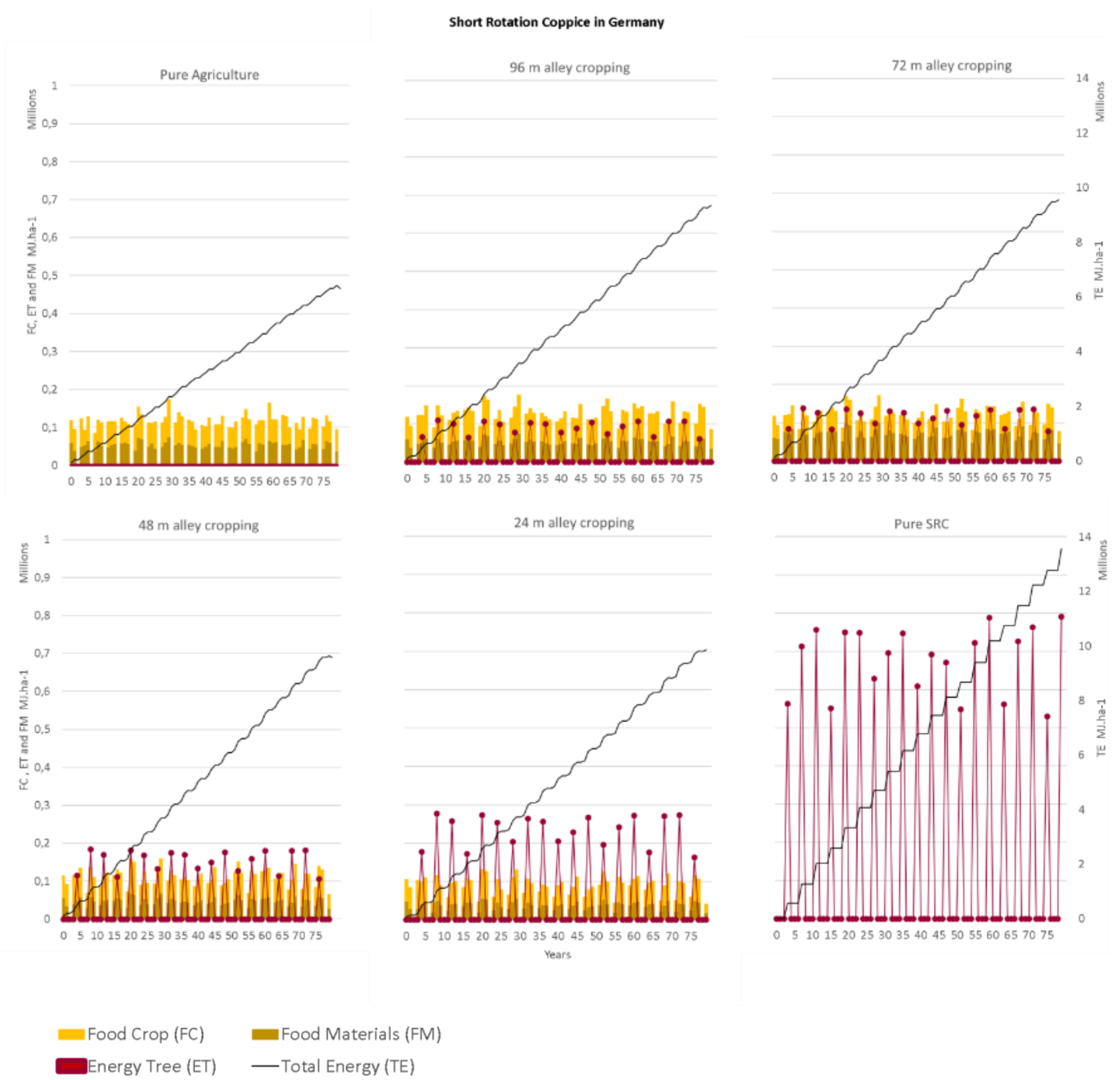

Figure 25. Comparison of the total energy provided in 80 years by the provisioning ecosystem services for six management alternatives in short rotation coppice

5.5.5 Tree effects on wind, temperature, shade, and livestock energy requirements

The new algorithms in Yield-SAFE quantifying the tree canopy effect on wind speed and temperature demonstrated important effects in all the systems. An evaluation of this effect was made by comparing the results on a 1:1 line when including and excluding these effects (Figure 26). As expected, the no-tree systems (MONTPT-A, CTCH-A, SAFUK-A and SRCDE-A) are located on a 1:1 line, showing that there was no tree canopy effect in these systems (Figure 26A and Figure 26B). But generally, there was a tendency to accumulate greater quantities of energy (more points in the upper section of the chart) in the tree based systems, particularly the SRCDE and SAFUK systems (Figure 26A), but also in the MONTPT systems (Figure 26B). The CTCH tree based systems (Figure 26A) were negatively affected by the tree canopy effect and it may be that in this case, reduced temperatures in the tree-based systems reduced the number of days above the minimum growing temperature. This effect requires verification in the future.

A B

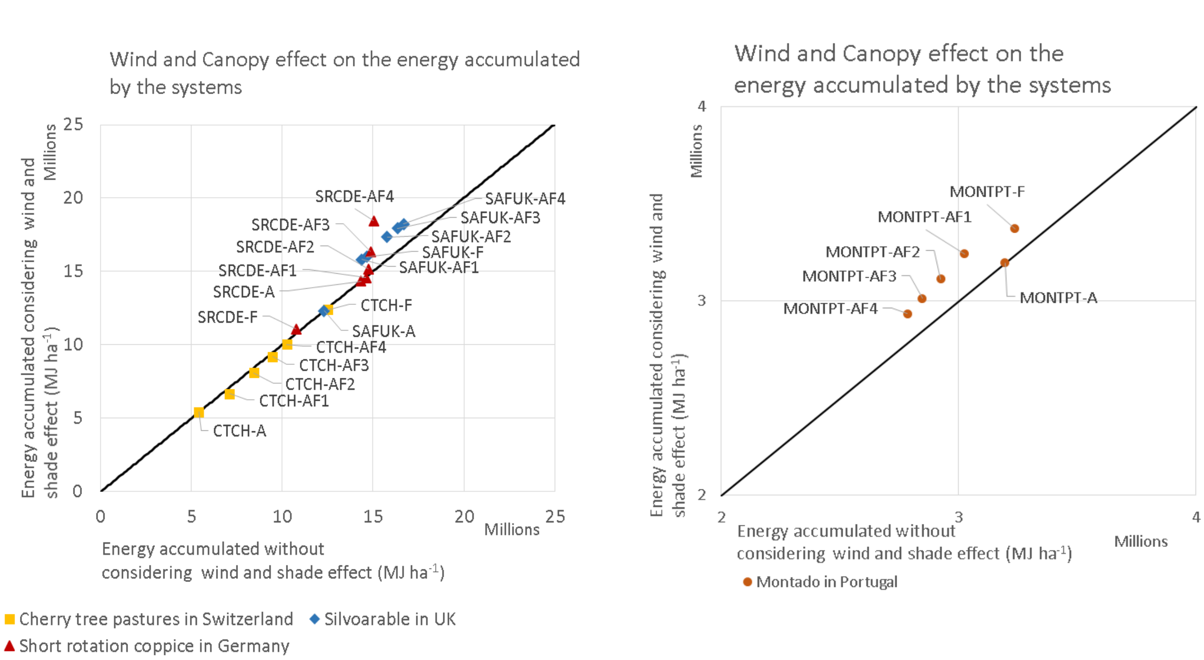

Figure 26. Comparison of the accumulated energy by different systems, including or not including the canopy effects on wind and temperature (affecting evapotranspiration)

Overall Figure 26 suggests that the tree canopy effect could lead to increases in productivity in crop or pasture growth in hotter or windier areas or reductions in cold climates. The Montado case study (Figure 26B) reveals that tree presence increased the total energy accumulated in the system when the canopy effect on temperature and wind speed was considered. As water is the limiting factor, a modelled reduction in evapotranspiration led to an increase in soil water content and consequently a higher pasture yield during the dry months. The Swiss cherry tree pastures are located in areas where water is abundant and temperatures are lower. In this system the modelled tree canopy effect on reducing wind speed and evapotranspiration had little benefit, and in fact, the observed reduction in accumulated energy associated with the canopy effect may have been due to an increase in the number of days during which pasture growth was restricted by low temperatures.

The tree canopy effect in the silvoarable systems in the UK resulted in greater total accumulated energy possibly due to an increase in total biomass caused by an increase in the use of light and water as a result of integrating trees and crops. The gain in energy was consistent (around 9%) as tree density increased and this may be explained by the fact that the tree lines remained constant, at a 10 m distance, as tree density was increased by increasing the number of trees on the tree lines.

For the SRC system in Germany (SRCDE) and in order to better understand the effects on tree and crop yields of the new algorithms simulating the tree presence, simulations including and excluding these wind and canopy effects were considered. On the other hand, in order to avoid possible effects derived from the different crop areas occupied by the different agroforestry alternatives, the results were also calculated using absolute and relative crop and tree areas.
Results showed not only that the effects of considering the new algorithms simulating tree presence effects on windspeed and temperature on the accumulated energy of the system was substantial, but also that: 1) the crop yields increase with the tree presence and these benefits increase with the alley width (Figure 27, x axis distance C to F is larger than distance from B to D); 2) at larger alley widths (96m) the tree presence effect produce a reduction in crop yields (Figure 27, x axis distance between B and D) and 3) with a relatively low impact, the tree presence als improves the energy provided by the tree component (Figure 27, y axis distance between A and E to C to F).
Figure 27

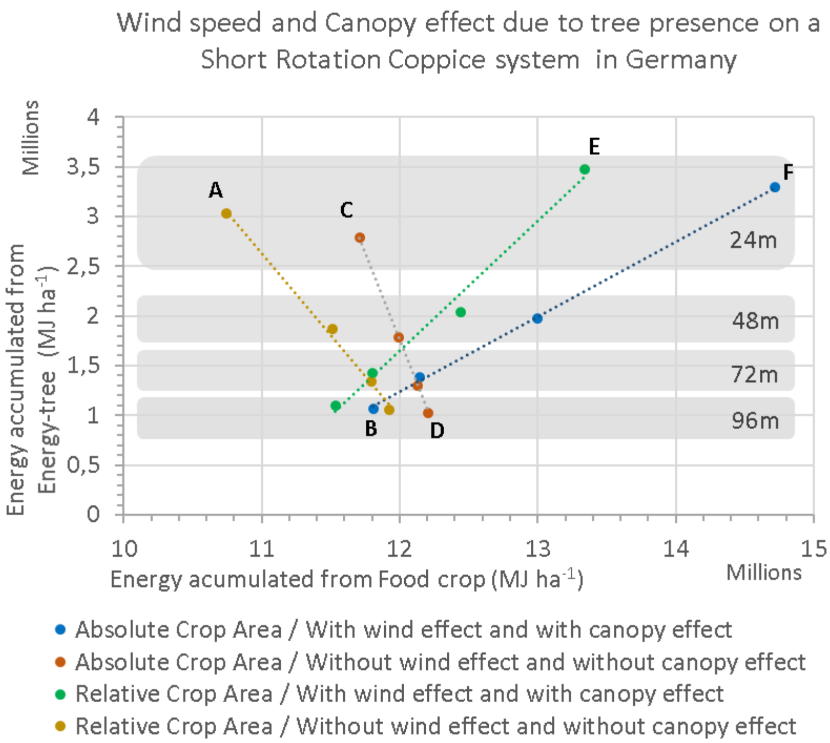

Figure 27. Modelled energy obtained considering (blue and green) and not considering (yellow and red) the canopy effect on wind speed and temperature for yield per cropped area and for the total area on a short term rotation coppice in Germany with four different crop alley widths.

5.6 Conclusions

Accumulated energy is an indicator of the provisioning ecosystem services that can provide an overview and allow comparison of the performance between land use alternatives. It is important to notice that the systems were simulated in areas where there were observed data to validate the model simulation, showing an acceptable fit between the model and the observations (see Annex VII – Tree calibration and Annex VIII – Crop calibration). The different locations at European level in different edapho-climatic conditions reveal contrasting energy responses between the systems. Drier areas, where the Montado and the Short Rotation Coppice were studied, with mean annual precipitation of less than 600 mm compared to the 750 and 1150 mm of the silvoarable systems in the UK and the cherry tree pastures in Switzerland, showed lower levels of accumulated energy (Figure 18).

In general, an increase in tree density leads to an increase in extractable energy for the studied systems. The exception was the Montado system, where the total energy being captured by the systems is underestimated as the tree stem is not considered as a source of materials.

In this study the "secondary" effects related to the presence of trees on evapotranspiration and wind speed were also analysed. The modelled results indicate that the greatest impact of including these attributes occurred in the systems most affected by water limitation (e.g. the Montado) or subject to high average wind speeds (Short Rotation Coppice in Germany).

However, using a common energetic unit to quantify the total amount of provisioning ecosystem services has some limitations. One example is that there can be different qualities of the energy. For example assigning any of the products to animal consumption instead of as a source of energy supposes that the energy accumulated in the product might be lower as usually the usable metabolic energy is lower than the calorific value.

6. Synthesis and moving forward

A set of agroforestry modelling tools, Yield-SAFE and Farm-SAFE, have been improved and have undergone model calibration and validation for additional species and designs under different soil and climate conditions across Europe. In particular the Yield-SAFE model allows different land use practices, either in agriculture, forestry or agroforestry, to be compared across Europe, now including microclimate effects and livestock carrying capacity effects.

Through a series of modelling workshops, multiple agroforestry assessments have been completed beyond those described in this report. Using models to support evaluation, allows individuals to identify where trees can be integrated into specialised farming systems.

A key development has been the inclusion, quantification, and valuation of additional regulating ecosystem services in the comparison of agricultural, agroforestry and forestry systems. This report describes some examples of how these services can help individuals and society to compare the relative benefits of these systems. Together with a financial analysis embedded within an umbrella of economic analysis developed in deliverable 6.18 - Modelling the economics of agroforestry at field- and farm-scale – this report can help determine when and how agroforestry could provide a focus for product marketing or public incentives such as payments for carbon sequestration or reduced greenhouse gas emissions.

The initial analysis continues to indicate that agroforestry can be a resource efficient land use. However it is worth noting that whilst financial and economic benefits are important, they are not the only determinants of whether a farmer implements agroforestry at a field- or farm-level.

Moving forward on agroforestry systems assessment will be supported by an enhanced suite of modelling tools developed during the development of tasks, milestones and deliverables of AGFORWARD work-package 6 (and 7) and also “ad-hoc” tools (originally not planned during project planning) such as Forage-SAFE[9] or EcoYield-SAFE[10]. These models help improve our understanding of the complex interactions in agroforestry systems. The process has also brought together a new cohort of talented European researchers to develop and use the models to produce a range of publications. The improved understanding of agroforestry interactions, by using the models, also supports knowledge-based decision making.

[9] García De Jalón S., Graves A., Moreno G., Palma J.H.N., Crous-Duran J., Oliveira T. and Burgess P.J., Forage-SAFE: a tool to assess the management and economics of wood pasture systems , 15th International Conference on Environmental Science and Technology, Rhodes, Greece. Available @: https://cest.gnest.org/sites/default/files/presentation_file_list/cest2017_00623_oral_paper.pdf

[10] Web version of EcoYield-SAFE. Accessible @ http://www.isa.ulisboa.pt/proj/ecoyieldsafe

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8. Annex I to V - Default Yield-SAFE soil, crop, tree and livestock parameters

8.1 Annex I – Yield-SAFE, soil parameters

Table 18. Soil parameters

ColumnName	Description	Unit /Value
Soil depth	Depth to rock	mm
Soil texture	texture based on 5 classes from FAO (coarse:1;very fine:5)	1-5
Soil OM	% of organic matter in Soil	0-1
Alpha	Fitting parameter [cm^{-1}] van Genuchten function	
D	Hydraulic conductivity as a fraction of Ks	
EffectiveSoilDept	Effective soil depth	mm
PotentialEvaporat	Potential evaporation (mm d^{-1}) from soil per MJ intercepted light	mm MJ^{-1}
FCpF	pF value at field capacity	log(cm)
KS	Hydraulic conductivity at saturation	mm d^{-1}
nSoil	Fitting parameter van Genuchten function	
mSoil	1 - 1/nSoil	
pFcritE	critical pF value for evaporation	log(cm)
pFeoffset		log(cm)
Thetas	Saturated volumetric water content	mm mm^{-1}
Thetar	Residual volumetric water content	mm mm^{-1}
Ccsoil	Clay content of the soil	0-1
MaxDiffInSummer	Reduction degrees in summer under canopy	°C
MaxDiffInWinter	Increase degrees in winter under canopy	°C
C:N	Carbon Nitrogen ratio of soil	
$Soil_{depth}$	Soil depth	m
BD	Bulk density	kg m^{-3}
OM	Organic matter in soil	kg ha^{-1}
Mineralization	Mineralization for crop (%)	0-1
OrgC in OM	Organic Carbon in organic matter (%)	0-1
Org N	Organic N in soil	kg ha^{-1}
Min N	Mineral N in soil	kg ha^{-1}
ISF	Indigenous soil fertility	kg ha^{-1}
FC	Field capacity	mm
N inputs		
A_{dep}	Atmospheric Nitrogen deposition (It is possible to get these values from www.emep.int for any lat-lon in europe)	kg ha^{-1}
N in Organic Fertilizer	Amount of N in the organic fertilizer	kg ha^{-1}
N in Mineral Fertilizer	Amount of N in the mineral fertilizer	kg ha^{-1}
Beta (β)	Recovery factor	0-1
Manure fertilizer	Use manure as fertilizer. 0-no; 1-yes	binary
Livestock source for manure	code for the livestock	
DOY_{manure}	Day of year to apply manure	DOY
N outputs		
D	Denitrification	kg ha^{-1}
D2	Denitrification when no N application exists	kg ha^{-1}
V_{minF}	Volatilization from mineral fertilizer	0-1

8.2 Annex II – Yield-SAFE, tree parameters

Table 19. Tree parameters

ColumnName	Description	Unit /Value
ap	parameter to adjust relationship between height and dbh - H=sigmaheight*dbh^ap	unitless
doybudburst	The day of year when budburst occurs	1-365
doyleaffall	The day of year when leaves fall. If perennial provide a value higher than 366	1-365
epst	Radiation use efficiency	g/MJ
F	Form Factor. relates to tree volume, height and diameter	unitless
gammat	Water use efficiency	m3/g
Kt	Radiation extinction coefficient	
Kta	Parameter A for radiation extinction coefficient	unitless
Ktb	Parameter B for radiation extinction coefficient	unitless
Kmain	Fraction of Biomass needed for maintenance respiration	0-1
LA max	Maximum leaf area	m2
LAsbMax	Maximum leaf area for a single bud	m2
ratiobranch	Ratio of branches to total biomass	0-1
ratiotimber	Ratio of timber to total biomass	0-1
Wood density	Wood density	g/m3
pFcritt	Critical pF value for tree, above which tree starts to drought induction	unitless
PWPt	pF for permanent wilting point	unitless
Sigmaheight	Ratio of height to diameter	unitless
dsigma/density	Response of Ht/diameter to density	unitless
Canopywidth/depth	Ratio of maximum width to canopy depth	unitless
TreeTau	Number of days after Bud Burst to reach 63.2% of final leaf area	days
Site factor	Site Factor. Usually 1	unitless
Tree Density	Mumber of tree per m^2	m^{-2}
Initial conditions		
nShoots0	Initial number of shoots	$tree^{-1}$
Biomass0	Initial biomass	g $tree^{-1}$
Boleheight0	Maximum bole height	m
LA0	Initial leaf area of the tree	m^2 $tree^{-1}$

Table 20. Additional parameters if tree fruit is to be modelled and tree leaves and root mortality is incorporated in soil carbon module

ColumnName	Description	Unit /Value
$DOY_{leaffallstart}$	DOY when leaves no longer grow and start to fall	1-365
$Leaf_{LeafFallEnd}$	DOY when leaves no longer fall	1-365
*f*LeafFall	Proportion of leaf area that will fall (1=deciduous). Is applied when doyleaffall is higher than 366 together with doyleaffal_start and doyleaffal_end	0-1
Weigth single leaf	Weight of a single leaf	g
Area Single leaf	Area of a single leaf	cm^2
SLA	Specific leaf area	cm^2/g
CCL	Ratio of Carbon Content in Leaves	0-1
RSR	Root to Shoot Ratio (IPCC broadleaves=0.25; conifers=0.2)	0-1
f^{FR}	Proportion of fine roots from root biomass	0-1
*f*CCL	Ratio of Carbon Content in leaves	0-1
$fCCR_t$	Ratio of Carbon Content in tree roots	0-1
Pi_{SR}	Ratio of structural root mass to aboveground biomass	0-1
r	Length of fine roots per unit of structure root	m/g
K_r	extinction coefficient governing the absorption of water per unit of root length	0-1
$Leaf_{UME}$	Utilizable Metabolizable Energy from leaves	MJ/t DM
$Branch_{UME}$	Utilizable Metabolizable Energy from branches	MJ/t DM
Fru_{UME}	Utilizable Metabolizable Energy from fruit	MJ/t DM
$Fruit_{Name}$	fruit name	
Fru_p	Fruit productivity per canopy area	g / m^2 LAI
$Fruit_{FallingDays}$	Number of days when 95% of fruit falls	days
$Fruit_{DOYPeak}$	DOY when fruit fall peak occurs	
$Fruit_{Weight}$	Weight of a single fruit	g $piece^{-1}$
Horizontal pruning	Year of horizontal pruning	years
Horizontal prune percentage	Percentage of pruned biomass	%
Pruned shoots %	Percentage of pruned shoots	%
Regular pruning events		
reg_prun_freq	Number of years between prunings	years
pbiomass_regprun	Proportion of biomass removed per regular pruning	0-1
min_th_prun	Minimum tree height for pruning	m

Table 21. Additional parameters if trees are considered in the nitrate leaching module

ColumnName	Description	Unit /Value
N_{treeAG}	N content in tree above ground biomass	0-1
N_{treeBG}	N content in tree below ground biomass	0-1

Table 22. Additional parameters to be used in the quantification of the trees effect on evapotranspiration and wind speed

ColumnName	Description	Unit /Value
CanopyEffectOnET	Tree canopy effect on evapotranspiration. 0:no,1:yes	binary
MaxDiffInSummer	Max reduction degrees of avg temp in summer under canopy	°C
MaxDiffInWinter	Increase degrees of avg temp in winter under canopy	°C
Z	Altitude	m asl
P	Atmospheric pressure	kPa
gamma	Psychrometric constant	kPa $°C^{-1}$
$Tmax_{uc}$	Tmax under canopy (2 x MaxDiffInSummer)	
$Tmin_{uc}$	Tmin under canopy (2 x MaxDiffInWinter)	
THmin	Tree height when the effect on temperature starts	
windEffectOnET	Wind effect on evapotranspiration. 0:no,1:yes	Binary
ThWind	Tree height when the effect on wind starts	0
A_w	Alley width	m

Table 23. Additional parameters when cork trees are being modelled

ColumnName	Description	Unit /Value
Is it cork oak?	Controller for cork debarking days. 1=yes 0=no	binary
$Age_{startdeb}$	Starting age for debarking	years
Debarking rotation length	Years between debarking	years
debarkCalendar	Cork calendar	year, year,...
DOYdebarking	Day of year when debarking occurs	J. day (1-365)
dcoef	Debarking coefficient (ratio between vertical debarking height and perimeter at breast height with cork)	unitless
PBHmin	Minimum perimeter at breast height for debarking	cm
H_{debark}	Vertical debarking height (cm)	cm

8.3 Annex III - Yield-SAFE, crop parameters

Table 24. Crop parameters

ColumnName	Description	Unit /Value
name	The name of the crop	unitless
DOYsowing	Day of sowing	1-365
DOYharvest	Day of harvest (if threshold not reached)	1-365
To	Temperature threshold for growth	°C
Tsumemerge	Temperature sum to emergence	°Cd
TsumRB	Temperature sum at which partitioning starts to decline	°Cd
TsumRE	Temperature sum at which partitioning to leaves = 0	°Cd
Tsumharvest	Temperature sum to harvest	°Cd
epsc	Potential growth (Light use efficiency)	$g\ MJ^{-1}$
gammac	Water needed to produce 1 gram of crop biomass when VPD=1kPa	$m^3\ g^{-1}$
HIcrop1	Harvest index	$g\ g^{-1}$
HIcrop2	Harvest index 2 (e.g. straw)	$g\ g^{-1}$
kc	Radiation extinction coefficient	
pFcritc	Critical pF value for crop, above which crop starts to drought induction	log(cm)
PWPc	Permanent Wilting Point for Crop	log(cm)
Thetacrop1	Moisture content of the crop 1(wet basis)	
Thetacrop2	Moisture content of the crop 2(wet basis)	
CropSLA	Specific Leaf Area	$m^2\ g^{-1}$
Site factor	Site factor	unitless
Kmainc_m	Maintenance respiration coefficient (fraction of biomass)	$g\ g^{-1}$
Kmainc_g	Amount of carbon respired to maintain existing biomass	$g\ g^{-1}$
Pasture/Grass?	Controller for crop manager to pick crop yield (1=yes; 0=no)	Binary
Initial conditions		
BiomassCrop0	Initial Biomass	g
Initial leaf area	Initial leaf area	$m^2\ m^{-2}$
CropPartition2leav	Partition to the leaves at emergence	0-1

Table 25. Additional parameters if crop is considered in the soil carbon and livestock modules

ColumnName	Description	Unit /Value
Soil carbon model		
RSR_c	root-to-shoot ratio - proportion of belowground to above ground biomass	0-1
$fCCR_c$	Ratio of carbon content in crop roots	0-1
CCAGstraw	Ratio of carbon content in crop straw	0-1
CCAGgrain	Ratio of carbon content in crop grain	0-1
StrawResidue	Above ground residue left after harvest	0-1
Livestock model		
$Crop_{UME}$	Utilizable Metabolizable Energy	MJ/t DM
$Straw_{UME}$	Utilizable Metabolizable Energy	MJ/t DM
Crop2Livestock	Use crop harvest to feed livestock. 0=no,1=yes	binary
DE	Digestibility energy (usually 45-55 for low quality forages)	%

Table 26. Additional parameters if crop is considered in the nitrate leaching module

ColumnName	Description	Unit /Value
Ymax	Crop maximum yield	ton ha^{-1}
Grow season	Crop growing season (in months)	months
N_{grain}	N content in grain (or harvested grass)	(0-1)
N_{straw}	N content in crop straw (or grass remain after harvest)	(0-1)
N_{fert}	Nitrogen fertilizer applied	kg ha^{-1}
N_{fix}	Biological nitrogen fixation	kg ha^{-1}

8.4 Annex IV – Yield-SAFE, livestock parameters

Table 27. Livestock parameters

ColumnName	Description	Unit/value
code	FADN (when exists)	D-
Name	Description	--
LU	Livestock Unit	
LMER	Livestock Unit Energy Requirement	MJ LU^{-1} $year^{-1}$
SLMER	Selected Livestock Energy requirement	MJ LU^{-1} d^{-1}
SReq	Shade Requirements	m^2/LU
Hts	Tree Height Threshold for Shadow effect	m
LMERr	Ration of LMER under shade (0-1)	ratio
ExcrRate	Excremental rate	kg/d
ExcrN	N content in excrement	0-1
LightBulb Equivalent	Energy spent by 1 light bulb of 7watts	MJ d^{-1}
Luw	Livestock Unit weight	kg
DE	Dry Matter Intake	kg d^{-1}
Nem		
Nea		
Nel		
NE		
ExcrC	C organic carbon content in excrement	0-1
Shadow	Consider shadow effects: 0:No; 1:yes	binary
Manure N		kg/m^3
Manure C		kg/m^3
Management options		
ULU	User defined LU carrying capacity	LU ha^{-1}

8.5 Annex V – Yield-SAFE, RothC parameters

Table 28. RothC parameters

ColumnName	Description	Unit/value
Vegetation and Soil inputs		
DPM_RPMr	Plant input fractioning to DPM/RPM	
DPM_P	Fraction of carbon in plant residue input that goes to DPM	0-1
RPM_P	Fraction of carbon in plant residue input that goes to RPM	0-1
$Soil_{depth}$	Depth of topsoil OM (cm)	cm
Ccsoil	Clay content in soil	0-1
Initial conditions		
DPM0	Initial Decomposable Plant Material	t C / ha
RPM0	Initial Resistant Plant Material	t C / ha
BIO0		t C / ha
HUM0		t C / ha
IOM0		t C / ha
total0		t C / ha
Decomposition rate constants		
kDPM	DcmpRateDPM for DPM	1 / y
kRPM	DcmpRateRPM fir RPM	1 / y
kBIO	DcmpRateBIOFv263 for BIO	1 / y
kHUM	DcmpRateHUM for HUM	1 / y
Topsoil Moisture Deficit		
MaxTSMD if SoilCov =1	Maximum topsoil moisture deficit (TSMD) for covered soil	
MaxTSMD related to Soildepth	Maximum TSMD related to soil depth	
MaxTSMD if SoilCov =0	Maximum topsoil moisture deficit (TSMD) for bare soil	
DPM/RPM fractioning		
RatioCO2ToSolids	Ratio CO_2/Bio+HUM	unitless
DcmpFracCO2_CO2	Ratio CO_2/Bio+HUM to CO_2	0-1
DcmpFracCO2_BIOHUM	Ratio CO_2/Bio+HUM to Bio-HUM	0-1
FracToBIOF	Fraction of carbon (in decomposing DPM, RPM, BIO) that goes to BIO	0-1
FracToHUM	Fraction of carbon in decomposing DPM, RPM, BIO) that goes to HUM	0-1
FracSolidToBIO	Fraction of carbon from DPM, RPM, BIO-F or BIO-S (not going to CO_2) that goes to BIO	0-1
FracSolidToHUM	Fraction of carbon from DPM, RPM, BIO-F or BIO-S (not going to CO_2) that goes to HUM	0-1
Composition of Farmyard Manure		
DPM_M	Fraction of carbon in farmyard manure as decomposable plant material (DPM)	0-1
RPM_M	Fraction of carbon in farmyard manure as resistant plant material (RPM)	0-1
BIO_M	Fraction of carbon in farmyard manure as fast decomposing biomass (BIO)	0-1
HUM_M	Fraction of carbon in farmyard manure as humified organic matter (HUM)	0-1

9. Annex VI – Comparison of Yield-SAFE outputs from 2007 to 2016

This Annex compares the Yield-SAFE described by van der Werf et al. (2007a) with those described by Palma et al. (2016a).

Table 29. Tree outputs[11]

ColumnName	Unit	Description	(van der Werf et al. 2007a)	(Palma et al. 2016a)
Nt	trees m^{-2}	Tree density	X	X
yest	0-1	Trees present	X	X
yesleaf	m2	Leaf development per shoot	X	X
LAt	m^2 $tree^{-1}$	Leaf area per tree	X	X
LAIt	m^2 m^{-2}	Leaf area index	X	X
fSt	m^{-2}	Fraction light interception	X	X
dBtpot	g $tree^{-1}$	Potential growth	X	X
fWredt1	g $tree^{-1}$	Proportion actual growth	X	X
fWredt2	g $tree^{-1}$	Check	X	X
dBtwred	g $tree^{-1}$	Water reduced growth	X	X
dBtact	g $tree^{-1}$	Actual growth	X	X
Bt	g $tree^{-1}$	Biomass per tree	X	X
Nshoot	$tree^{-1}$	Number of shoots per tree	X	X
Wt	m^3 $tree^{-1}$	Water uptake	X	X
Vt	m^3 $tree^{-1}$	Volume of timber	X	X
H	m	Height	X	X
dbh	cm	Diameter at breast height	X	X
yespr	0-1	Prune event	X	X
Nharv	trees m^{-2}	Number of harvested trees	X	X
yeshar	0-1	Harvest event	X	X
Vtperha	m^3 ha^{-1}	Timber volume of stand	X	X
Vthar	m^3 ha^{-1}	Harvested timber	X	X
Vbr	m^3 ha^{-1}	Volume of branch wood	X	X
Vbrhar	m^3 ha^{-1}	Harvested branch wood	X	X
Bh	m	Clear stem height	X	X
Ct_perc	%	Canopy area	X	X
thinningDay	0-365	Thinning day of year	X	
Ntthinning	nr	Number of trees thinned	X	
Bt_tonha	Mg ha^{-1}	Biomass per tree	X	
Vt_m3ha	m^3 ha^{-1}	Volume of timber	X	

[11] http://home.isa.utl.pt/~joaopalma/projects/agforward/webyieldsafe/output_list.php?f=webyieldsafe.xml&parent=OUTPUT&family=TREE

Table 30 Crop outputs[12]

ColumnName	Unit	Description	(van der Werf et al. 2007a)	(Palma et al. 2016a)
Ac	0-1	Proportion of crop area		X
DOYc		Crop time		X
YESc	0-1	Crop present		X
dTsum	ºC	Temperature sum		X
Tsum	°C	Temperature sum		X
Yrcp		Crop year		X
Yesemg	0-1	Crop emerge		X
pL1		Leaf partitioning stage 1		X
pL2		Leaf partitioning stage 2		X
SfSc		Radiation intercepted		X
dBcpot	g m^{-2} crop	Potential growth		X
fcwred1	g m^{-2} crop	Actual growth ratio stage 1		X
fcwred2	g m^{-2} crop	Actual growth ratio stage 2		X
dBcact	g m^{-2}	Actual growth		X
LAIc	m^2 m^{-2}	Leaf area index		X
Bc	g m^{-2}	Biomass per crop		X
Wc	m^3 m^{-2}	Water uptake		X
Yrcrp2		Crop year		X
Bcperha	t ha^{-1}	Total dry weight per cropped area		X
Yc1	t ha^{-1}	Yield per cropped area		X
S	t ha^{-1}	Yield 2 per cropped area		X
Yc1Ac	t ha^{-1}	Total weight per total area		X
Yc2Ac	t ha^{-1}	Yield per total area		X

[12] http://home.isa.utl.pt/~joaopalma/projects/agforward/webyieldsafe/output_list.php?f=webyieldsafe.xml&parent=OUTPUT&family=CROP

Table 31. Soil and water[13]

ColumnName	Unit	Description	(van der Werf et al. 2007a)	(Palma et al. 2016a)
theta1	mm mm^{-1}	Volumetric water content	X	X
theta2		Remove surface runoff		X
pF	log(cm)	pF	X	X
fSsoil	0-1	Proportion of radiation reaching soil	X	X
Epot	mm	Potential evaporation	X	X
fWredE1		Ratio of actual to potential evaporation	X	X
fWredE2		Check	X	X
Eact	mm	Actual evaporation	X	X
Fgw	mm	Flow to groundwater	X	X
Fc	mm	Crop water uptake	X	X
Ft	mm	Tree water uptake	X	X
Irri	mm	Overhead irrigation application		X
Phi	0-1	Ability of root to intercept water Modifier for water assimilation		X
Runoff	mm	Runoff		X
Es	kPa	Mean Saturation Pressure		X
Ea	kPa	Actual Vapour Pressure		X
VPD	kPa	Vapour Pressure Deficit		X
dSat	kPa	Slope of saturation vapour pressure curve (D)		X
ETo	mm	Reference evapotranspiration		X

Table 32. Tree leaf fall

ColumnName	Unit	Description	(van der Werf et al. 2007a)	(Palma et al. 2016a)
Basal Area	m^2 ha^{-1}	Basal Area		X
LAtDOYLeafFallStart	m^2 tree^{-1}	Leaf area when DOY is DOYLeafFallStart		X
fLS	0-1	Leaf fraction reaching the soil		X
BLeafFall	kg ha^{-1}	Cumulative biomass of leaf fall		X
BLeafFall	g tree^{-1}	Cumulative biomass of leaf fall		X
LAtDOYLeafFallStart*(fLS_t-fLS_{t-1})	m^2 tree^{-1}	Delta tree Leaf area		X
LAt-LAt-1	m^2 tree^{-1}	Delta tree Leaf area		X
dLFt	g tree^{-1}	Delta Tree Leaf fall		X
dLFt	kg ha^{-1}	Delta Tree Leaf fall		X
dLFtCLF	kg C ha^{-1}	Carbon content in Leaf fall		X
CLF	kg C ha^{-1}	Tree Leaves Cumulative Carbon Content		X

[13] http://home.isa.utl.pt/~joaopalma/projects/agforward/webyieldsafe/output_list.php?f=webyieldsafe.xml&parent=OUTPUT&family=SOIL

Table 33. CARBON from TREE and CROP roots

ColumnName	Unit	Description	(van der Werf et al. 2007a)	(Palma et al. 2016a)
Btroots	g tree^{-1}	Tree Root Biomass		X
Bfineroots	g tree^{-1}	Tree Fine root biomass		X
Bfineroot DOY to litter	g tree^{-1}	Tree Fine Root Biomass at DOY start leaf fall, available to litter		X
Accumulated root soil	g tree^{-1}	Tree accumulated root litter stored in soil		X
Accumulated root soil	kg ha^{-1}	Tree accumulated root litter stored in soil		X
Delta Root litter soil	g tree^{-1}	Tree Delta Root litter stored in soil		X
Delta Root litter in soil	kg ha^{-1}	Tree Delta Root litter stored in soil		X
dCRLsCRM	kg C ha^{-1}	Tree Delta C in Root litter stored in soil		X
Rc	g m^{-2}	Crop maintenance respiration		X
Bcroots	t ha^{-1}	Crop root biomass		X
CRMc	kg C ha^{-1}	Crop root Carbon		X
CRstraw	kg C ha^{-1}	Carbon content in straw after harvest		X
Crafterharvest	kg C ha^{-1}	Crop Carbon after harvest (residues)		X
Root Biomass tree	g tree^{-1}	Root Biomass tree		X
Excrements	kg ha^{-1}	Livestock excrements		X
Carbon from livestock excrements	kg ha^{-1}	Carbon from livestock excrements		
C Seq above + Root	t ha^{-1}	Carbon Sequestration aboveground + Root		X
CO2 Sequestration	t ha^{-1}	CO_2 Sequestration aboveground + Root		X

Table 34. FRUIT production

ColumnName	Unit	Description	(van der Werf et al. 2007a)	(Palma et al. 2016a)
DOYnorm		Modified DOY for normal distribution for fruit fall distribution		X
FruitFallPDOY	0-1	Probability of fruit fall		X
CanopyCover	m^2 tree^{-1}	Canopy cover		X
FruyDOY	kg ha^{-1}	Daily fruit production		X
Fruyyear	kg ha^{-1} yr^{-1}	Annual Fruit production		X
	nº ha^{-1}	Total number of fruits		X
FruytreeDOY	kg tree^{-1}	Fruit production per tree		X
FruytreeY	kg tree^{-1}	Yearly accumulation of Fruit production in a tree		X

Table 35. Prunings

	ColumnName	Unit	Description	(van der Werf et al. 2007a)	(Palma et al. 2016a)
Horizontal pruning			Year		X
	yesprune	Binary	Prune event		X
	P_branch_g	g tree^{-1}	Pruned branch wood		X
	P_branch_m3	m^{3} ha^{-1}	Pruned branch wood		X
	pshoots	0-1	Pruned shoots		X
Formation pruning event	Bformprun	Mg ha^{-1}	biomass formation pruning		X
	UMEformprun	MJ ha^{-1}	delta UME from tree formation pruning		X
	CCprunLU	SLU ha^{-1}	Carrying capacity from tree formation pruning		X
	CCSDprun	days	number of sequential days available for selected livestock to graze/browse		X
Regular pruning event	Yesrp	0 or 1	regular pruning event		X
	Brp	Mg ha^{-1}	biomass regular pruning		X
	Brpleav	Mg leaves ha^{-1}	leaves biomass regular pruning		X
	Brpbran	Mg branches ha^{-1}	Branches biomass regular pruning		X
	Perc_Pleaves	% leaves of biomass pruned	Proportion of leaves of total biomass pruned		X
	Perc_Pbranches	% branches of biomass pruned	Proportion of branches of total biomass pruned		X

Table 36. Carrying capacity

ColumnName	Unit	Description	(van der Werf et al. 2007a)	(Palma et al. 2016a)
UMEFru	MJ ha^{-1}	daily UME from fruit		X
UMEFruY	MJ ha^{-1}	Accumulated UME from fruit		X
CCfruLU	LU ha^{-1}	Carrying capacity from fruit production		X
CCfruSLU	SLU ha^{-1}	Carrying capacity from fruit production		X
CCSDfru	days	number of sequential days available for livestock to graze/browse		X
CCSDfruy	days/year	number of sequential days available for livestock units to graze/browse		X
SLCCSDfruy	days	number of sequential days available for selected livestock to graze/browse		X
SLCCSDfruyy	days/year	number of sequential days available for selected livestock to graze/browse		X
SDULUfru	days	counter for sequential days for user defined livestock units from fruit yields		X
SDULUfruyr	days/year	counter for sequential days for user defined livestock units from fruit yields		X
UMEcrop	MJ ha^{-1}	delta UME from crop		X

UMEcropY	MJ ha^{-1}	Accumulated UME from crop		X
UMEstraw	MJ ha^{-1}	delta UME from straw		X
UMEstrawY	MJ ha^{-1}	Accumulated UME from straw		X
CCcropLU	SLU ha^{-1}	Carrying capacity from crop+straw production		X
CCSDcrop	days	number of sequential days available for selected livestock to graze/browse		X
UMEregprunleav	MJ ha^{-1}	∆ UME from tree regular pruning – leaves		X
UMEregprunbran	MJ ha^{-1}	∆ UME from tree regular pruning branches		X
UMEregpruntot	MJ ha-1	∆ UME from tree regular pruning total		X
CCregprunleavLU	SLU ha^{-1}	Carrying capacity from tree regular pruning – leaves		X
CCregprunbranch LU	SLU ha^{-1}	Carrying capacity from tree regular pruning – branches		X
CCpruntotLU	SLU ha^{-1}	Carrying capacity from tree regular pruning – total		X
SD_punings	days	number of sequential days available for selected livestock based on tree prunings		X
Fruit, crop and pruning used by LU	MJ ha^{-1}	∆ UME from fruit, crop and tree prunings		X
accUME	MJ ha^{-1}	Accumulated UME from fruit, crop and tree prunings		X
CC	SLU ha^{-1}	Carrying capacity from fruit, crop and tree prunings		X
SD	days	Number of sequential days available for selected livestock based on fruit, crop and tree prunings		X
SDULU	SLU ha^{-1}	Number of sequential days available for selected livestock for a given Carrying capacity		X

Table 37. Microclimate: Shadow effect on livestock energy requirements

ColumnName	Unit	Description	(van der Werf et al. 2007a)	(Palma et al. 2016a)
YesShade	0-1	Shade availability		X
ShadeC	LU ha^{-1}	Shade capacity		X
THI	unitless	Temperature and humidity index		X
Sm	0-1	Livestock Metabolizable Energy Requirement modifier due to shadow		X
mLMER	MJ d^{-1}	Modified LMER		X

Table 38. Microclimate: combined effects on temperature

ColumnName	Unit	Description	(van der Werf et al. 2007a)	(Palma et al. 2016a)
Equinox_1		"-1 to 1 Function for DOY between 80 and 265 to describe equinoxes"		X
Equinox_2		"-1 to 1 function for 265<DOY<79		X
fTmax		Applied function to summer for Tmax		X
fTmin		Applied function to winter to Tmin		X
TaddTmax	°C	Temperature to add to Tmax		X
TaddTmin	°C	Temperature to add to Tmin		X
mTmax	°C	Modified maximum temperature		X
mTmin	°C	Modified minimum temperature		X

Table 39. Microclimate: combined effects on Evapotranspiration

ColumnName	Unit	Description	(van der Werf et al. 2007a)	(Palma et al. 2016a)
Delta_svp	kPa $°C^{-1}$	Slope of saturation vapour pressure curve (D) (without tree effect)		X
ET0	mm	Reference Evapotranspiration without tree present effects		X
ET0-ET0´	mm	Difference between without and with tree effect on Eto		X
	mm	Accumulated difference between without and with tree effect on Eto		X
fETo	0-1	ETo with tree effect / without tree effect		X
fWind	0-1	Wind speed modifier reduction factor of wind speed		X
Wss	m s^{-2}	Modified wind speed		X

Table 40. Cork oak related output

ColumnName	Unit	Description	(van der Werf et al. 2007a)	(Palma et al. 2016a)
D	cm	Diameter at breast height with virgin cork (cm)		X
Debarknr		Sequential number of debarking event (0,1, …)		X
Yeardebark	0/1	Debarking Year		X
Daydebark	0/1	Day of debarking (0 = true or 1 = false)		X
wcv	kg ha^{-1}	Dry weight of extracted virgin cork (kg)		X
wca	kg ha^{-1}	Dry weight of extracted mature cork (kg)		X
wc	kg ha^{-1}	Dry weight of extracted cork (kg)		X
wc	kg tree	Dry weight of extracted cork (kg)		X

10. Annex VII – Tree calibration

The following pages refer to a calibration process which is still ongoing with constant interaction between researchers' interest in modelling with Yield-SAFE. In some cases they might be close to final parameter sets, but others the calibration is in an earlier stage requiring further improvement. Most importantly they store a relatively intensive bibliography review regarding physiological thresholds for needed parameters and as much validation as possible.

The following pages present the follow up of the newest undergoing calibrations for different tree species:

- Blue gum – *Eucalyptus globulus*
- Holm oak – *Quercus rotundifolia*
- Black walnut – *Juglans major*
- Spruce – *Picea abies*
- Cherry tree – *Prunus avium* – fruit production
- Cherry tree – *Prunus avi*um – timber production
- Apple tree – *Malus domestica*
- Poplar – *Populus* spp – in Short Rotation Coppice
- Short Rotation Coppice systems in Europe: Poplar (*Populus* spp) and Willow (Salix spp)
- Radiata pine – *Pinus radiata* D. Don
- Chestnut – *Castanaea sa*tiva Miller

10.1 Eucalyptus globulus

10.1.1 Brief description of the experiment where data was measured

Data from irrigated and control plots from a fertilization and irrigation trial installed in Óbidos, Portugal was used.

The experiment is located at Quinta do Furadouro (32º 9' latitude and - 09º 15' longitude), in the central region of Portugal, 10 km from the Atlantic Ocean, where the climate is of Mediterranean type with maritime influence. Mean annual rainfall is 607 mm, but less than 10% occurs between May and September. An atmospheric humidity rate usually higher than 80% in the morning, during summer, as well as frequent summer fogs, contributes to reduce the impacts of summer drought (Fabião et al. 2002).

The soils are of low fertility, with a low organic carbon content (0.23-0.28%), mostly sandy and may be classified as Arenosols (FAO/UNESCO) (Pereira et al. 1989; Madeira et al. 1995).

The experimental design consisted of 8 plots of equal size grouped in two blocks. Each plot was surrounded by a buffer zone consisting of two rows of trees and divided into two sub-plots: (a) for non-destructive biometric measurements (1089 m^2) and (b) for destructive biomass sampling (792 m^2).

Plants were planted at March 1986 at 3x3 m after ploughing up to 80 cm depth. Before planting 1.5 t ha^{-1} of dolomitic limestone (66.5% of $CaCO_3$, 32.5% of $MgCO_3$) was applied to the experimental area (Madeira et al. 2002). Three months after planting following treatments were applied:

- irrigation (I): from April through October, water was supplied daily in order to avoid plant water stress through drip irrigation tubes placed along each row of trees; the amount of water varied with the season and was estimated to maintain at least 80% of the field capacity in the soil;

The control plots (C) were considered and consisted of rain fed plots without fertilization except the initial application of fertilizers at the plantation.

Biomass production (aboveground) and partitioning was estimated from the destructive sampling of trees following the scheme:

Table 41. Number of plots measured in the experiment

Date	Tree age	Plot 1 Irrigated	Plot 2 Irrigated	Control 1	Control 2
01-Sept-86	0.5	6	6	6	6
01-Feb-87	0.9	6	6	6	6
01-Feb-88	1.9	4	6	6	4
01-Feb-89	2.9	5	5	5	5
01-Jan-92	5.8	8			8
01-Ago-03	17.4			10	

The sampling in 1986 and 1987 was based on the height distribution in each plot and in 1988 on the diameter distribution. The trees were randomly selected as follows: four trees with a total height equal to the plot mean and four trees with a height equal to the mean plus one standard deviation of the mean, four trees with a height equal to the mean minus one standard deviation.

10.1.2 Literature review of tree parameters

Tree parameter values values for *Eucalyptus globulus* growth where obtained from literature review.

Table 42. Parameters values and respective references for *Eucalyptus globulus*

Parameter	Value	Reference
Light use efficiency (LUE)	0.93-2.23	(Landsberg and Hingston 1996)
LUE	1.14 (high productivity class)	(Stape et al. 2004)
Water use efficiency (WUE - kg m^{-3})	1.59-3.21	(Stape et al. 2004)
WUE (kg m^{-3})	1.5-4	(Forrester et al. 2010)
Wood density (kg m^{-3})	550-650	(Miranda and Pereira 2015)
Wood density (kg m^{-3})	492-600	(Miranda et al. 2001)
Tree Tau	20-50	(Metcalfe et al. 1991)
Leaf area (juvenile leaves) (cm^2)	50-60	(Metcalfe et al. 1991)
Extinction coefficient - k	0.5	(White et al. 2000; Sands and Landsberg 2002)
Specific Leaf Area (SLA)	3.5 m^2 leaf kg^{-1} DM	(Battaglia 2015)
SLA (m^2 kg^{-1})	3.5-11	(Landsberg and Sands 2011)
SLA (m^2 kg^{-1})	4-11	(Sands and Landsberg 2002)
Initial Leaf Area	0.002 m^2 (assuming a 20 cm height plant)	(Humara et al. 2002)
Maximum Leaf Area (m^2)	76-99.3	(Pereira et al. 1997)
Ratio timber (1-branch and bark fraction)	branch and bark fraction for mature stands = 0.15	(Sands and Landsberg 2002)
Ratio timber	0.70	

10.1.3 Measured data for calibration

Data used for the calibration procedure was organized considering the day since 1st of January from the day of plantation, as depicted in the following Table.

Table 43. Measurements dated from the 1st of January of the year when tree was planted

		Average values per plot					
Plot	Day	dbh cm	Height m	La m^2	Bt kg $tree^{-1}$	N tree ha^{-1}	Volume m3 $tree^{-1}$
Irrigated 1	184	1.3	2.2	6.12	1.051638	1111	0.0002
	337	3.4	3.5	15.34	3.598053	1056	0.0018
	702	8.1	7.9	19.13	15.57832	1001	0.0203
	1068	11.6	12.4	29.46	37.70739	964	0.0639
	2132	19.6	22.8	65.39	173.4313	918	0.3131
Irrigated 2	184	1.6	2.4	6.63	1.084833	1111	0.0003
	337	4.0	4.0	17.99	3.986776	1056	0.0028
	702	8.6	8.1	17.90	15.92428	1001	0.0238
	1068	11.3	13.0	25.53	35.01023	946	0.0630
Control 1	184	0.7	1.8	2.54	0.444365	1056	0.0001
	337	2.1	2.5	6.24	1.389833	1001	0.0005
	702	6.3	6.6	11.00	8.372068	946	0.0110
	1068	9.8	10.5	22.60	26.67	900	0.0404

	6362	29.5	35.0	56.57	5924.652	1074	1.0794
Control 2	184	0.6	1.6	4.13	0.706513	1056	0.0000
	337	2.3	2.6	10.45	2.039167	1001	0.0006
	702	6.8	6.5	18.41	11.6025	964	0.0119
	1068	9.3	10.2	19.34	23.01	918	0.0356
	2132	14.3	16.3	44.25	84.9	845	0.1312

10.1.4 Calibration results

The calibration process produced the following set of parameter values

Table 44. Parameter values for Eucalyptus globulus growth after calibration

Parameter	Description	Unit	Value	Reference from literature
nShoots0	Initial number of shoots	shoots tree^{-1}	1	
Biomass0	Initial biomass per tree	g tree^{-1}	200	
LA0	Initial leaf area	m^2	0.6	0.002
ap	function describing tree height and diameter relationship		0.9	
epst	Radiation use efficiency	g MJ^{-1}	1.8	0.93-2.23
F	Tree form factor		0.4	
gammat	water needed to produce 1 g of biomass	m^3 g^{-1}	0.00019	0.00015-0.0004
kta			20	
ktb			0.4	
kmain	Maintenance coefficient		0.00012	
LAMax	Maximum leaf area of a tree	m^2	250	76-99.3
LAsbMax	Maximum leaf area	m^2	0.14	0.005-0.006 for young leaves
SLA	Specific leaf area		7	4-11
ratiotimber	Proportion of above ground biomass that forms timber		0.85	0.85
WoodDensity		g m^3	500000	492 000 – 650 000
pFCritt	Critical pF value for tree growth	(log cm)	4	
PWPt	Permanent wilting point	(log cm)	4.2	
SigmaHeight	Ratio of tree height to tree diameter	(log cm)	80	
dsigma_density	The change in SigmaHeight with density		350	
canopyWidthDepth	Ratio of canopy with to canopy depth		1.6	
TreeTau	number of days after bud-burst at which the leaf area reached 63.2% of its maximum area		30	20-50

10.1.5 Observed vs predicted

The first step was the calibration of the potential growth, turning off the water module and concentrating on the bio-physical parameter values that control tree growth. This first step of the calibration results are in Figure 48, that shows the measured and simulated values of tree biomass, volume, diameter, height and leaf area.

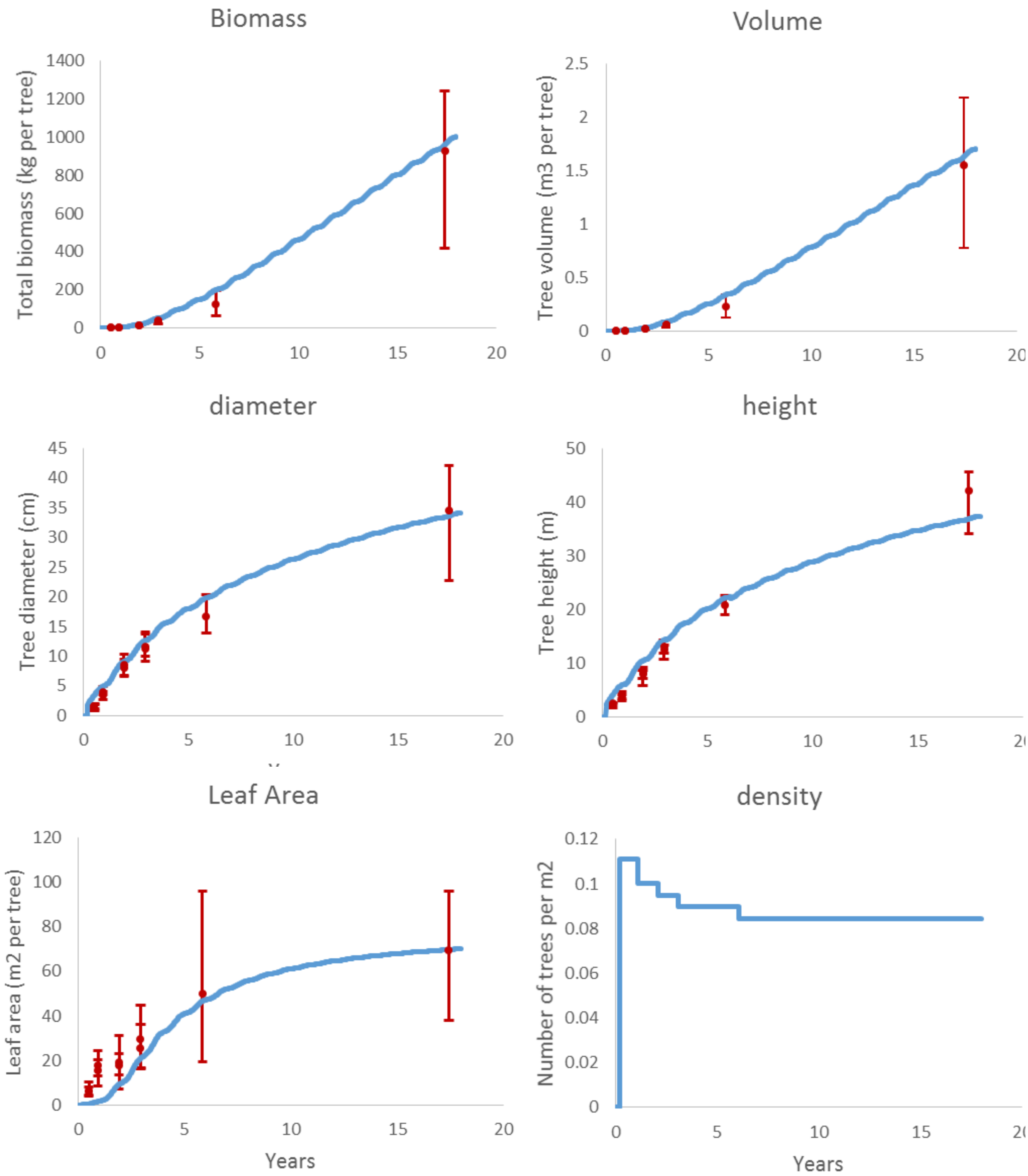


Figure 28. Observed and Yield-SAFE estimation for potential yield of Eucalyptus globulus

Once the potential yield is calibrated, by finding the set of parameters that minimize the differences between observed and predicted, the same procedure was done by adjusting solely the parameters related to the water resource usage (gammat and pFCritical). The results are shown in Figure 29 for the same variables used above (Figure 28) and comparing the control plot (non-irrigated) with the potential growth.

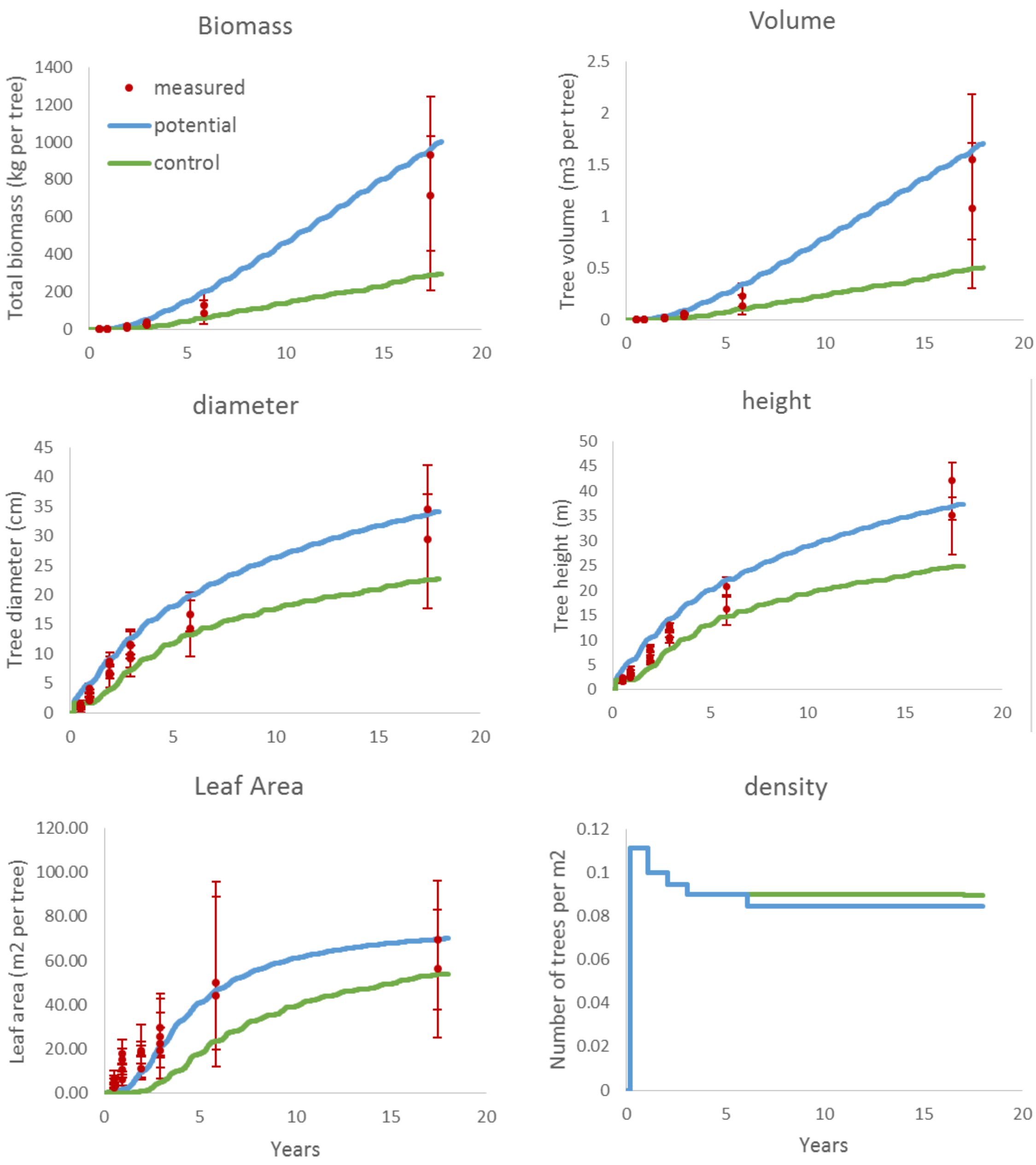


Figure 29. Observed and Yield-SAFE estimation for potential and control yields of *Eucalyptus globulus*

10.2 Holm oak

10.2.1 Brief description of the experiment where data was measured

Data from 13 trees, located in the sites described in Table 45 was used. The trees where destructively sampled for biomass and leaf area.

Table 45. Location and characteristics of the trees used

Site location	Latitude (N)	Longitude (W)	N (tree ha^{-1})	Number of trees	Details
Alqueva	38.220	7.483	28-120	11	Trees near and away from the river
Vila Velha de Rodão	39.650	7.677	53-134	2	Near water

Age was not known and no stem disks where available to determine the age. Thus tree age was estimated using an equation developed by Gea-Izquierdo et al. (2008) – equation 1 . The equation allowed to estimate the diameter of the previous year (dhb_2), given the initial measured dbh from the tree (dbh_1), while maintaining the condition t_2-t_1 =-1. The result of dbh_2 becomes dbh_1 in the next iteration until dbh_2 reaches a value of zero. Because t_2-t_1 has an absolute value of 1, the elapsed number of years is equivalent to the number of iterations. However more years are needed to account for the time until trees reach the height of 1.30 m (breast height). Based on empirical knowledge and site index values, we considered that trees need 5 or 10 years to reach the height of 1,30m if they are non-limited or limited by water, respectively. We therefore added 5 or 10 years to the previous age estimation to the trees assumed to have potential growth or water limited growth, respectively.

$$dbh_2 = \frac{(F + (t_2 - t_1))^{0.859611}}{(0.002797\ x\ density + 31.4296/SI) + \left[\left(\frac{-0.06588}{density}\right) + 0.000123\ x\ SI\right]\ (F + (t_2 - t_1))^{0.859611}}$$

with

$$F = \sqrt[0.859611]{\frac{dbh_1\ x\ (0.002797\ x\ density + 31.4296/SI}{\left\{1 - \left[\left(\frac{-0.06588}{density}\right) + 0.000123\ x\ SI\right]\ dbh_1\right\}}}$$

Equation 2. Estimation of diameter of breast height in previous year: Where dbh2 and dbh1 are diameter at breast height at time t2 and t1, respectably; density is the number of trees per hectare and SI is Site Index in m.

10.2.2 Literature review of tree parameters

Tree parameter values for Holm oak (Quercus ilex) growth were obtained from existing data and literature review. The following Table presents the found values and the references used.

Table 46. Parameters values and respective references for Holm oak

Parameter	Value	Reference
Pruning height	1.1 - 4.2	Data collection
Maximum proportion of bole	0.1 – 0.4	Data collection
DOY when leaves start to fall	105	Data collection
DOY when leaves no longer fall	304	Data collection
SLA	50	(Sala et al. 1994)
RUE	0.169-0.187	(Faria et al. 1998)
gammat	0.00026-0.00046	(Faria et al. 1998)
SLA	49.1-52.1	(Faria et al. 1998)
ap	0.63	Data collection
F	0.29-1.12	Data collection
SLA	37.3-55.12	Data collection
ratiotimber	0.22-0.83	Data collection
WoodDensity	70000-90000	Data collection
SigmaHeight	10.24-36.30	Data collection
canopyWidthDepth	1.03-2.52	Data collection

10.2.3 Measured data for calibration

Some of the variables used to calibrate the model where estimated. The following Table gives the values of the measured variables and of the estimation of age (with equation 1) and site index on the trees used to calibrate the model.

Table 47. Measured values for calibration

			Average values per plot				
Number of trees	Estimated age	dbh cm	Height m	La m^2	Bt kg $tree^{-1}$	Volume m3 $tree^{-1}$	Estimated site index (m)
13	34-238	14.3-70.7	4.9-13.5	15.8-297.6	67.96-4146.3	0.026-4.463	30-40

10.2.4 Calibration results

The calibration process produced the following set of parameter values for holm oak growth:

Table 48. Parameter values for holm oak after calibration

Parameter	Description	unit	Value	Reference from literature
nShoots0	Initial number of shoots	shoots $tree^{-1}$	0.6	
Biomass0	Initial biomass per tree	g $tree^{-1}$	55	
LA0	Initial leaf area	m^2	0.01	
ap	function describing tree height and diameter relationship		0.5	0.63
epst	Radiation use efficiency	g MJ^{-1}	0.17	0.169-0.187
F	Tree form factor		0.6	0.29-1.12
gammat	water needed to produce 1 g of biomass	m^3 g^{-1}	0.00046	0.00026-0.00046
kta			10	
ktb			0.4	
kmain	Maintenance coefficient		0.0001	
LAMax	Maximum leaf area of a tree	m^2	400	
LAsbMax	Maximum leaf area	m^2	0.025	
SLA	Specific leaf area		50	4.9-55.12
ratiotimber	Proportion of above ground biomass that forms timber		0.7	0.22-0.83
WoodDensity		g m^3	800000	70000-90000
pFCritt	Critical pF value for tree growth	(log cm)	4	
PWPt	Permanent wilting point	(log cm)	4.2	
SigmaHeight	Ratio of tree height to tree diameter		12	10.24-36.30
dsigma_density	The change in SigmaHeight with density		0.63	
canopyWidthDepth	Ratio of canopy with to canopy depth		1.6	1.03-2.52
TreeTau	number of days after bud-burst at which the leaf area reached 63.2% of its maximum area		10	

10.2.5 Observed vs Predicted

We considered that trees growing in Vila Velha de Rodão have a potential growth and that trees growing in Alqueva have control growth, so these 2 scenarios where selected has having potential and control growth characteristics:

Potential: trees growing in Vila Velha de Rodão with an initial plating density of 100 trees per ha and a thinning regime of: year 25 (75), 50 (50), 75 (25)

Control: trees growing in Alqueva, in a type 1 soil with 20 cm depth and an initial plating density of 505 trees per ha and a thinning regime of: year 35 (429), 45 (343), 55 (275), 65 (220), 75 (176), 85 (141), 95 (113), 105 (90), and 115 (85).

Once the potential yield is calibrated, by finding the set of parameters that minimize the differences between observed and predicted, the same procedure was done by adjusting solely the parameters related to the water resource usage (gammt and pFCrit). The results are shown in Figure 30.

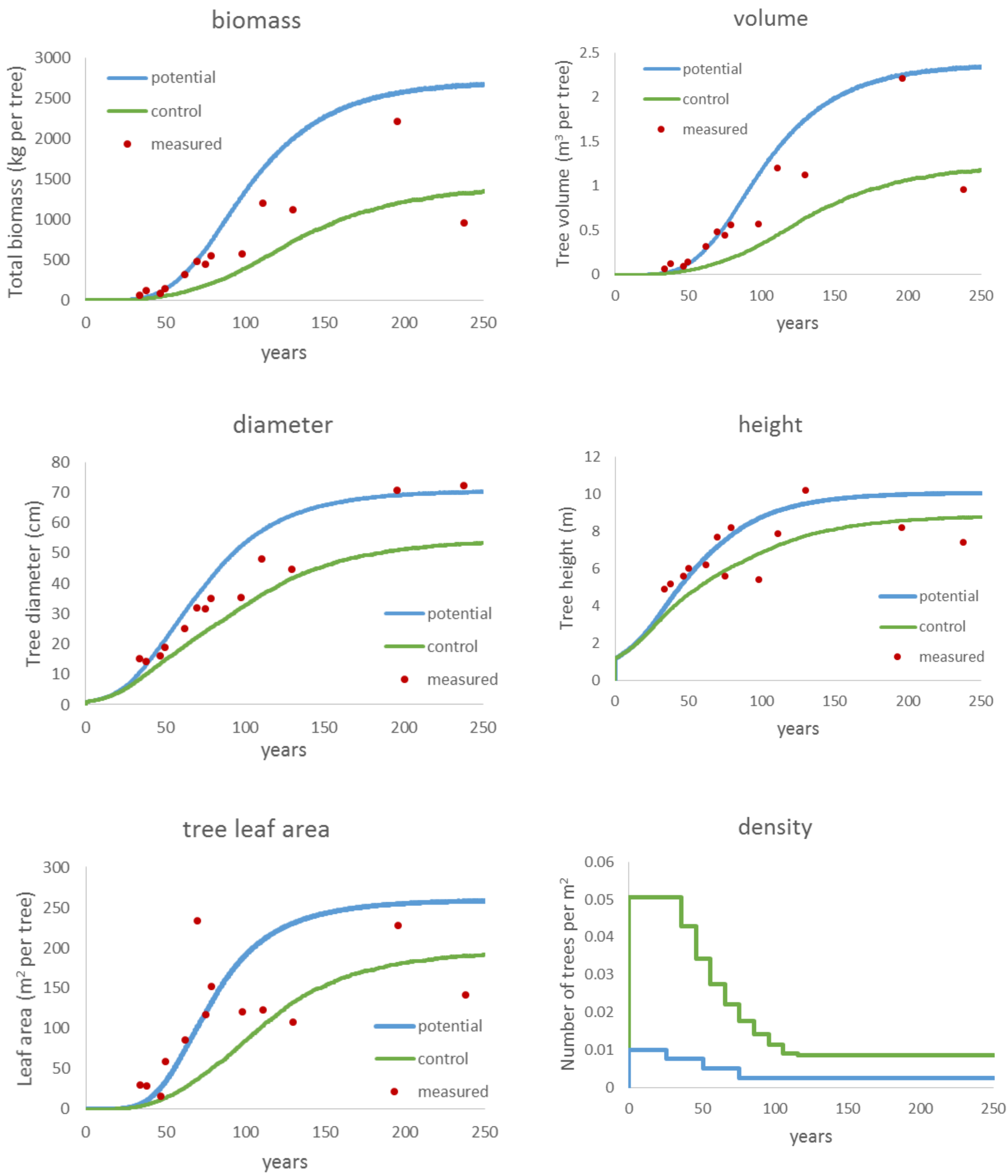


Figure 30. Measured and Yield-SAFE estimation for potential and control yield of Quercus ilex

10.3 Black walnut

10.3.1 Brief description of the experiment where data was measured

The study was carried out in an experimental silvoarable plantation that combines hybrid walnut (hybrid Mj209xRa Juglans major that comes of the pollination from J. major with pollen of J. regia) planted in 2007 for quality timber with annual crops (winter cereals: wheat, barley and triticale). The experiment includes the respective control plots of cereal without trees, and of walnuts without crops.

The experiment is located at El Carpio de Tajo (Toledo, Spain; coordinates: ETRS 89 UTM 30 N = 374444 W; 4411877 N; latitude 39.848 and longitude -4.470), at 411 m of altitude, mean annual temperature of 15,3 °C and 437.6 mm of mean annual precipitation (data from 1961-2002 from the 3303E weather station at Carpio de Tajo, accessed from website

http://sig.magrama.es/93/ClienteWS/siga/Default.aspx?nombre=CH_ESTACIONES&claves=DGA.CH_ESTACIONES.CLAVE&valores=3303E

The soil is a Fluvisol, > 140 cm depth, pH ~ 6. The management is intensive with irrigation and fertilization. The plot has a total area of 68.4 ha, of which 0.5 ha were under study.

Three replicated plots of 20 x 4 m were selected as pure plantation control. There were 5 replicated plots of 20 x 4 m with the silvoarable combination.

In 2013-2014 growing season 2 varieties of wheat (Kilopondio and Bologna) and 2 of barley (Azara y Doña Pepa) were tested. In 2014-2015 the cultivars were Ingenio, Sublim and Nogal for wheat and Basic, Lukhas, Hispanic and Dulcinea for barley. This second year, a local variety of triticale (Verato) was also tested. The agriculture control plots consisted of 4 replicate plots of a size of 2 x 2 m for each cultivar.

The study started in autumn 2013 where all plots were fertilized with 600 kg ha^{-1} of NPK 8:12:12. In spring 2014, a dose of 120 kg urea (46%) ha^{-1} was applied. Same dose was applied in 2014 and 2015. The diameter of the trees at breast height was measured in February 2014, 2015 and 2016. Crop yield was measured through 3-4 herbage samples (50x50 cm) per plot, which were taken using hand clippers at a height of 2.5 cm in June 2014 and 2015.

10.3.2 Literature review of tree parameters

Tree parameter values for Black walnut (*Juglans nigra*) growth were obtained from existing data and literature review. The following Table presents the found values and the references used.

Table 49. Parameters values and respective references for Black walnut

Parameter	Value	Reference
doybudburst	135	WS lisboa
doyleaffall	281	WS lisboa
epst	0.8815	WS Lisboa
LabsMax	0.022	WS lisboa
ratiobranch	0.18	WS lisboa
ratiotimber	0.72	WS lisboa
Wood density	660000	WS lisboa
Sigma height	51.6	WS lisboa

Wood density	562000	http://www.csudh.edu/oliver/chemdata/woods.htm
ratiobranch	0.7	(Coelho et al. 2008)
ratiotimber	0.3	(Coelho et al. 2008)
WUE µmol CO2 (mol^{-1} H2O^{-1})	30-85 (0.00007-0.00021)	(Gauthier and Jacobs 2009)
A (net photosynthetic rate) µmol mol^{-2} s^{-1}	9-12 (0.493-0.657)	(Gauthier and Jacobs 2009)
Total Leaf area (m^2)	57.4 – 167.1 (10 years) 84.2 – 296.5 (27 years)	(Zellers et al. 2012)
Mean dominant height at age 60 in the best SI (24)	27 m	(Ares and Brauer 2004)
Mean dbh at age 60	48 cm	(Ares and Brauer 2004)
Mean dominant height at age 60 in the best SI (80 feet – 24,38 m)	27 m	(Schlesinger)
Mean dbh at age 60 in the best SI (80 feet – 24,38 m)	38 cm	(Schlesinger)
Mean height at age 60	25-30 m	(Šálek and Hejcmanová 2011)(Šálek and Hejcmanová 2011)
Mean dbh at age 60	30 cm	(Šálek and Hejcmanová 2011)(Šálek and Hejcmanová 2011)
Mean height at age 60	27 m	(Čavlovic´ et al. 2010)
Mean dbh at age 60	30 – 40 cm	(Čavlovic´ et al. 2010)
Mean height at age 60	26 m	(Nicolescu 1998)
Mean dbh at age 60	46 cm	(Nicolescu 1998)
Light use efficiency (LUE)	0.1 g / MJ	(Rosati and Dejong 2003)
Water use efficiency	1.33 – 1.55	(Yang et al. 2008)
Wood density (kg m-3)	610 - 640 kg / m^3	(Meier 2015)
Tree Tau	10	(Data not available, taken from database of Swiss walnut)
Leaf area (juvenile leaves) (cm2)	50 – 100	(Keramatlou et al. 2015)
Extinction coefficient – k	0.7	(Data not available , taken from database of Swiss walnut)
SLA (m2 kg-1)	16.13 – 30.30	(Piel et al. 2002)
Initial Leaf Area (m2)	0.1 – 0.2	Estimated for 20 leaves per tree (planting 1-year seedling) (Keramatlou et al. 2015)
Maximum Leaf Area (m2)	150	Adapted from (Tokár 2009)
Ratio timber (1-branch and bark fraction)	0.80	Own data (experimental site Bosques Naturales in Madrigal)

10.3.3 *Measured data for calibration*

During an AGFORWARD modelling workshop held in Lisbon, data was collected consisting in 3 measurements, therefore additional data sets were used for calibration, as described in the following Tables.

Table 50. Description of the used data for calibration

Data set	Measured variables		Stand age	Location	Reference
WS data	Dbh, height, volume, biomass, LAI	7-9	Toledo (latitude 39º85´ and longitude -4º47´)	WS lisboa	
SAFE data	dbh, height, volume	1-60	Montpelier (latitude 43º71´ and longitude -4º02´)	Dupraz et al. 2005	
Zellers data	Height, LAI	3-27		(Zellers et al. 2012)	
Tokar data	dbh, height, volume, biomass, LAI	39-64	Želiezovce (latitude 48º03´ and longitude -18º67´)	(Tokár and Krekulová 2005)	

Table 51. Measurements dated from the 1st of January of the year when tree was planted

Plot	Day	Average values per plot						
		dbh cm	Height m	La m^2	LAI	Bt kg $tree^{-1}$	Bt ton ha^{-1}	Volume m3 $tree^{-1}$
WS data	2555	15.425	9.83	76.38		55.67		0.0703
	2920	16.435	10.48	83.18		65.13		0.0823
	3285	17.275	11.01	89		73.54		0.093
Zellers data	1095	2.3	2.3	6.3				
SAFE data	3650	14.1	9.2	104				
	9855	24.8	17	159.8				
	3650							0.2
	7300							0.4
	10950							0.6
	14600							0.7
	18250							1
	21900	30-48	27					1.2
	545	13	2.27			0.172		
	910	25	2.59			0.843		
	1275	39	3.04			2.838		
	1640	55	3.61			7.098		
	2005	77	4.57			17.116		
	2370	92	4.88			27.168		
	2735	108	5.62			41.562		
	3100	126	6.14			62.181		
	3465	143	6.25			88.182		
	3830	158	6.70			114.873		
	4195	170	7.00			138.634		
	4560	185	7.51			172.505		
	4925	199	7.72			209.945		

Tokar data	14235	16	18			0.3	67.72667	188
	16060						107.85	
	17885						165.39	
	19710						169.6033	
	21535						181.6833	
	23360	27	27		2.88	0.9	192.05	433

10.3.4 Calibration results

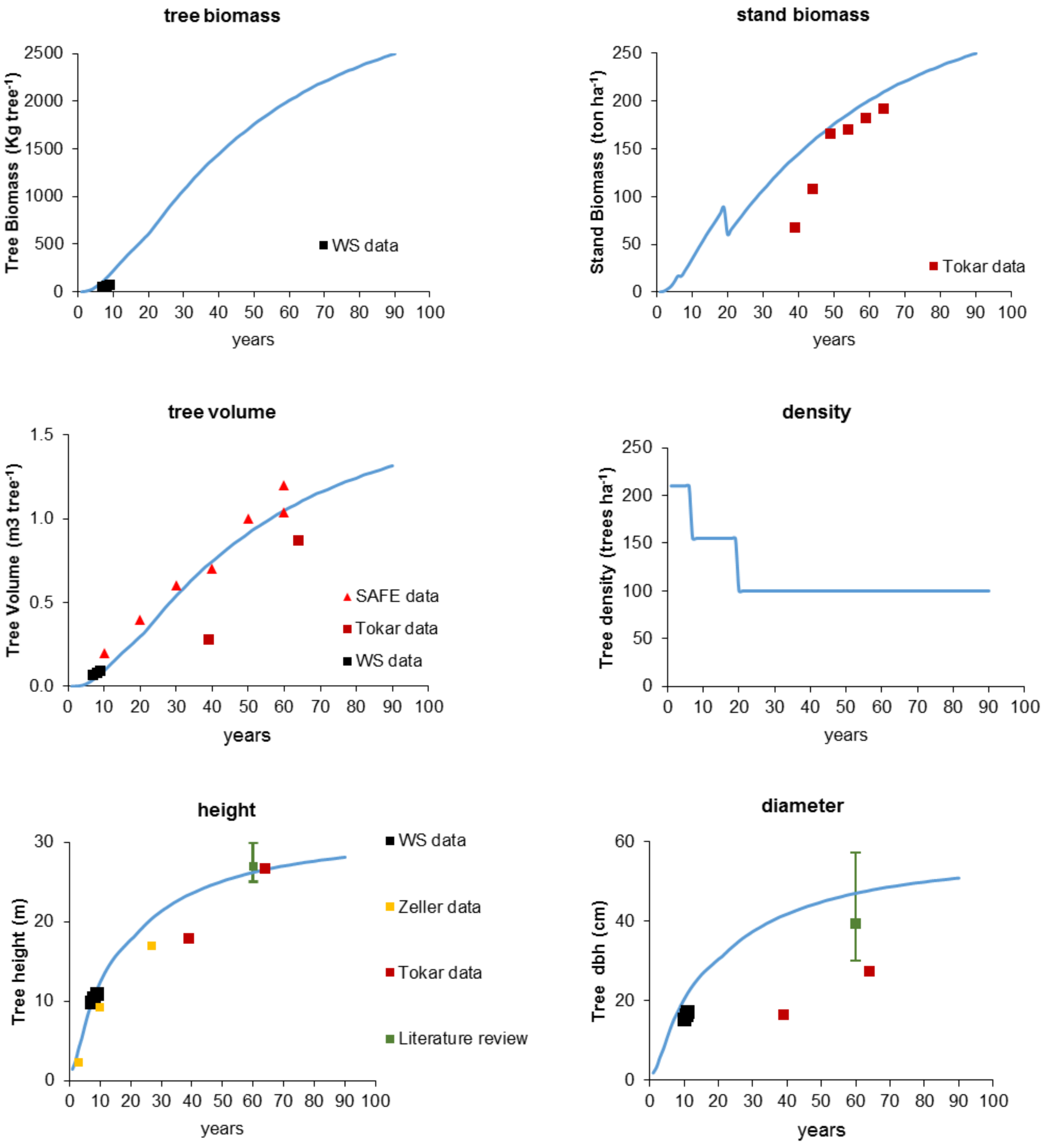
The calibration process produced the following set of parameter values for *Juglans nigra* growth:

Table 52. Parameter values for holm oak after calibration

Parameter	Description	unit	Value	Reference from literature
nShoots0	Initial number of shoots	shoots tree^{-1}	1	
Biomass0	Initial biomass per tree	g tree^{-1}	10	
LA0	Initial leaf area	m^2	0.5	
ap	function relating tree height and diameter		0.9	
epst	Radiation use efficiency	g MJ^{-1}	0.3	0.493-0.8815
F	Tree form factor		0.23	
gammat	water needed to produce 1 g of biomass	m^3 g^{-1}	0.0002	0.00007-0.00021
kta			10	
ktb			0.4	
kmain	Maintenance coefficient		0.0001	
LAMax	Maximum leaf area of a tree	m^2	250	167.1-296.5
LAsbMax	Maximum leaf area	m^2	0.03	0.022
SLA	Specific leaf area		168	
ratiotimber	Proportion of above ground biomass that forms timber		0.3	0.3-0.72
WoodDensity		g m^3	562000	562000 – 660000
pFCritt	Critical pF value for tree growth	(log cm)	4	
PWPt	Permanent wilting point	(log cm)	4.2	
SigmaHeight	Ratio of tree height to tree diameter		51.6	51.6
dsigma_density	The change in SigmaHeight with density		0	
canopyWidthDepth	Ratio of canopy with to canopy depth		0.6	
TreeTau	number of days after bud-burst at which the leaf area reached 63.2% of its maximum area		10	

10.3.5 *Observed vs Predicted*

On a first stage, the potential growth was calibrated considering a compromise between all the data sets available. The results are shown in Figure 31 for all the variables considered in the calibration process, tree and stand biomass, tree volume, height and diameter, tree leaf area and LAI.



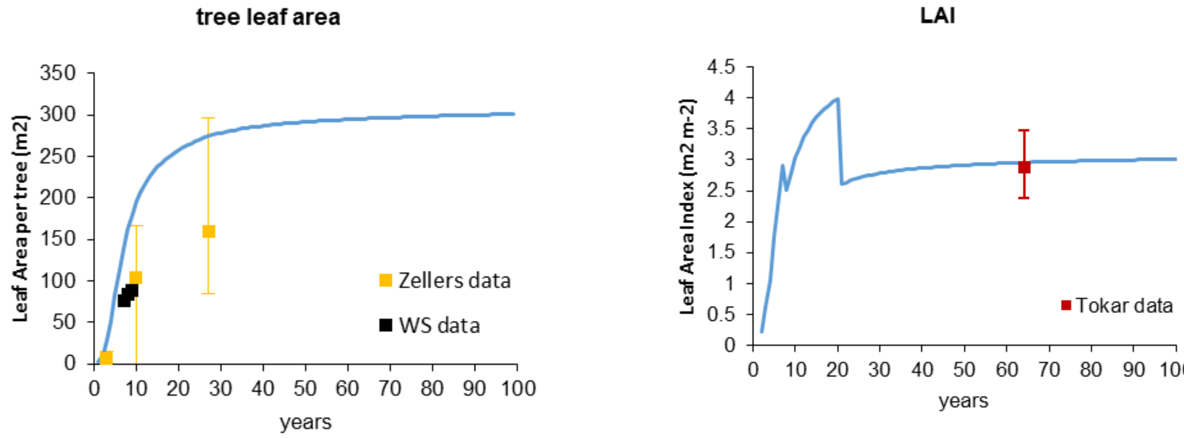
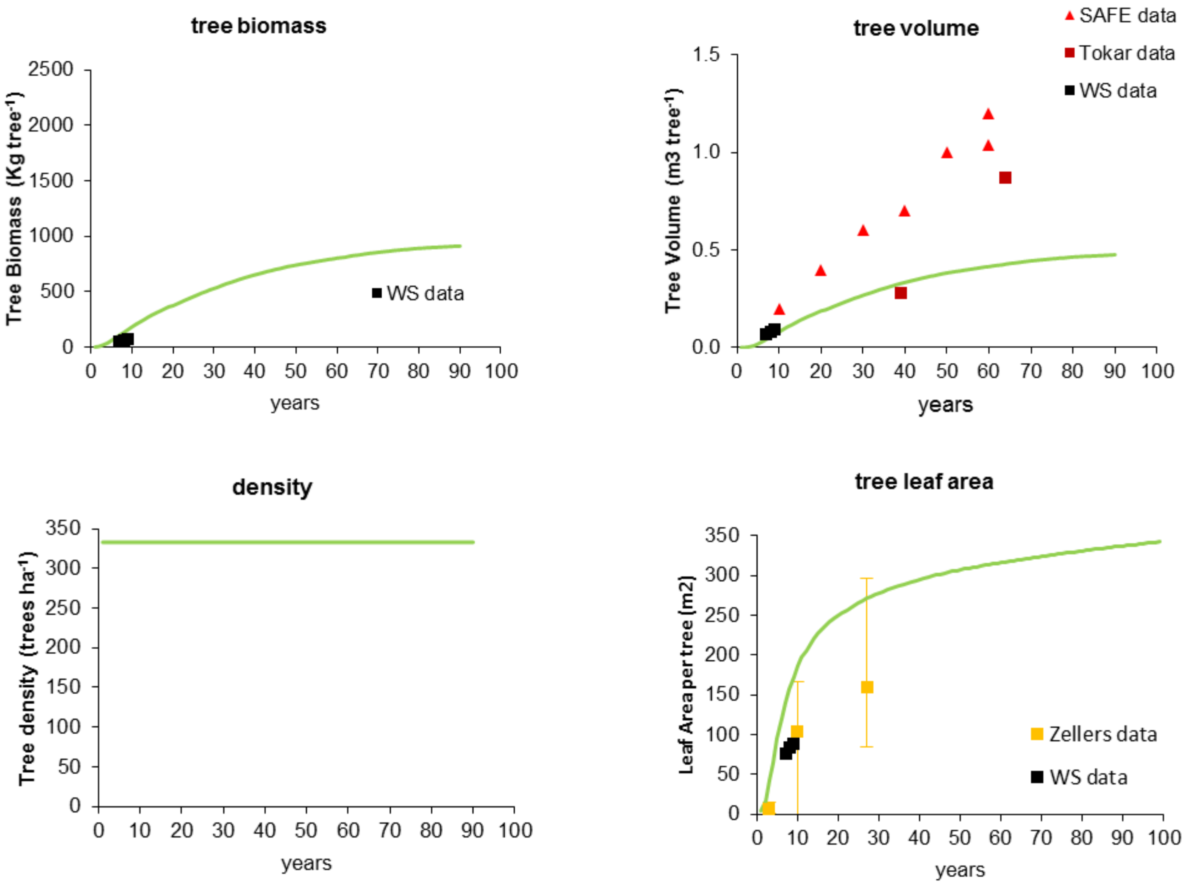


Figure 31. Observed and Yield-SAFE estimation for potential yield of *Juglans nigra*

Once the potential yield is calibrated, by finding the set of parameters that minimize the differences between observed and predicted, the same procedure was done by adjusting solely the parameters related to the water resource usage (gammt and pFCrit). The results are shown comparing the control data from Spain – Figure 32 – and a low density stand – Figure 33.



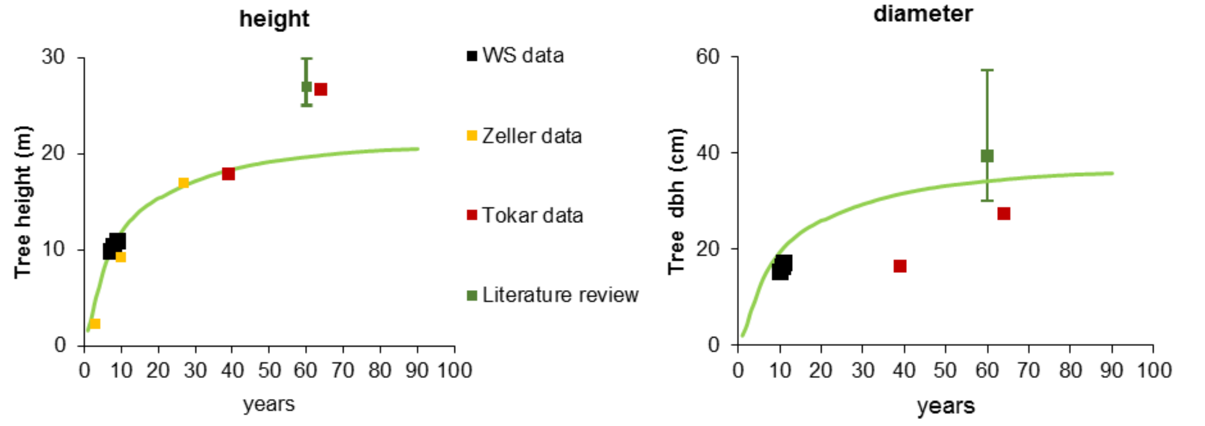
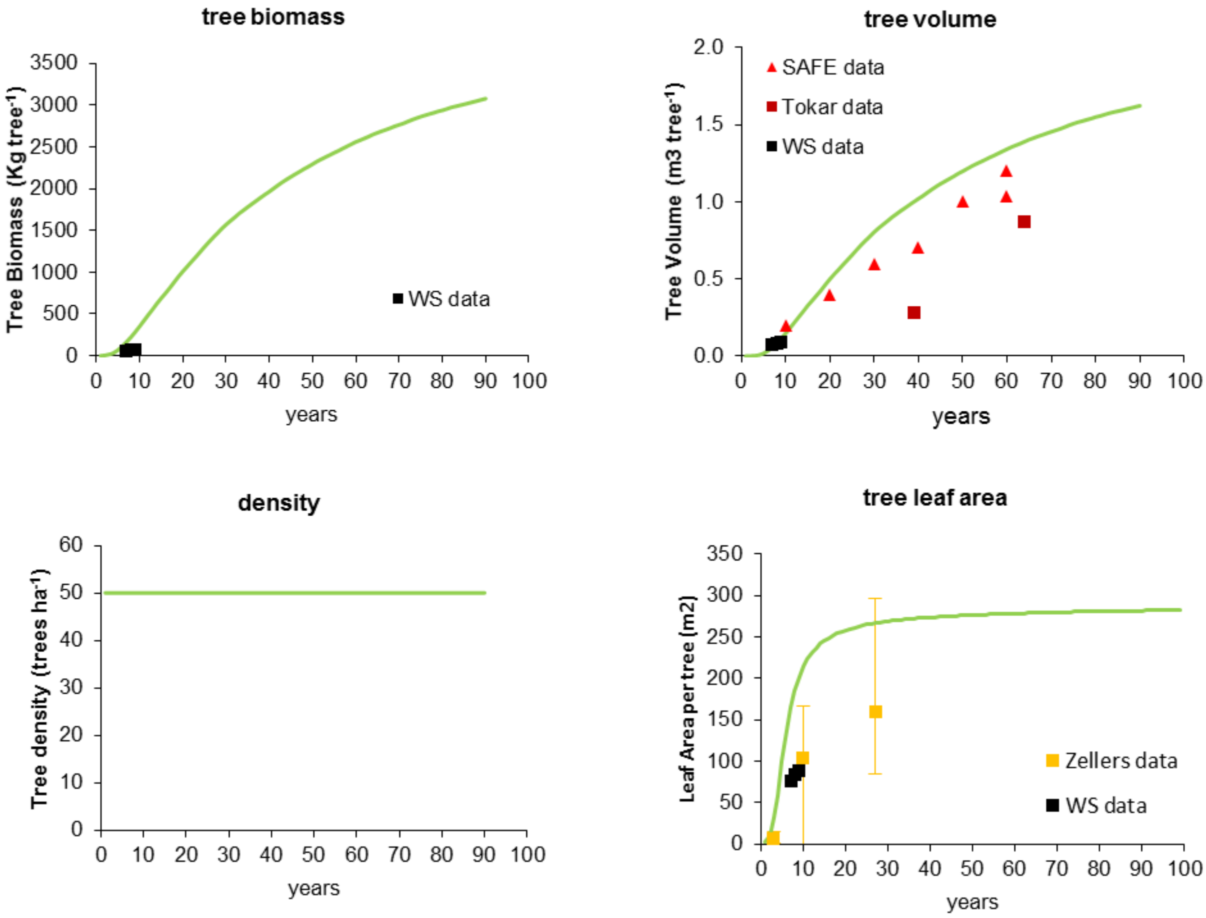


Figure 32. Observed data (points) and Yield-SAFE estimation for potential and control yield of *Juglans nigra*



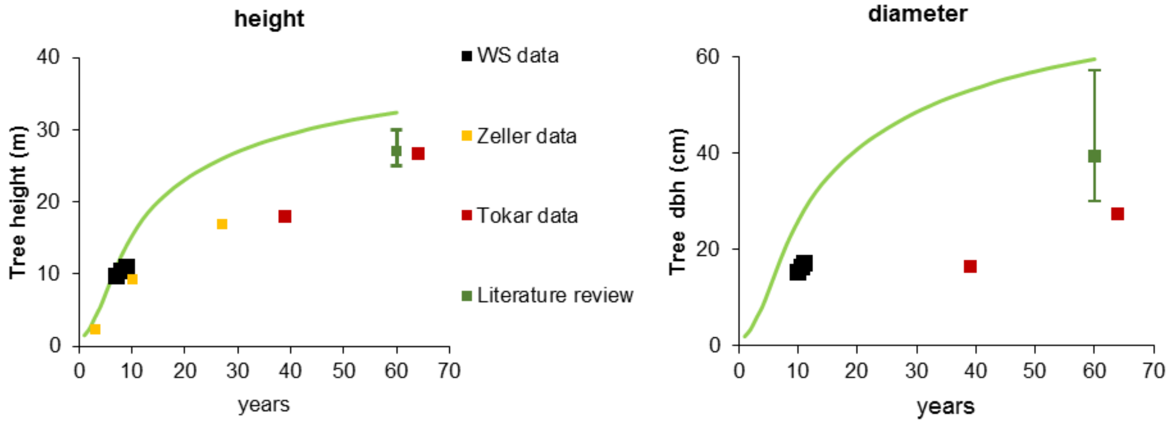


Figure 33. Observed and Yield-SAFE estimation for potential and a low density stand of *Juglans nigra*

10.4 Spruce and grassland in Switzerland

10.4.1 Brief description of the experiment where data was measured

The daily climate data was retrieved from the tool Clipick, an online tool developed under AGFORWARD project to ease the access to climate data for modelling (Palma, 2015). The information was collected for the municipality Muriaux, Switzerland (Lat: 47.2299 Lon: 6.9943) for the years 1960-1990 and was duplicated for modelling 1990 to 2020.

The area is located at approximately 1 000 m elevation on Karst Mountains (Barbezat et al. 2008) . The barren landscape with calcareous rocky elements and crevices is not yet suitable for arable cropping. The trees typically grows on the ridges and the pasture is located on the deeper stands with deep marly colluvial soils (Chételat et al. 2013). The soil is classified by the FAO standard as very fine.

The trees have an average survival time of 150 years without and 80 with competition to other trees (Gillet, 2008).

Table 53. Description of the used data for calibration of spruce in Switzerland

Column Name	Unit	Description	Picea CH	Literature
Specie	Name	Tree name	Picea abies	
Tree density	Tree/ha	Trees present per hectare	80	
Soil texture		FAO classification of texture	Very fine	(Chételat et al. 2013)
Soil depth	Cm	Soil depth	low	(Chételat et al. 2013)

In case of forest modelling for the Swiss case study the thinning regime is as followed: 20,1500; 40, 500; 60, 100.

The calibration of grassland is described below in Grassland (Spruce) in Switzerland

10.4.2 Literature review of tree parameters

Data for the performance of spruce comes from Martin and Jokela (2004) for radiation use efficiency, from Cienciala et al. (1994) for water use efficiency, from Herzog et al. (1995) for the maximum leaf area and the leaf area per tree. Homolová et al. 2013 provided the maximum leaf area for a single bud and Bouriaud et al.(2005) the wood density. Data for root assessment comes from Finér et al. (2007) and Borden et al. (2014).

Table 54. Tree parameter values for Spruce (*Picea abies*) obtained from literature review

Parameter	Value	Reference
doybudburst	10-13 °C (-1 default)	(Ebert 2002)
epst	0.53-0.87	(Martin and Jokela 2004)
f	0.486	(Assmann 1961)
gammat	4.8 g/kg total dry matter produced per unit of water transpired =0,0002 m3/g	(Cienciala et al. 1994)
	175 kg /day. T	(Herzog et al. 1995)
lamax	447 (25 m height, 36 cm)	(Herzog et al. 1995)
labsmax	52.2 (±9.5) mm^2 => 0.00052 m^2	(Homolová et al. 2013)
ratiotimber	0.51 - 0.59	(Pulkkinen and Pöykkö 1990)
ratiobranches	0.40 - 0.48	(Pulkkinen and Pöykkö 1990)
wooddensity	354,000-542,000	(Bouriaud et al. 2005)
sigmaheight	80-120 (38 m/47cm //34m/41cm // 30m/35cm) Max 56-70m (height)	Calculated by (Ebert 2002)
Canopy widthdepth	0.5 (default)	(Elke and Georg 2007)
SLA	50-+17 40 +- 7 33+-2	(Hager and Sterba 1985) (Gower et al. 1993)
LAt	447 (25 m, 36 cm) Leaf area: sapwood 0.36	(Herzog et al. 1995) (McDowell et al. 2002)
LAIt	10.2+-1.8	(Gower et al. 1993)
CCL	0.45-0.55	(Niinemets 1997)
FRR	297 g/m^2 (x)	(Finer et al. 2007)
CCRt	47.8 % ± 1.2	(Borden et al. 2014)

X mean fine root biomass of beech was 389 g m^{-2}, and that of spruce and pine 297 g m^{-2} and 277 g m^{-2}

10.4.3 Measured data for calibration

Picea abies is a typical forest and wood pasture tree and was measured by BADOUX (1969). An extract of the report is shown in the following table and the resulting growth curves in Figure 54.

Table 55. Growth curve for Spruce in Switzerland (source: BADOUX, 1969)

Age	Height (m)			Diameter (cm)			Volume (m^3)	
	Mini-mum	Maxi-mum	Measured	Mini-mum	Maxi-mum	Measured	Mini-mum	Maxi-mum
10	2.00	6.00	5.00	2.00	5.00		0.00	0.01
15	2.86	10.00	9.70	2.82	7.95	15.00	0.00	0.02
20	3.71	14.00		3.64	10.91		0.00	0.06
25	4.57	16.00		4.45	13.86		0.00	0.12
30	5.43	18.00	16.00	5.27	16.82		0.01	0.19
35	5.90	23.00	20.00	6.09	19.77		0.01	0.34
40	6.00	25.00		6.91	22.73		0.01	0.49
45	7.00	30.00		7.73	25.68		0.02	0.76
50	8.00	32.00		8.55	28.64		0.02	1.00
55	9.00	33.00	17.00	9.36	31.59	20.00	0.03	1.26
60	10.00	34.00	16.00	10.18	34.55		0.04	1.55
65	11.00	35.00		11.00	37.50		0.05	1.88
70	13.00	38.00		11.82	40.45		0.07	2.37
75	14.00	39.00		12.64	43.41		0.09	2.81
80	16.00	40.00		13.45	46.36	40.00	0.11	3.28
85	16.00	40.00	35.00	14.27	49.32		0.12	3.71
90	16.00	41.00	25.00	15.09	52.27		0.14	4.28
95	17.00	41.00		15.91	55.23		0.16	4.77
100	17.00	42.00	30.00	16.73	58.18	70.00	0.18	5.43

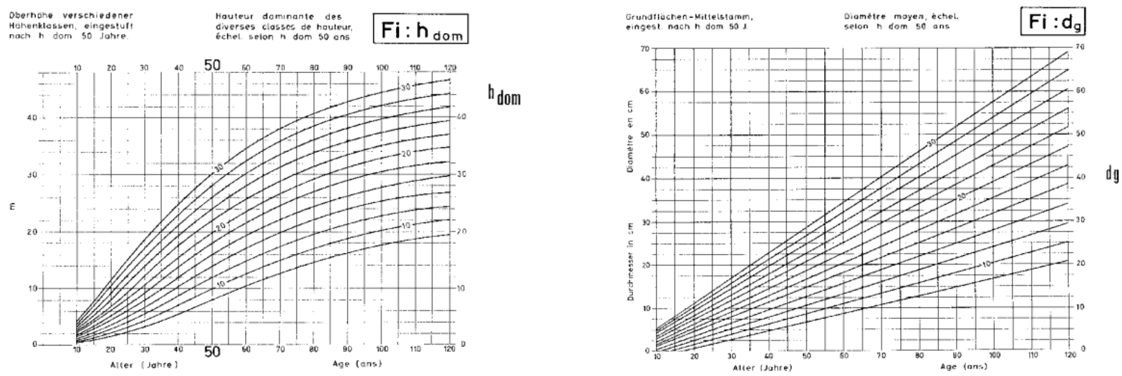


Figure 34. Growth curves for Spruce in Switzerland: left: age to height; right: age to diameter (BADOUX, 1969)

The focus is on wood production and to reach a DBH of 60 to 80 cm (Elke and Georg 2007). Some trees are harvested at 90+ cm (Kändler et al. 2003). The maximum measured was around 1.5 m. The height is between 30 and 60 m, in rare cases 80 m. An overview is given by (Hunger 1986).

The tree density per hectare was mapped using aerial photographs.

10.4.4 Calibration results

Table 56. YIELD-SAFE parameter values for Spruce growth after calibration

Parameter	Description	Unit	Value	Reference from literature
Management parameters				
DOYplanting	DOY = Day Of Year	J. day	1	
DOYpruning		J. day	350	
Pruning height		M	1	
Pbiomass	Proportion of biomass removed per prune		0	
Pshoots	Proportion of shoots removed per prune		0	
	Maximum proportion of bole		0.5	
DOYthining			300	
Site factor			1	
Initial conditions				
nShoots0		$tree^{-1}$	60	
Biomass0		$g\ tree^{-1}$	100	
Boleheight0		m	1	
LA0		$m^2\ tree^{-1}$	0.6	
Parameters				
Ap	parameter to adjust relationship between height and dbh		1	
DOYbudburst	Time of bud burst		-1 (default)	
DOYleaffall	Time of leaf fall		10000	
Epst	Radiation use efficiency	$g\ MJ^{-1}$	0.5	0.53-0.87
F	form factor		0.486	0.486
Gammat	water needed to produce 1 g of tree biomass	$m^3\ g^{-1}$	0.0005	0,0002
Kt	Extinction coefficient		0.8 (default)	
Kmain	Fraction of Biomass needed for maintenance respiration		0.00001 (default)	
LA max	Maximum leaf area	m^2	477	477
LAsbMax	Maximum leaf area for a single bud	m^2	0.00045	0.00052
ratiobranch	ratio of branches to total biomass		0.41	0.40 - 0.48
ratiotimber	ratio of timber to total biomass		0.59	0.51 - 0.59
Wood density	wood density	$g\ m^{-3}$	500000	354000-542000
pFcritt	Critical pF value for tree	(log cm)	2.3 (default)	
PWPt	Permanent Wilting Point for Trees	(log cm)	4.2 (default)	

Sigmaheight	Ratio of height to diameter		100	80-120
dsigma/density	Response of Ht/diameter to density		0 (default)	
Canopywidth/depth	Ratio of maximum width to canopy depth		0.5 (default)	
TreeTau	Number of days after BudBurst to reach 63.2% of final leaf area		10 (default)	
	DOY when leaves start to fall		10000	
	DOY when leaves no longer fall		10000	
ratioLeafFall	ratio of tree leaf area to fall, 1=deciduous		-1	
	Weight of a single leaf	g	0.15	
	Area of a single leaf	cm^2	15	
SLA	Specific Leaf Area	cm^2/g	40	31-67
RSR	Root to Shoot Ratio (IPCC broadleaves=0.25; conifers=0.2)		0.2	0.2
FRR	Fine root ratio from root biomass		0.1	
CCL	Ratio of Carbon Content in Leaves		0.5	0.45-0.55
CCRt	Ratio of Carbon Content in tree roots		0.48	
PiSR	Proportion of biomass to structural roots		0.22	
R	Length of fine roots per unit of structure root		50000	
Kr	Water interception per root length coefficient		0.0007	

10.4.5 Observed vs predicted

The trees show a constant growth and reach a maximum height of over 30 m. The maximum diameter is around 35 cm. Figure 55 shows the simulation results for the potential growth of Spruce in Freiberge and the measured values used as reference and Figure 56 has the results for a minimum scenario (a poor and shallow soil).

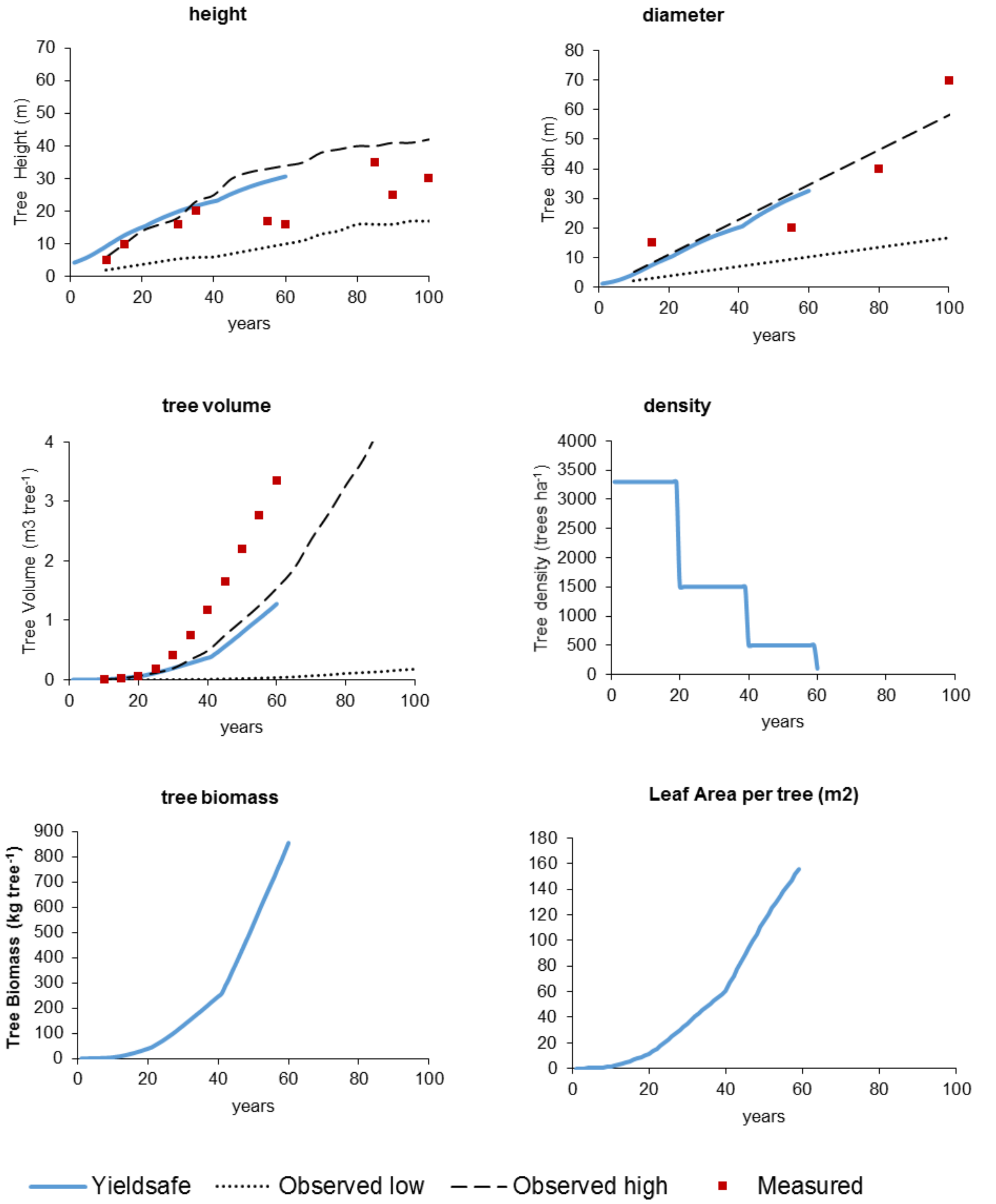


Figure 35. Measured data (points), minimum and maximum values from BADOUX (1969) and Yield-SAFE estimation for potential yield of Picea abies in Freiberge

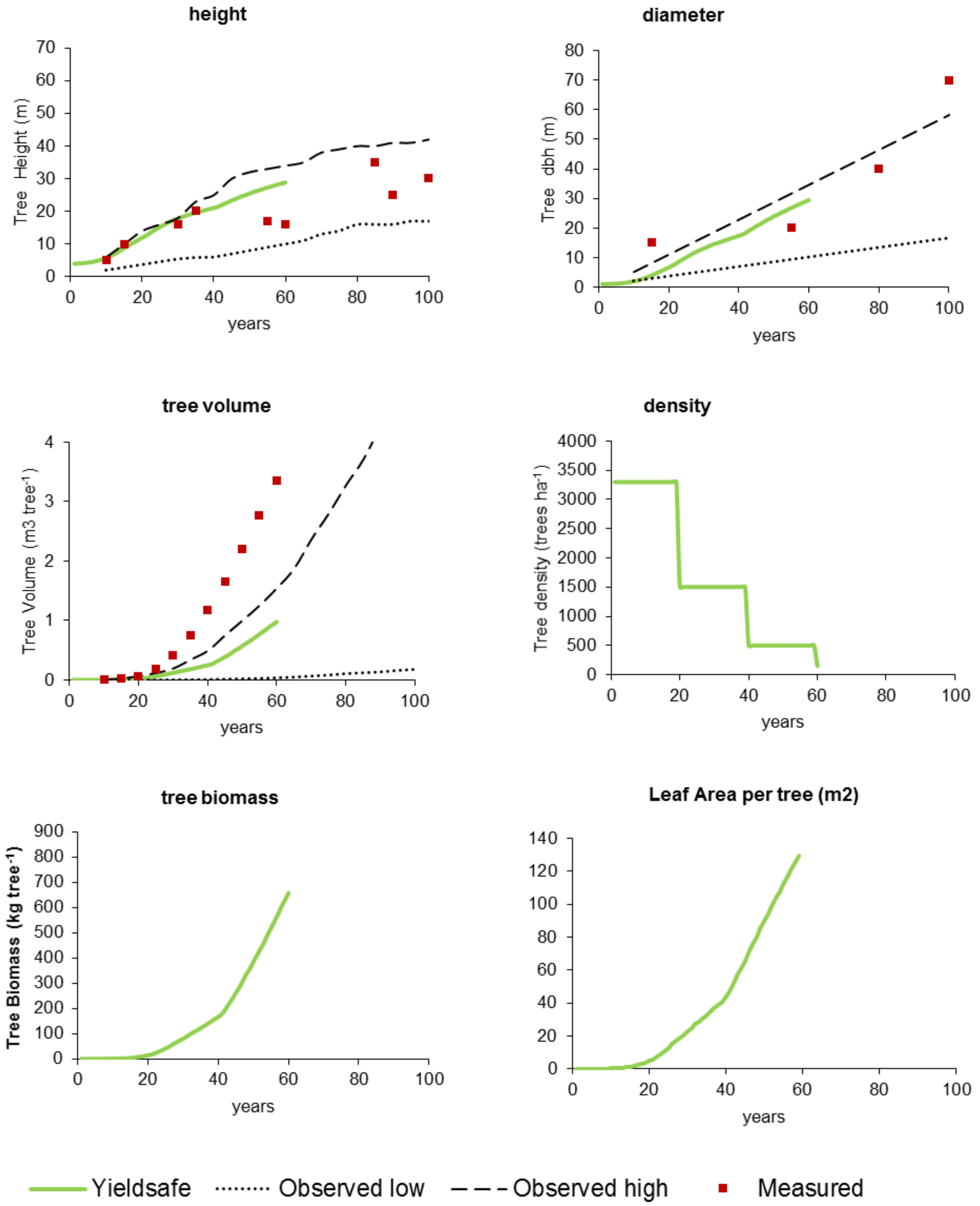


Figure 36. Measured data (points), minimum and maximum values from BADOUX (1969) and Yield-SAFE estimation for yield of Picea abies in minimum scenarios in Freiberge

10.5 Cherry tree – fruit production

10.5.1 Brief description of the experiment where data was measured

Cherry orchards in combination with pasture are widespread traditional agroforestry systems in Switzerland. Our case study took place in northwestern Switzerland; in the municipalities Büren, Gempen, Hochwald, Lupsingen, Nuglar-St. Pantaleon, Seewen, Seltisberg. The system consists of a heterogeneous pattern of young and old cherry trees, namely *Prunus avium*, with a focus on cherry production. A tree life span is around 60 years. The permanent grasslands below are either mown for or grazed by cattle. The cherries are used for liquor, tins or direct consumption, but the consumption and production are declining, suffering the effects of the cherry fruit fly.

For the model calibration we used the climate data from the tool Clipick for Gempen (Lat: 47.2299 Lon: 6.9943, Alt: 700) for the years 1960-1990. Herein the area is characterized by an average annual temperature of 7.7 °C and range between -0.8°C in January to 16.5°C in July. The average annual rainfall is 1081 mm of which monthly falls between 70 mm (October) and 125 mm (August). As input parameter the minimum and maximum temperature, humidity, rainfall, wind speed and solar radiation were used.

The soil was classified as “fine” based on European soil maps (Wösten et al. 1999; Hiederer 2013a; Hiederer 2013b). The region consists of a plateau with shallow soils (30-50 cm) and fine structure and a valley with better soils (partly 50-70 cm). The soil carbon content was measured in the field and analyzed by Extremadura University. This data was validated by the European soil database.

Table 57. Measured data used for calibration of Wild cherry

Column name	Unit	Description	Value	Literature
Species	name	Tree name	*Prunus avium*	
Tree density	ha^{-1}	Trees presente per hectare	80	Measured in plots
Soil texture		FAO classification of texture	Fine	Soil map
Soil depth	cm	Soil depth	1000	Soil map

10.5.2 Literature review of tree parameters

The tree calibration is mainly based on literature data. Herein the general background information for cherry trees comes from Schmid (2006); regional data from Sereke et al. (2015). Special performance parameter as radiation use efficiency and water use efficiency are from research projects from Yorgey et al. (2011) . Data from Reich et al. (1998) and Cittadini et al. (2008) are used for the specific leaf area and the leaf area index. Flowers and Fruits start with the age of 20-25; cultivated species with age 4-15 (Schmid, 2006).

Table 58. Tree parameter values for Cherry tree (*Prunus avium*) growth obtained from literature review

Parameter	Value	Reference
doybudburst	92-130	(Schmid, 2006)
doyleaffall	260-290	(Schmid, 2006)
doyleaffall_start	250	(Schmid, 2006)
doyleaffall_end	350	(Schmid, 2006)
SLA	90-170 (20-30 m2)	(Reich et al. 1998)
LAIt	3.6 ha / ha	(Cittadini et al. 2005)
FruitFallingDays	100 (June / Aug)	(Schmid, 2006)
FruitPeakDOY	210 (Mai / June)	(Schmid, 2006)
epst	2.7	(Yorgey et al. 2011)
gammat	4.8 g /kg (=0.20 m3/g)	(Yorgey et al. 2011)
Canopy widthdepth	0.5	(Yorgey et al. 2011)

10.5.3 Measured data for calibration

22 cherry trees were measured in the field in the summer of 2016. Herein tree height, tree diameter, crown length and crown radius were recorded. Also fruit production was analyzed. All data was summarized by Kühn (2016). The tree density per hectare was mapped by using aerial photographs.

10.5.4 Calibration results

Table 59. YIELD-SAFE parameter values for Cherry tree growth after calibration

Parameter	Description	Unit	Value	Reference from literature
nShoots0		$tree^{-1}$	1.8	
Biomass0		$g\ tree^{-1}$	100	
Boleheight0		m	1	
LA0		$m^2\ tree^{-1}$	0.5	
Parameters				
Ap			1	
DOYbudburst	Time of bud burst		130	92-130
DOYleaffall	Time of leaf fall		290	260-290
Epst	Radiation use efficiency	$g\ MJ^{-1}$	0.526	2.7
F	form factor		0.6	
gammat	water needed to produce 1 g of tree biomass	$m3\ g^{-1}$	0.00020	4.8 g /kg
Kt	Extinction coefficient		0.8	
Kshoot			555500	
Kmain	Fraction of Biomass needed for maintenance respiration		0.00008	
LA max	Maximum leaf area	m^2	500	
LAsbMax	Maximum leaf area for a single bud	m^2	0.05	
NshootsMax	Maximum number of buds on a tree		10000	
ratiobranch	ratio of branches to total biomass		0.7	
ratiotimber	ratio of timber to total biomass		0.3	

Wood density	wood density	g m^{-3}	608000	
pFcritt	Critical pF value for tree	(log cm)	4.00	
PWPt	Permanent Wilting Point for Trees	(log cm)	4.2	
Sigmaheight	Ratio of height to diameter		18	
dsigma/density	Response of Ht/diameter to density		0	
Canopywidth/depth	Ratio of maximum width ro canopy depth		0.5	
TreeTau	Number of days after BudBurst to reach 63.2% of final leaf area		10	
$DOY_{leaffallstart}$	DOY when leaves no longer grow and start to fall	1-365	240	250
$Leaf_{LeafFallEnd}$	DOY when leaves no longer fall	1-365	330	350
*f*LeafFall	Proportion of leaf area that will fall (1=deciduous)	0-1	1	
	Weight of a single leaf	g	0.5	
	Area of a single leaf	cm2	20	
SLA	Specific Leaf Area	cm2/g	90	90-170
RSR	Root to Shoot Ratio (IPCC broadleaves=0.25; conifers=0.2)	0-1	0.25	
f^{FR}	Proportion of fine roots from root biomass	0-1	0.1	
*f*CCL	Ratio of Carbon Content in Leaves	0-1	0.5	
$fCCR_t$	Ratio of Carbon Content in tree roots	0-1	0.5	
Pi_{SR}	Ratio of structural root mass to aboveground biomass	0-1	0.22	
r	Length of fine roots per unit of structure root	m/g	50000	
K_r	extinction coefficient governing the absorption of water per unit of root length	0-1	0.0007	
$Leaf_{UME}$	Utilizable Metabolizable Energy from leaves	MJ/t DM	18260	
$Branch_{UME}$	Utilizable Metabolizable Energy from branches	MJ/t DM	18260	
Fru_{UME}	Utilizable Metabolizable Energy from fruit	MJ/t DM	7000	
$Fruit_{Name}$	fruit name		cherry	
Fru_p	Fruit productivity per canopy area	g / m^2 LAI	45	
$Fruit_{FallingDays}$	Nr of days when 95% of fruit falls	days	100	100
$Fruit_{DOYPeak}$	DOY when fruit fall peak occurs	DOY	210	210
$Fruit_{Weight}$	weight of a single fruit	g $piece^{-1}$	13	
Kta	a parameter for Kt		10	
Ktb	b parameter for Kt		0.4	

10.5.5 Observed vs predicted

The model was able to predict tree growth according to the various conditions. The results from Figure 37 show also a good response to regional conditions. The cherry trees show a fast youth growth until the age of 20 and a constant slow growth until the age of 60. The trees reach a maximum height of 10 m with a diameter of 60 cm. During the life span of these trees, 1.7 m^3 of biomass could be produced by a single tree. One single tree could produce up to 20 kg cherries per year. However, the fruit production is very volatile depending on the weather during spring time.

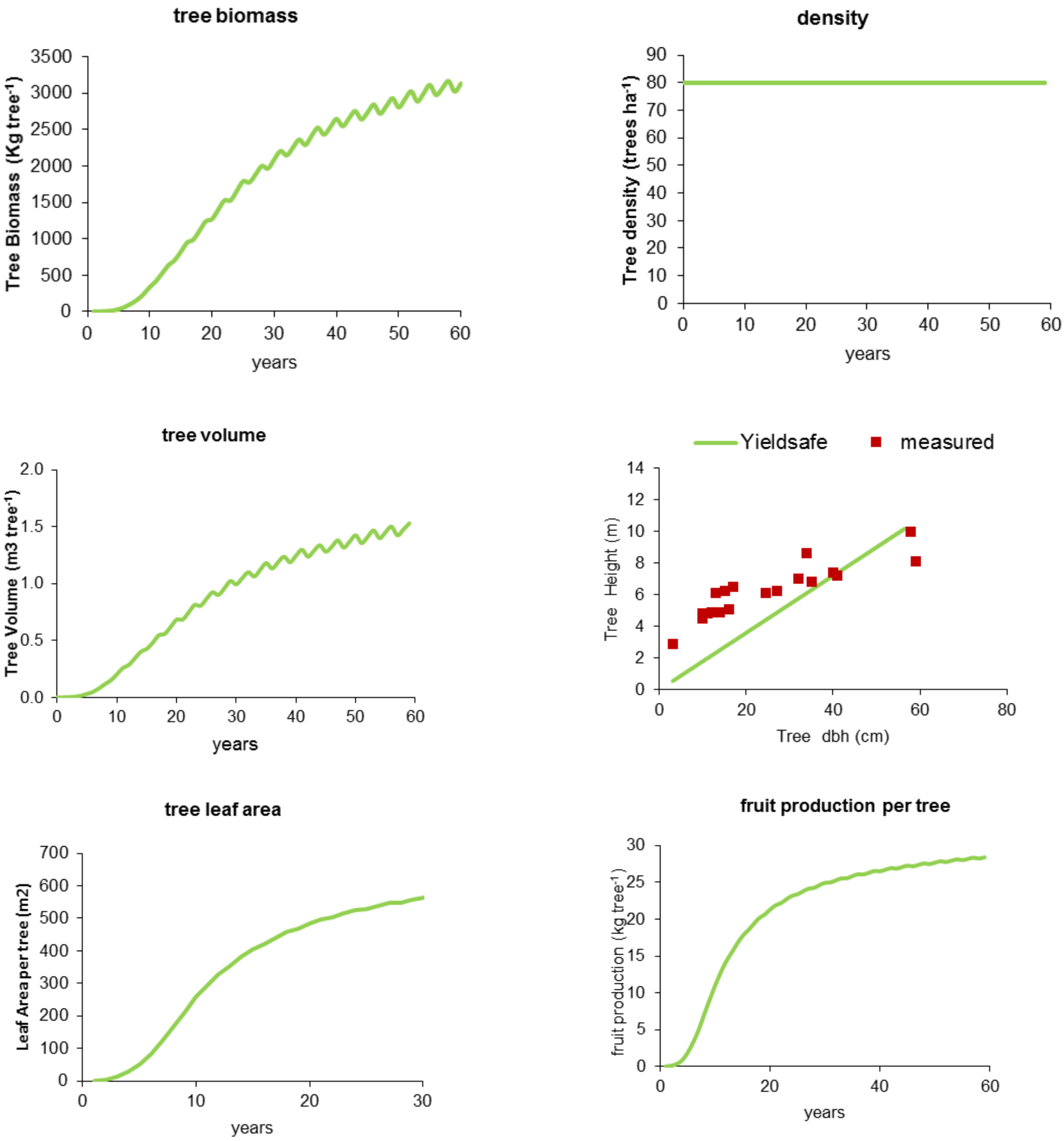


Figure 37. Yield-SAFE estimation of potential cherry trees growth and measured data summarized by Kühn (2016) (points)

10.6 Cherry tree – timber production

The main output from the Yield-SAFE model is tree biomass. From the biomass value, volume, diameter and height of the average tree are calculated. Whenever a pruning is made, the amount of biomass is reduced and consequently, the values of volume, height and diameter. Due to this model structure, there is a need to calibrate the model with two sets of different parameters for the same species when the same tree can be conducted to produce timber or fruit. The types of management options are different and so are the results in the tree growth. When the tree is managed to fruit production, the prunings are made to increase leaf area and fruit productivity, so the calibration has to be made in order to respond that way. When the main output is timber, initial planting density is higher (800 to 1000 trees per hectare) and all the operations made are to insure straight and tall trees.

Considering this, a second calibration was made for cherry, but for timber production. The same simulation as the one used for fruit production was used and measured data from (Duick 1997) was used.

10.6.1 Calibration results

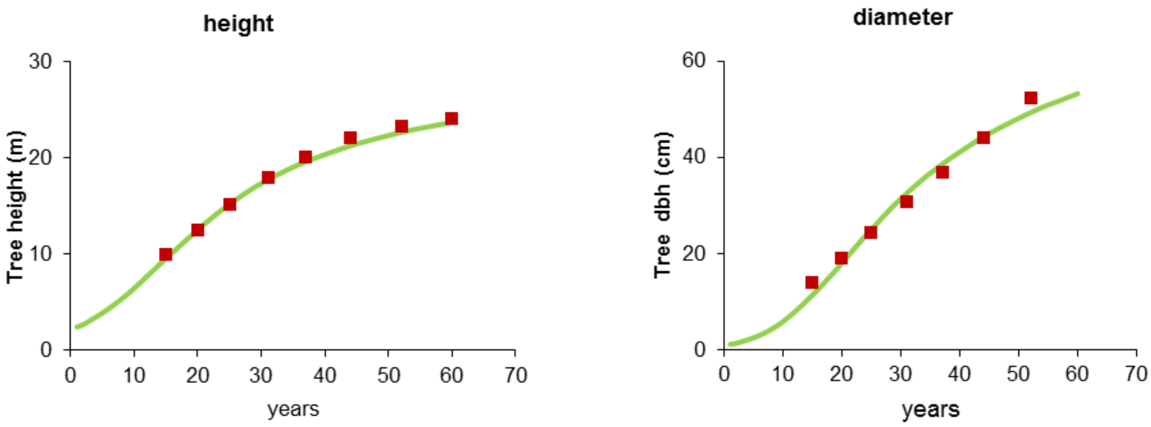
Table 60. YIELD-SAFE parameter values for Cherry tree growth for timber after calibration

Parameter	Description	Unit	Value
nShoots0		tree^{-1}	0.57
Biomass0		g tree^{-1}	100
Boleheight0		m	0
LA0		m^2 tree^{-1}	0.5
ap			0.59
DOYbudburst	Time of bud burst		100
DOYleaffall	Time of leaf fall		300
epst	Radiation use efficiency	g MJ^{-1}	0.5626
F	form factor		0.6
gammat	water needed to produce 1 g of tree biomass	m3 g^{-1}	0.00035
kt	Extinction coefficient		0.8
Kmain	Fraction of Biomass needed for maintenance respiration		0.0001
LA max	Maximum leaf area	m^2	500
LAsbMax	Maximum leaf area for a single bud	m^2	0.05
NshootsMax	Maximum number of buds on a tree		10000
ratiobranch	ratio of branches to total biomass		0.4
ratiotimber	ratio of timber to total biomass		0.45
Wood density	wood density	g m^{-3}	608000
pFcritt	Critical pF value for tree	(log cm)	4.00
PWPt	Permanent Wilting Point for Trees	(log cm)	4.2
Sigmaheight	Ratio of height to diameter		34.35
dsigma/density	Response of Ht/diameter to density		0
Canopywidth/depth	Ratio of maximum width ro canopy depth		0.6

TreeTau	Number of days after BudBurst to reach 63.2% of final leaf area		10
DOY$_{leaffallstart}$	DOY when leaves no longer grow and start to fall	1-365	240
Leaf$_{LeafFallEnd}$	DOY when leaves no longer fall	1-365	330
*f*LeafFall	Proportion of leaf area that will fall (1=deciduous)	0-1	1
	Weight of a single leaf	g	0.5
	Area of a single leaf	cm^2	84
SLA	Specific Leaf Area	cm^2/g	168
RSR	Root to Shoot Ratio (IPCC broadleaves=0.25; conifers=0.2)	0-1	0.25
f^{FR}	Proportion of fine roots from root biomass	0-1	0.1
*f*CCL	Ratio of Carbon Content in Leaves	0-1	0.5
*f*CCR$_t$	Ratio of Carbon Content in tree roots	0-1	0.5
Pi$_{SR}$	Ratio of structural root mass to aboveground biomass	0-1	0.22
r	Length of fine roots per unit of structure root	m/g	50000
K$_r$	extinction coefficient governing the absorption of water per unit of root length	0-1	0.0007
Kta	a parameter for Kt		10
Ktb	b parameter for Kt		0.4

10.6.2 Observed vs predicted

The results of the calibration are shown in Figure 58 along with the measured data from (Duick 1997).



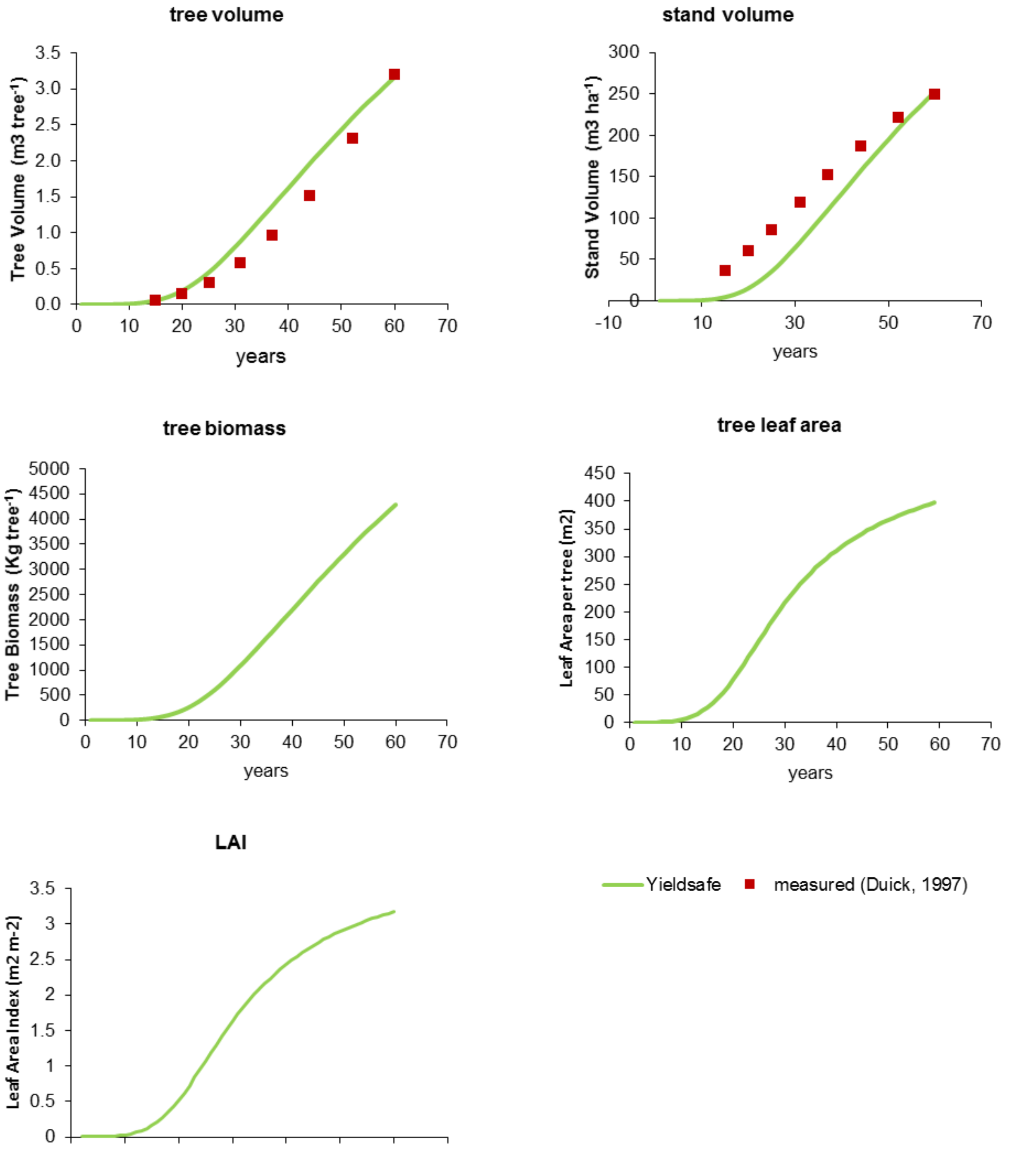


Figure 38. Observed data from (Duick 1997) – points – and Yield-SAFE estimation for the yield of Prunus avium

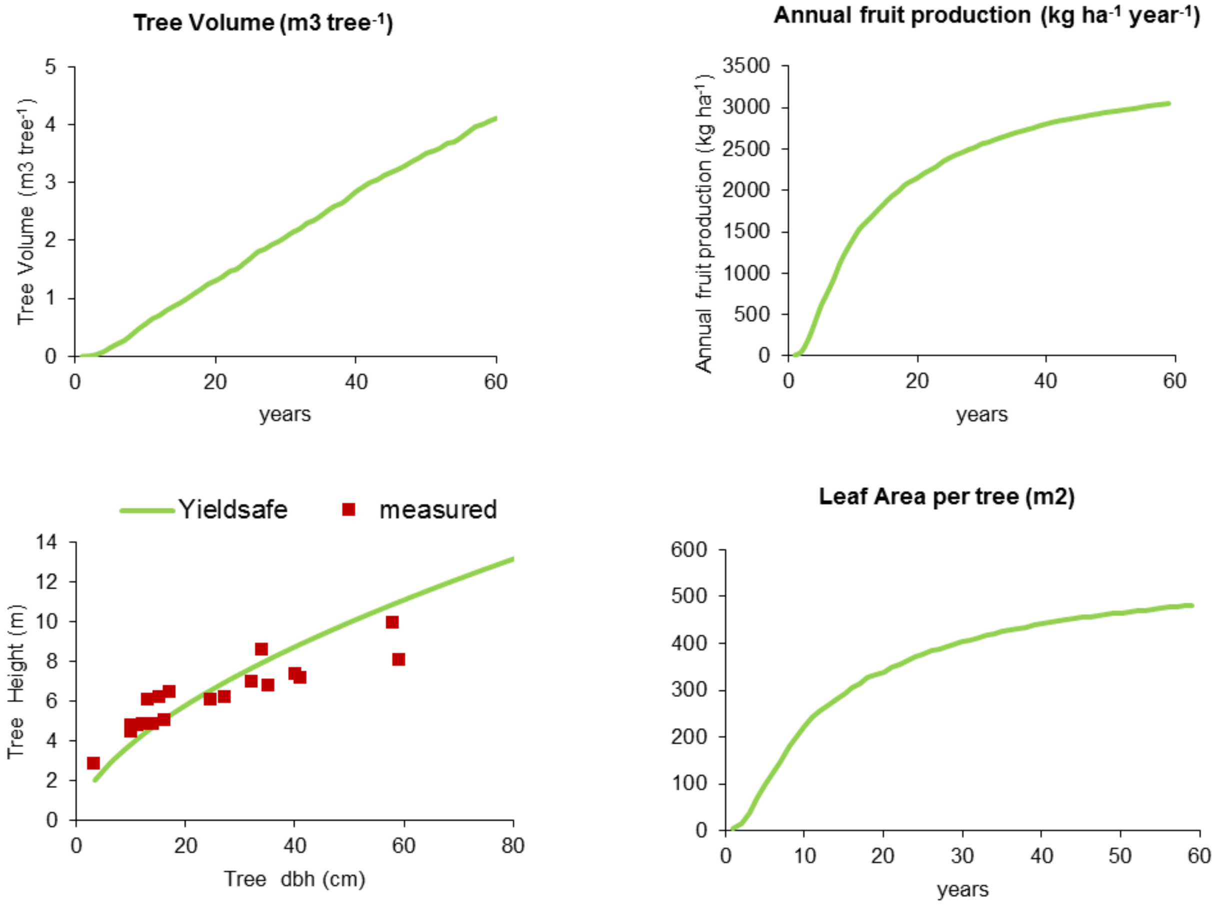


Figure 39. Yield-SAFE estimation of cherry trees growth and measured data summarized by Kühn (2016) (points)

10.7 Apple tree and rye in Switzerland

10.7.1 Brief description of the experiment

The agroforestry system consists in apple trees with mainly winter wheat and is located in canton of Lucerne, central Switzerland. The experiment takes place on 50 hectare. Herein 545 apple trees (varieties Boskoop and Spartan) were planted. The fruits are used for juice and cider production. The cropland is used for winter wheat, rapeseed, strawberries and sown flower strips.

The model was calibrated using climate data for Sursee (Lat: 47.1715, Lon: 8.1111, Alt: 500) from Clipick for the years 1960-1990. Herein the area is characterized by an average annual temperature of 8.9 °C. The average annual rainfall is 967 mm of which monthly falls between 65 mm (October) and 135 mm (August). As input parameter the minimum and maximum temperature, humidity, rainfall, wind speed and solar radiation were used.

The soil type is an eutric camisole, with a soil depth of > 100 cm. The soil texture is sandy-loam and the field is north-west orientated. As input into the model the European soil maps classification (Wösten et al. 1999; Hiederer 2013a; Hiederer 2013b) was used.(Wösten et al. 1999; Hiederer 2013a; Hiederer 2013b) was used.

10.7.2 Literature review of parameters

The tree calibration mainly based on literature data. The general background information comes from Wagner (2005), regional data comes from measurements. Performance parameters like radiation use efficiency are from projects from (Kiniry 1998)(Kiniry 1998), water use efficiency and transpiration rate from Ma et al. (2010)Ma et al. (2010). Furthermore data from Kurz and Machatschek (2008) were used to assess the maximum leaf area and from Bassett et al. (2011) and Schumacher (1962) the maximum leaf area for a single bud. Wood density, ratio of height to diameter and specific leaf area come from Jenkins et al. (2004), Gerhold (2000) and Friedrich (1993)). As further sources, data from Friedrich (1993), Auzmendi et al. (2013) and Barvin et al. (2014) were used. Table 61 presents the found values and the references used:

Table 61. Tree parameter values for apple obtained from literature review

Parameter	Value	Reference
doybudburst	100-130	(Wagner, 2005)
doyleaffall	260-290	(Wagner, 2005)
Epst	1.3-1.9	(Kiniry, 1998)
gammat	3.19- 3.83 mg ml-1 (3g pro 0.001 m3) 0.000261-0.000313	(Ma et al. 2010)
Kmain	Transpiration rate leaf area 0.16-0.17 TRate roof 12.62-14.96	(Ma et al. 2010)
Lamax	64-100	(Kurz and Machatschek, 2008)
Labsmax	0,0008 - 0,2846	(Bassett et al. 2011)
Labsmax	0.0014 – 0.0020	(Schumacher, 1962)
wooddensity	610 kg/m3 -> 610000	(Jenkins et al. 2004)
sigmaheight	50-120	(Gerhold, 2000)

Canopy widthdepth	1.25 Apple (width:2.5; depth: 2) Cherrie: 0.8 -1.3 Width: 12m^2 (~4m) depth: 2.9-4.5 m	(Friedrich, 1993) p.355
SLA	29.9 cm2/g +- 3.54	(Poblete-Echeverría et al. 2015)
LAIt	2.46 +-0.57 (young plants)	(Poblete-Echeverría et al. 2015)
LAIt	14.38 (waterstressed) 15.24 (irrigated)	(Ma et al. 2010)
LAIt	2-31 – 2.45	(Auzmendi et al. 2013)
RSR	0.25 0.25-0.3 Root part to canopy 0.66 (6.099 woody biomass/ 3.999 coarse root)	 (Friedrich, 1993) p.29 (Panzacchi et al. 2012)
FRR	0.9	(Friedrich, 1993) p.27
FruitProductivity_gm2	100-200 kg/tree	(Barvin et al. 2014)
FruitPeakDOY	240-270	(Schumacher, 1962)
FruitWeight_gFreshFruit	90-150g	(Schumacher, 1962)
FruitWeight_gFreshFruit	Boskoop (180-200g)	(Friedrich, 1993) p.137
Fruit productivity	900 g/m^2 (100 kg per tree = 660 fruits per tree = 6 fruits per canopy area)	(Volz, 1988)

10.7.3 Measured data for calibration

Field measurements described in the research and development protocol of WP4 (Herzog, 2015 were started in June and July 2011, and a second assessment was carried out in 2014, when the trees were measured for the second time and soil properties were assessed.

Winter rye field data comes from the annual regional statistic and the research plots at university Freiburg (Germany).

10.7.4 Calibration results

Table 62. YIELD-SAFE parameter values for apple tree growth for timber after calibration

Parameter	Description	Unit	Value	Reference from literature
ap	parameter to adjust relationship between height and dbh - H=sigmaheight*dbh^ap	unitless	0.6	
Doybudburst	The day of year when budburst occurs	1-365	130	100-130
Doyleaffall	The day of year when leaves fall. If perennial provide a value higher than 366	1-365	290	260-290

Epst	radiation use efficiency	g/MJ	1	1.3-1.9
F	Form Factor. relates to tree volume, height and diameter	unitless	0.35	
Gammat	Water use efficiency	m3/g	0.00031	0.000261-0.000313
Kta	parameter A for radiation extinction coefficient	unitless	0.8	
Ktb	parameter B for radiation extinction coefficient	unitless		
Kmain	Fraction of Biomass needed for maintenance respiration	0-1	0.00001	Transpiration rate leaf area 0.16-0.17 TRate roof 12.62-14.96
Lamax	Maximum leaf area	m2	100	64-100
Labsmax	Maximum leaf area for a single bud	m2	0.0035	0.0008 – 0.2846
Ratiotimber	ratio of timber to total biomass	0-1	0.65	
Ratiobranches	ratio of branches to total biomass	0-1	0.35	
Wooddensity	wood density	g/m3	610000	610000
Pfcritt	Critical pF value for tree, above which tree starts to drought induction	unitless	2.3	
Pwpt	pF for permanent wilting point	unitless	4.2	
Sigmaheight	Ratio of height to diameter	unitless	35	50-120
Dsigmadensity	Response of Ht/diameter to density	unitless	0	
Canopy Widthdepth	Ratio of maximum width to canopy depth	unitless	0.6	1.25
Treetau	Number of days after BudBurst to reach 63.2% of final leaf area	days	10	
nshoots0	Initial number of shoots	nr	2.2	
biomass0	Initial biomass	g/tree	100	
boleheight0	Maximum bole height	M	1	
lat0	Initial leaf area of the tree	m2/tree	0.5	
Sitefactor	Site Factor. Usually 1	unitless	1	
Doyleaffall	The day of year when leaves fall. If perennial provide a value higher than 366	1-365	290	

doyleaffall_start	The day of year when leaves start to fall	1-365	260	
doyleaffall_end	The day of year when leaves no longer fall	1-365	290	
ratioLeafFall	The ratio of leaves that fall when tree is perennial. Is applied when doyleaffall is higher than 366 together with doyleaffal_start and doyleaffal_end	0-1	1	
SLA	specific leaf area	cm2/g	50	29.9 +- 3.54
CCL	Ratio of Carbon Content in Leaves	0-1	0.49	
RSR	Root to Shoot Ratio (IPCC broadleaves=0.25; conifers=0.2)	0-1	0.25	0.25-0.3 0.66
FRR	Fine root ratio from root biomass	0-1	0.1	0.9
CCRt	Ratio of Carbon Content in tree roots	0-1	0.5	
FruitEnergy_MJtDM	Energy of the fruit	MJ/ t DM	11650	
FruitName	Name of the fruit	text	Apple	
FruitFallingDays	Number of days the fruit is falling	1-365	30	
FruitPeakDOY	the day of the year when there is a peak for fruit falling	1-365	270	240-270
FruitWeight_gFreshFruit	Fresh weight for each piece of fruit	g/ FreshPiece	150	90-150g 180-200g
Fruit productivity	Gram of fruit per canopy area	g / m2 canopy	900	900

10.7.5 Observed vs predicted

The model was able to predict tree growth according to the various conditions. The results show also a good response to regional conditions. Figure 40 shows the simulation results for the potential growth and the measured data used as reference for the calibration.

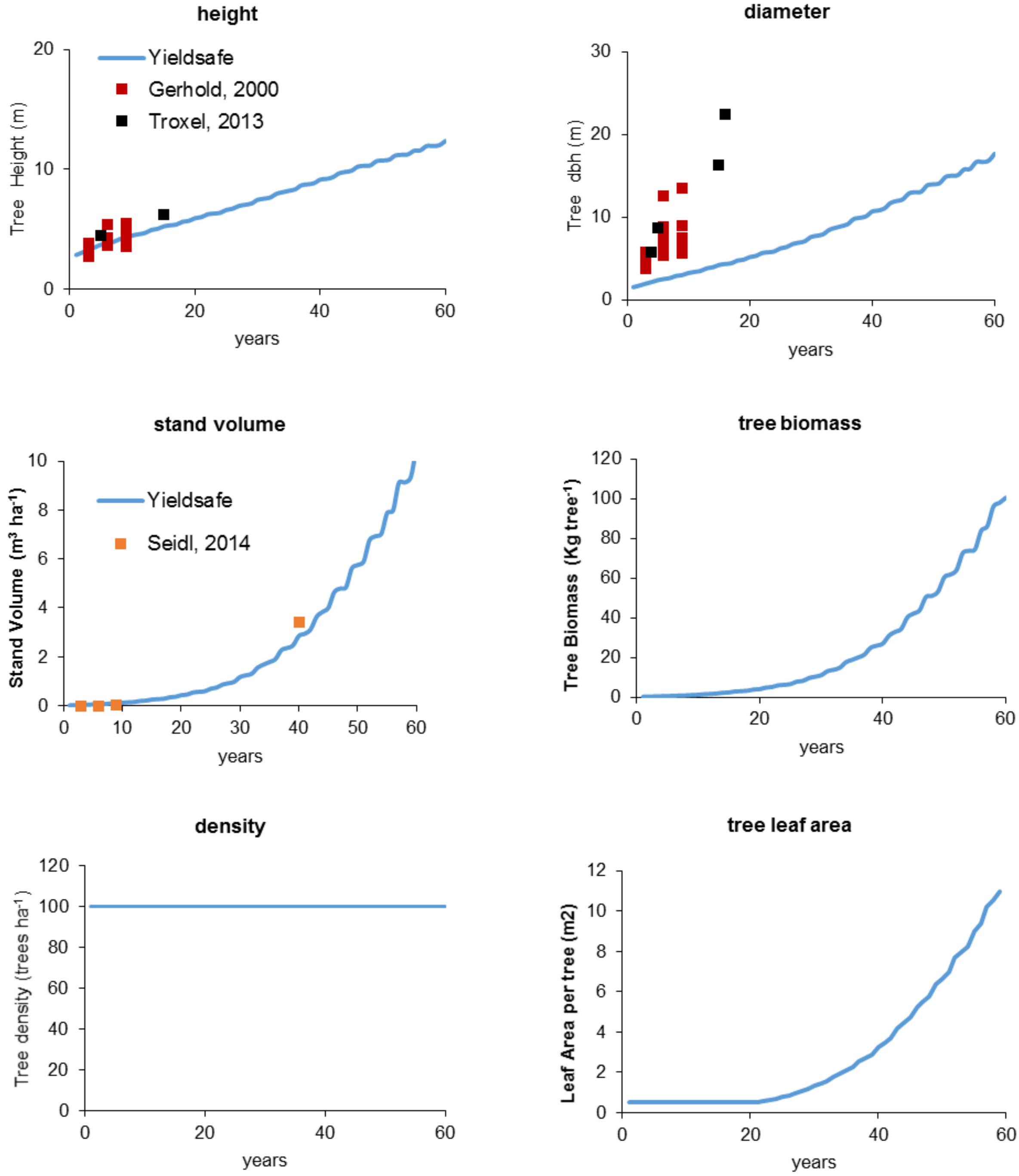


Figure 40. Observed data (points from (Gerhold 2000; Troxel et al. 2013; Seidl 2014) and Yield-SAFE (blue line) estimation for potential yield of *Malus domestica*

10.8 Short Rotation Coppice systems in Europe

Silvoarable or silvopastoral systems with Short Rotation Coppice (SRC) have in common the establishment of fast-growing trees (e.g. willow or poplar) combined either with arable crops or with livestock. In this section we explore some existing systems and data from poplar with arable crops in Germany, with pigs in Denmark, willow systems in UK and the Netherlands.

10.8.1 Brief description of the experiment where data was measured

10.8.1.1 SRC poplar in silvoarable system (DE)

The experiment is located in Neu Sacro (Lausitz), Germany (51°47'21"N, 14°37'42"W (or: N51.789278; W14.628202). Mean annual rain is 608 mm and mean monthly temperature is 9.3 °C. The soils have a humus content of 1.9%, are a sandy loam and can be classified as (WRB classification) Gleyic Fluvisol. Research focused on the northern section of the system, which was planted in 2010/2011. This section of the field consists of seven tree hedgerows that are 11 m wide (four double rows) and approximately 600 m long. The distance between the tree hedgerows varies between 24, 48 and 96 m. The southern part of the alley cropping system is 33 ha and was planted in 2014 and 2015. It consists of six hedgerows of poplars that are 17.4 m wide and three hedgerows of mixed planting. The spacing between the tree hedgerows in the southern area is 72 m and 144 m. For the AGFORWARD modeling we will focus on the northern section of the field.

Trees: The tree hedgerows of short rotation coppice alley cropping systems consist of fast growing woody crops. Common fast growing woody crops include poplar (*Poplar* spp), black locust (*Robinia pseudoacacia), w*illow (*Salix* spp.), and alder (Alnus *glutinosa*). The northern part of the alley cropping system is 40 ha and consists of poplar (*Poplar* spp, varieties Max 1 (*Populus nigra L.× P. maximowiczii*) and Fritzi-Pauley (*P. trichocarpa*) and black locust (*Robinia pseudoacacia*). This part of the experimental site was planted in 2010 and the poplars were replanted in 2011. The southern part consists of poplar Max 1, Matrix 49 (*P. maximowiczii × P. trichocarpa*) and Hybrid 275 (*P. maximowiczii x P. trichocarpa).*

Crops: The crop alleys in between the tree hedgerows are planted with conventional arable crops common to Germany. The crops in the previous years have been 2010: maize (*Zea mays*), 2011: maize, 2012: alfalfa (*Medicago sativa*)/SolaRigol (legume and not legume mix for potatoes), 2013: potatoes (*Solanum tuberosum*), 2014: winter wheat (*Triticum durum*), and 2015: sugar beet (*Beta vulgaris*). In 2016 the crop is again winter wheat. Crop spacing and design is according to common agricultural practice. For this year’s sugar beet crop at the research site in Forst crop densities ranged from 8 to 13 beets m^{-2}. For the modelling activities we will focus on the 2014 winter wheat (422.7 kg/ha seeds) and the 2015 sugar beet crops.

The experimental design consisted of 4 Poplar and 4 Black Locust plots of equal size grouped in a complete randomized design. The plots had 4 double rows of trees (Figure 41). Each plot consisted of 40 measurement trees of which 20 were located in the two outside rows. In addition, a buffer strip of 1.30 m between the trees and crop is present. In the area weeds have been establishing.

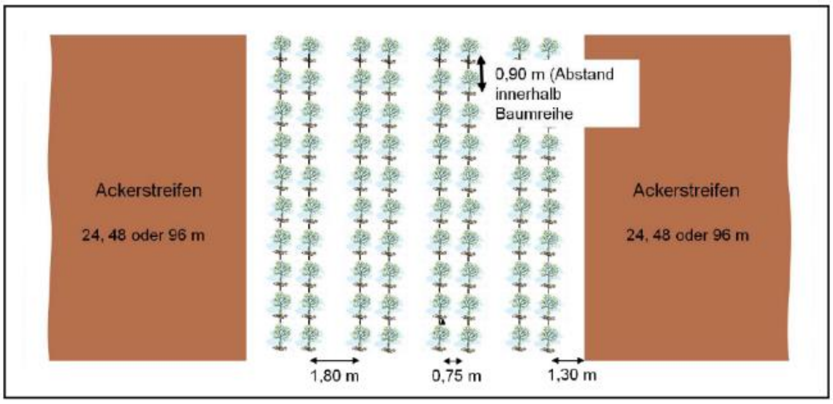


Abb. 3: **Abstände in den Doppelreihen** *(Quelle: C. Böhm)*

Figure 41. Double row planting of tree hedgerows. Measurement plots included an equal number (20 measurement trees) in the 2 outside double rows and in the 2 center double rows.

For the tree control plots the centre 2 rows of the tree hedgerow will be used. For the crop control 4 plots were measured in an adjacent conventional agricultural field. For biomass production (aboveground) measurements allometric relationships were established between diameter at 10cm above the ground and biomass. For biomass estimations of the plots, diameters and heights were measured on the 40 measurement trees. The number of measured plots in the experiment are detailed in the following Table.

Table 63. Number of plots measures in the experiment

Date	Tree age black locust (years)	Tree age poplar (years)	Poplar	Black locust	Forest control poplar	Forest control black locust	Crop control
30.11.2010	0.6	0		4		4	3
17.01.2012	1.75	0.75	4	4	4	4	3
01.12.2012	2.6	1.6	4	4	4	4	3
01.12.2013	3.6	2.6	4	4	4	4	3
12.02.2015	4.83	3.83	4	4	4	4	4

10.8.2 SRC poplar with pigs (DK)

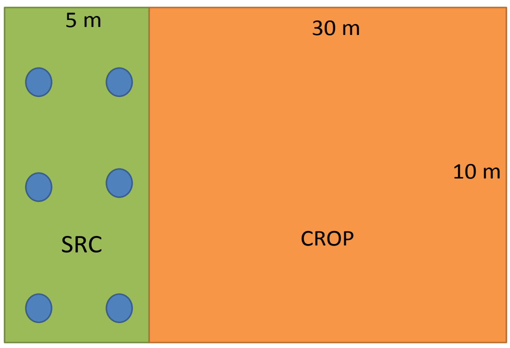
In Denmark, poplar is grown as energy crop under short rotation coppice together with free-range pig production. The experimental site is located near Brørup, Denmark (55°34’38.1”N; 8°59’36.5”E). Daily climate data can be retrieved from a weather station located approximately 4 km from the experimental site. The soil type is Podzol and the texture is classified as a mixture of coarse and loamy sand. The experimental design is illustrated in Figure 42.

Research focus on evaluating nutrient emissions, crop damages, crop yields and animal behaviour in a combined energy crop and pig production system. A comparative study including paddocks for lactating sows has been carried out on a commercial organic farm in South West Jutland, Denmark from May 2015 to April 2016. In each of four farrowing batches, 21 ringed sows (Landrace x Yorkshire) were randomly assigned to 21 individual paddocks (10 m x 33 m) with a) grass clover and a zone of poplar trees where the sows had access to the trees, b) clover grass and a zone of poplar where the sows had no access to the trees or c) solely clover grass.

The poplar (*Populus* spp.) trees were established in 2011 with the objective of being harvested for energy or woo-chip production on an intra-row spacing of 3.5 m and an inter-row spacing of 2.5 m (1200 trees.ha^{-1}). The grass clover was established in spring 2013 and pigs gained access to the grass land May 2015. Tree stem diameter will be measured in 2016 also.

Data for reference yield for poplar and grass clover was collected from experts and Yield-SAFE was calibrated to reach the reference yield. The reference yield considered is between 1-2 t ha^{-1} for grass-clover production while around 5 t ha^{-1} is expected every second when barley is also grown to feed the pigs (expert oral communication). Tree stem diameter measured 1 m above ground level was 5.7 cm in average at the beginning of the experimental period (May 2015). The low level of grass production could be explained because of grass being partially destroyed by the pigs browsing. Related to tree yield, around 13 kg tree^{-1} is expected for a 2-year rotation in the experimental site. Related to the second rotation a tree's yield increase of 25% is considered as the reference yield.

DK – Poplar SRC and pigs



The SRC line has a density of 1200 trees ha^{-1} (3.3mx2.5m).

To model the plot scale agroforestry in Yield-SAFE, the agroforestry corresponds to 14.3 % (5/(5+30)) and therefore to a trees density of 172 trees ha^{-1}

Figure 42. Pigs in energy crops experimental design established in Brorup, DK

10.8.3 SRC willow and cattle (UK)

In UK, the Silvopastoral agroforestry trial was installed in Elm Farm near Newbury on a 3.5 ha experimental site. The trees species installed in 2011 were Willow (*Salix viminalis*: mixed varieties); common alder (*Alnus glutinosa*) and a mix of willow and common alder together. Grassland for pastures, including cocksfoot (*Dactylis glomerata*), perennial ryegrass (*Lolium perenne*) and clover (*Trifolium repens, Trifolium pratense*) is considered as the crop element of the system. Livestock introduced from March to October were dairy cows (12x Friesian x Jersey heifers) and beef (2x Friesian x shorthorns). Cattle had access to 4 ha (agroforestry trial plus headlands). Trees design establish in twin rows of trees with 1 m between tress and 0.7 m between rows and alley widths of 24 m (see Figure 43 and 66) and is translated in a 5666 trees.ha^{-1} density.

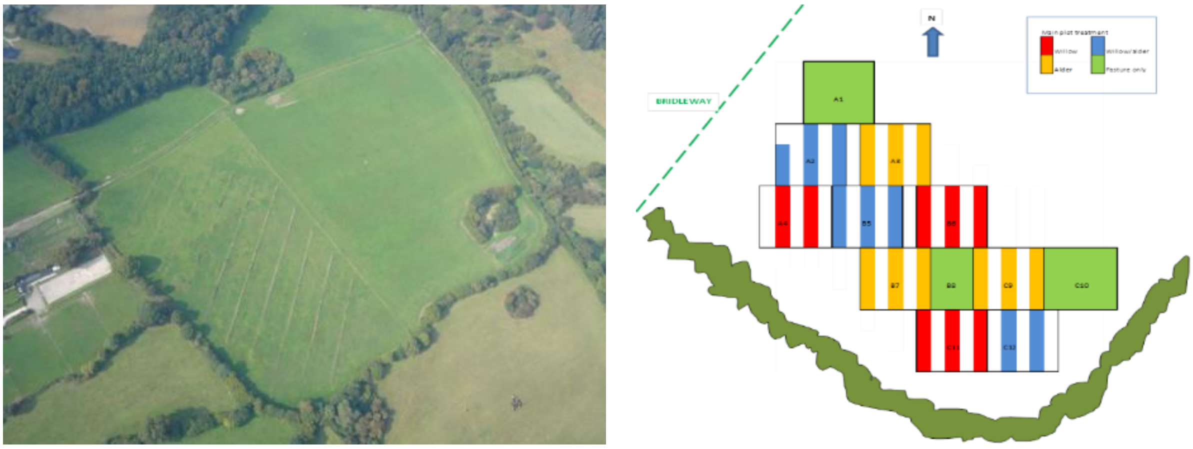
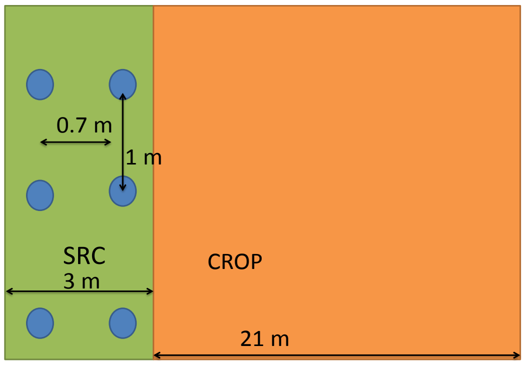


Figure 43. Aerial view (photo by Daria Eric) and Elm Farm Silvopastoral system design, Flatbottom Field, Elm Farm, Hamstead Marshall, UK (not to scale)

UK - Silvopasture



The SRC line occupying 3 meters wide has 166 trees per 300 m^2, corresponding to 5533 trees ha^{-1}. However, the SRC proportion is 23% (3/13) corresponding to a density of 1282 trees ha^{-1}.

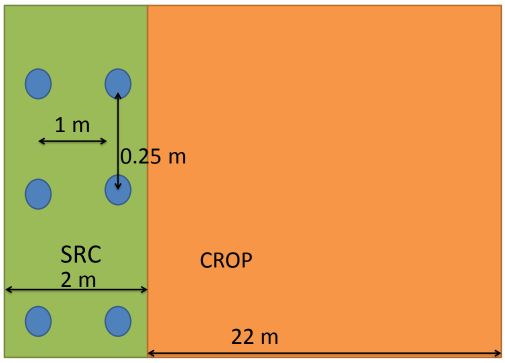
Figure 44. SRC agroforestry trial with willow installed near Newbury, UK

Data for reference yield for willow and grass form the Silvopastoral site in the UK were collected and Yield-SAFE was calibrated to reach the reference yield. Related to the grassland, the average yield of the site was 7 t ha^{-1} $year^{-1}$. For willow in pure SRC yields obtained were between 7 and 9 t ha^{-1} for a two year rotation period.

10.8.4 SRC willow in a silvoarable system (UK)

Also in the UK, several Silvoarable systems were conducted at Wakelyns Agroforestry in Suffolk. Trials of short rotation coppice (SRC) with willow, hazel, mixed top fruit and nut trees, and mixed hardwood trees with 10-12 m-wide crop alleys between tree rows were established in 2014. Crop trial entries included a spring oat variety (Canyon), a spring barley variety (Westminster), a spring triticale variety (Agrano), two spring milling wheat varieties (Paragon and Tybalt), an equal mixture of Paragon and Tybalt and a spring wheat Composite Cross Population (CCP). The layout of trees design was established in twin rows of trees with 1.2 m between tress and 0.7 m between rows and alley widths of 12 m (see Figure 45) providing a 6667 trees ha^{-1} density. Measured crops yields are around 7 t ha^{-1} $year^{-1}$ for spring wheat; 3.5 t ha^{-1} $year^{-1}$ for barley and 6 t ha^{-1} $year^{-1}$ for oats. For willow SRC the observed values were around 7 t ha^{-1} $year^{-1}$ (Smith, personal communication) for a pure SRC rotation.

UK - Silvoarable



The SRC line occupying 3 meters wide has 200 trees per 300 m^2, corresponding to 6667 trees ha^{-1}. However, the SRC proportion is 12.5% (3/24) corresponding to a density of 833 trees ha^{-1}. The crop includes an organic wheat, barley and oats rotation.

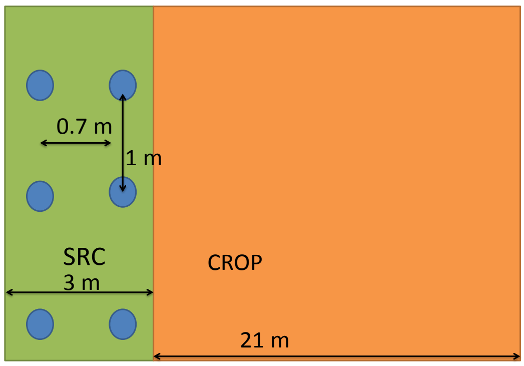
Figure 45. Silvoarable system with SRC willow at Wakelyns Agroforestry, Suffolk, UK

10.8.5 SRC willow and cattle/goats (NL)

Hedgerows and wooded banks used to be common in the Netherlands. Conservation managers from nature organisations maintain the vegetation, or sometimes organic farmers are hired to maintain the landscape. Farmers receive additional grants to maintain the trees or hedgerows as it costs more than the economic benefits for the farmer.

The trial field for fodder trees has a different design than the above mentioned traditional silvopastoral systems of the Netherlands (Figure 46). Instead of pastures with borders of hedgerows or wooded banks, the tree rows were planted within the pasture. To study the potential of short rotation coppice for fodder purposes, fast growing tree species were selected, which were planted in high densities in twin rows. Two short rotation coppice (SRC) species were selected: Willow (two varieties of *Salix viminalis* and Alder (*Alnus glutinosa*) and planted in 2013. The trial spacing established consisted in twin rows separated by 0.7 m of distance and 0.25 between trees and 24m between twin rows. SRC plantation was combined with grassland including perennial ryegrass (*Lolium perenne*) and clover (*Trifolium repens, Trifolium pratense*) and grazing cattle. Observed yields included crop yields for pastures of around 10 t DM/ha/yr.

NL - Silvopasture



The SRC line occupying 2 meters wide has 800 trees per 200 m^2, corresponding to 40000 trees ha^{-1}. However, the SRC proportion is 8.3% (2/24) corresponding to a density of 3200 trees ha^{-1}.

Figure 46. Silvopasture system in the Netherlands

10.8.6 Literature review of tree parameters

The following Tables present the values found for Poplar, Robinia and Willow growth found in literature:

Table 64. Tree parameter values for poplar (*Poplar* spp) obtained from literature review

Parameter	Value	Reference
epst	0.2-1.9	(Broeckx et al. 2015) (Tallis et al. 2013)
gammat	0.34-0.93	(Blake et al. 1984)
Wood density	179400-676100	(Pliura et al. 2007)
Wood density	340800-390300	(Verlinden et al. 2013)
Specific leaf area	10.8-14.4	(Verlinden et al. 2013)
SLA	93-144	(Benomar et al, 2011; Verlinden et al. 2013)
LAI max	1-4.5	(Verlinden et al. 2013)
LAI max	0.21-2.93	(Benomar et al. 2011)
Leaf area per leaf	66-254	(Barigah et al. 1994)
Max leaf area	0.0025	(Rae et al. 2004)
Yield	0.04-23.68	(Rae et al. 2004)

Table 65. Tree parameter values for Black locust (*Robinia Pseudoacacia*) obtained from literature review

Parameter	Value	Reference
epst	PAR: 500-1500 (micromo/m2/s); assimilation: 9-12 (micromolCO2 /m/s) --> 0.634-1.426 g/MJ	(Zheng et al. 2012)
gammat	0.00046-0.00084	(Mantovani et al. 2014a)
gammat	0.00036-0.0004	(Mantovani et al. 2014b)
wooddensity	900000-950000	(Niklas 1997)
wooddensity	650000-750000	(Annighöfer et al. 2012)
sigmaheight	111-132	(Zheng et al. 2012)
treetau	10-15	(Zhou et al. 2015)
Specific leaf area	14.3-20 (LMA: 50-70 g/m2)	(Jin et al. 2011) Jin et al 2007 Chinese Geographical Science
Specific leaf area	1.64-34 (LMA: 29-609 g/m2)	(Zheng and Shangguan 2007)
Specific leaf area	6.8-41 (LMA: 24-147 g/m2)	(Zheng and Shangguan 2007)
Max leaf area	log10leaves=1.689+1.93 9log10*diam; diam range: 1.2-7.6 cm --> log10 leaves:1.843-3.397 --> leaves: 69.66-2494.59 g/tree	(Boring and Swank 1984)
Max leaf area	4 year: 4285 kg/ha; 17 year: 5297 kg/ha; 38 year: 6088 kg/ha	(Boring and Swank 1984)

Table 66. Tree parameter values for Willow obtained from literature review

Parameter	Value	Reference
epst	0.86-1.89	(Borek 2009)
gammat	0.00016-0.00095	(Lindroth and Cienciala 1996; Tallis et al. 2013)
Wood density	350000-480000	(Tharakan et al. 2003; Verlinden et al. 2013)
Ratio branch	0.92	(Matthews 2001)
SLA	123-214	(Merilo et al. 2006)

10.8.7 Measured data for calibration

Table 67 details the measurements made in the silvoarable poplar and black locust plots in Cottbus (Germany).

Table 67. Measurements dated from the 1st of January of the year when tree was planted

			Diameter at 10 cm	DBH	Height	Bt	N	N	96m N	48m N	24m N	Standing Biomass	96m Standing Biomass	48m Standing Biomass	24m Standing Biomass
	Year	DOY	Cm		m	kg/tree	tree/ha	tree/ha	tree/ha	tree/ha	tree/ha	Mg/ha	Mg/ha	Mg/ha	Mg/ha
Planting date		94					8715.0		504.6	953.9	1719.6				
Max 1	1	382	0.9	0.2	1.0	0.1	8497.1	100.0	492.0	930.1	1676.6		28.8	54.5	98.2
Max 1	2	701	2.1	1.2	2.2	0.4	7053.3	83.0	408.4	772.0	1391.7		181.6	343.3	618.8
Max 1	3	1066	4.2	2.7	4.5	1.8	6295.5	74.1	364.5	689.1	1242.2		672.8	1271.9	2292.8
Max 1	4	1504	5.6	3.8	5.9	3.5	6362.7	74.9	368.4	696.4	1255.5		1296.5	2451.0	4418.4
Planting date		95					8715.0		504.6	953.9	1719.6				
Robinie	1	334	1.1	0.7	0.9	0.1	8715.0	100.0	504.6	953.9	1719.6		34.4	65.0	117.2
Robinie	2	747	2.1	1.4	1.8	0.3	6917.5	79.4	400.5	757.2	1364.9		140.1	264.8	477.4
Robinie	3	1066	4.0	2.7	3.3	1.7	7215.3	82.8	417.7	789.8	1423.7		730.8	1381.7	2490.7
Robinie	4	1431	5.0	3.4	4.4	3.3	7113.1	81.6	411.8	778.6	1403.5		1359.8	2570.8	4634.3
Robinie	5	1869	5.6	3.9	4.7	4.8	7009.0	80.4	405.8	767.2	1383.0		1939.2	3666.2	6609.0
Planting date		94										0.0			
Max 1	1	382	0.8	0.6	0.9	0.0	8279.3	100.0				310.2			
Max 1	2	701	2.0	1.5	2.1	0.3	6560.7	79.2				2205.1			
Max 1	3	1066	3.9	3.0	4.6	1.6	5912.8	71.4				9273.3			
Max 1	4	1504	5.2	3.9	6.0	3.0	6047.7	73.0							
Planting date		95										0.0			
Robinie	1	334	1.2	0.5	1.0	0.1	8715.0	100.0				880.6			
Robinie	2	747	2.3	1.4	1.9	0.5	6972.0	80.0				3521.0			
Robinie	3	1066	4.2	2.8	3.6	2.3	7219.3	82.8				16727.8			
Robinie	4	1431	5.1	3.5	4.7	3.8	7117.2	81.7				27286.4			
Robinie	5	1869	5.7	4.0	5.1	5.4	7046.9	80.9				37960.4			

Willow and Poplar were calibrated for first and second rotation following data from the UK SRC trial Network presented in (Tallis et al. 2013). The trials were established with a stocking density of 10000 cuttings ha-[1] and were designed to generate an extensive database on SRC poplar and willow yields for model developments (Aylott et al. 2008; Aylott et al. 2010). Plots were cut back after a single establishment year to initiate a multi-stemmed coppice re-growth and there after harvested on a 3-year cycle, as typical for the United Kingdom (DEFRA 2004). In the below Table the characteristics of the six trial sites used for the calibration are presented.

Table 68. Soil characteristics of the UK SRC trial sites

Trial site	Code	Soil depth (mm)	Soil bulk density (g cm^{-3})	Soil texture
Alice Holt	AH	1000	1210	Medium-Fine
Loyton Bampton	LY	1000	1140	Medium-Fine
Loughall	LU	800	1190	Medium-Fine
Trefeinon	TF	800	1030	Medium-Fine
Thorpe Theewles	TH	500	980	Fine
Trumpington	TU	1100	840	Medium-Fine

10.8.8 Calibration results

Table 69. YIELD-SAFE parameter values for poplar growth in short rotation coppice 1st rotation after calibration

Parameter	Description	Unit	Value	Reference from literature
nShoots0	Initial number of shoots	shoots $tree^{-1}$	1	
Biomass0	Initial biomass per tree	g $tree^{-1}$	40	
LA0	Initial leaf area	m^2	0	
Ap	function describing tree height and diameter relationship		1	
Epst	Radiation use efficiency	g MJ^{-1}	1.05	0.2-0.98
F	Tree form factor		0.367	
Gammat	water needed to produce 1 g of biomass	m^3 g^{-1}	0.0002	0.34-0.93
LAMax	Maximum leaf area of a tree	m^2	400	25000
LAsbMax	Maximum leaf area	m^2	0.025	
SLA	Specific leaf area		168	9.3 – 14.4
Ratiotimber	Proportion of above ground biomass that forms timber		0.15	
WoodDensity		g m^3	365000	179400-676100
pFCritt	Critical pF value for tree growth	(log cm)	4	
PWPt	Permanent wilting point	(log cm)	4.2	
SigmaHeight	Ratio of tree height to tree diameter	(log cm)	120	
dsigma_density	The change in SigmaHeight with density		0	

canopyWidthDepth	Ratio of canopy with to canopy depth		0.53	
TreeTau	number of days after bud-burst at which the leaf area reached 63.2% of its maximum area		10	

Table 70 and Table 71 present the set of parameter values found for poplar and willow growth in short rotation coppice, for 1st and 2nd rotations.

Table 70. YIELD-SAFE parameter values for poplar in short rotation coppice for 1st and 2nd rotation

Parameter	Description	Unit	Value 1st rotation	Value 2nd rotation	Reference from literature
nShoots0	Initial number of shoots	shoots $tree^{-1}$	1	1	
Biomass0	Initial biomass per tree	g $tree^{-1}$	30	30	
LA0	Initial leaf area	m^2	0	0	
ap	function describing tree height and diameter relationship		0.7	0.7	
epst	Radiation use efficiency	g MJ^{-1}	1.89	2	0.86-1.89
F	Tree form factor		1.75	1.75	
gammat	water needed to produce 1 g of biomass	m^3 g^{-1}	0.00045	0.00045	0.00015-0.00095
kmain	Maintenance coefficient		0.0003	0.0003	
LAMax	Maximum leaf area of a tree	m^2	400	400	0.0025
LAsbMax	Maximum leaf area	m^2	0.0025	0.0025	
ratiobranch	Proportion of above ground biomass that forms timber	0-1	0.95	0.95	
WoodDensity		g m^3	350000	350000	179400-676100
pFCritt	Critical pF value for tree growth	(log cm)	4	4	
PWPt	Permanent wilting point	(log cm)	4.2	4.2	
SigmaHeight	Ratio of tree height to tree diameter	(log cm)	120	120	
dsigma_density	The change in SigmaHeight with density		0	0	
canopyWidthDepth	Ratio of canopy with to canopy depth		0.53	0.53	
TreeTau	number of days after bud-burst at which the leaf area reached 63.2% of its maximum		10	10	

	area				
$DOY_{leaffallstart}$	DOY when leaves no longer grow and start to fall	1-365	280	280	
$Leaf_{LeafFallEnd}$	DOY when leaves no longer fall	1-365	310	310	
*f*LeafFall	Proportion of leaf area that will fall (1=deciduous)	0-1	1	1	
	Weight of a single leaf	g	0.5	0.5	
	Area of a single leaf	cm^2	84	84	
SLA	Specific Leaf Area	cm^2/g	228	228	108-144
RSR	Root to Shoot Ratio (IPCC broadleaves=0.25; conifers=0.2)	0-1	0.25	0.25	
f^{FR}	Proportion of fine roots from root biomass	0-1	0.1	0.1	
*f*CCL	Ratio of Carbon Content in Leaves	0-1	0.5	0.5	
$fCCR_t$	Ratio of Carbon Content in tree roots	0-1	0.5	0.5	
Pi_{SR}	Ratio of structural root mass to aboveground biomass	0-1	0.22	0.22	
r	Length of fine roots per unit of structure root	m/g	50000	50000	
K_r	extinction coefficient governing the absorption of water per unit of root length	0-1	0.0007	0.0007	

Table 71. YIELD-SAFE parameter values for willow in short rotation coppice for 1st and 2nd rotation

Parameter	Description	Unit	Value 1st rotation	Value 2nd rotation	Reference from literature
nShoots0	Initial number of shoots	shoots $tree^{-1}$	1	1	
Biomass0	Initial biomass per tree	g $tree^{-1}$	40	40	
LA0	Initial leaf area	m^2	0	0	
ap	function describing tree height and diameter relationship		0.7	0.7	
epst	Radiation use efficiency	g MJ^{-1}	1.7	1.7	0.86-1.89
F	Tree form factor		1.75	1.75	
gammat	water needed to produce 1 g of biomass	m^3 g^{-1}	0.00055	0.00055	0.00015-0.00095

kmain	Maintenance coefficient		0.0003	0.0003	
LAMax	Maximum leaf area of a tree	m^2	400	400	
LAsbMax	Maximum leaf area	m^2	0.025	0.025	
ratiobranch	Proportion of above ground biomass that forms timber		0.92	0.95	0.92
WoodDensity		g m^3	350000	350000	350000-480000
pFCritt	Critical pF value for tree growth	(log cm)	4	4	4
PWPt	Permanent wilting point	(log cm)	4.2	4.2	
SigmaHeight	Ratio of tree height to tree diameter	(log cm)	120	120	
dsigma_density	The change in SigmaHeight with density		0	0	
canopyWidthDepth	Ratio of canopy with to canopy depth		0.53	0.53	
TreeTau	number of days after bud-burst at which the leaf area reached 63.2% of its maximum area		10	10	
$DOY_{leaffallstart}$	DOY when leaves no longer grow and start to fall	1-365	280	280	
$Leaf_{LeafFallEnd}$	DOY when leaves no longer fall	1-365	310	310	
*f*LeafFall	Proportion of leaf area that will fall (1=deciduous)	0-1	1	1	
	Weight of a single leaf	g	0.5	0.5	
	Area of a single leaf	cm^2	84	84	
SLA	Specific Leaf Area	cm^2/g	228	228	123-214
RSR	Root to Shoot Ratio (IPCC broadleaves=0.25; conifers=0.2)	0-1	0.25	0.25	
f^{FR}	Proportion of fine roots from root biomass	0-1	0.1	0.1	
*f*CCL	Ratio of Carbon Content in Leaves	0-1	0.5	0.5	
$fCCR_t$	Ratio of Carbon Content in tree roots	0-1	0.5	0.5	
Pi_{SR}	Ratio of structural root mass to aboveground biomass	0-1	0.22	0.22	
r	Length of fine roots	m/g	50000	50000	

	per unit of structure root				
K_r	extinction coefficient governing the absorption of water per unit of root length	0-1	0.0007	0.0007	

10.8.9 Observed vs predicted

10.8.9.1 Poplar calibration (DE)

Potential yields for SRC were obtained from Pérez-Cruzado et al (2014), that estimated yields of almost 20 Mg ha^{-1} yr^{-1} in irrigated areas in warmer locations in Spain for a 3-year rotation stands with initial densities of between 6666 and 33333 stems ha^{-1}. The measured yields obtained in the site S06 were compared to the yields estimated by YS. The Table below presents the characteristics of the site S06. A density of 33333 stems ha^{-1} was considered for this site and the weather data was obtained using Clipick tool (Palma 2014). For the total stand biomass production the average value of 18.3 Mg ha^{-1} yr^{-1} was considered for the 3 years.

Table 72. Sites characteristics

	Coordinates		Alt	Rain	Temp	SOM	Texture	Yield (Mg ha^{-1} yr^{-1})		
Site	Latitude	Longitude	M asl	mm	°C	%	UK-ADAS/FAO classification	Avg	Min.	Max
S04	42° 10'30.5"N	1° 40'08"W	268	405	14.1	0.9	Sandy- Loam /Medium	18.5	5	32.9
S06 Santa Fé	37° 11'43.1"N	3° 46'03.7"W	554	355	15.3	0.9	Loam /Medium	18.3	6.9	25.2

Once the potential yield is calibrated (Figure 47), by finding the set of parameters that minimize the differences between observed and predicted, the same procedure was done by adjusting solely the parameters related to the water resource usage (gammt and pFCrit). The results obtained comparing estimated values with observed values from field sites are shown in Figure 48.

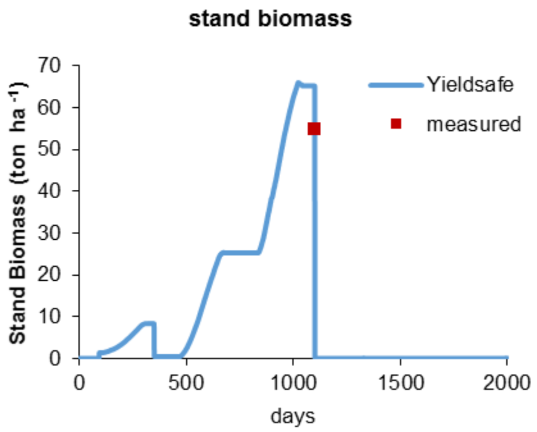


Figure 47. Observed and Yield SAFE daily potential stand biomass (Mg ha^{-1}) estimation

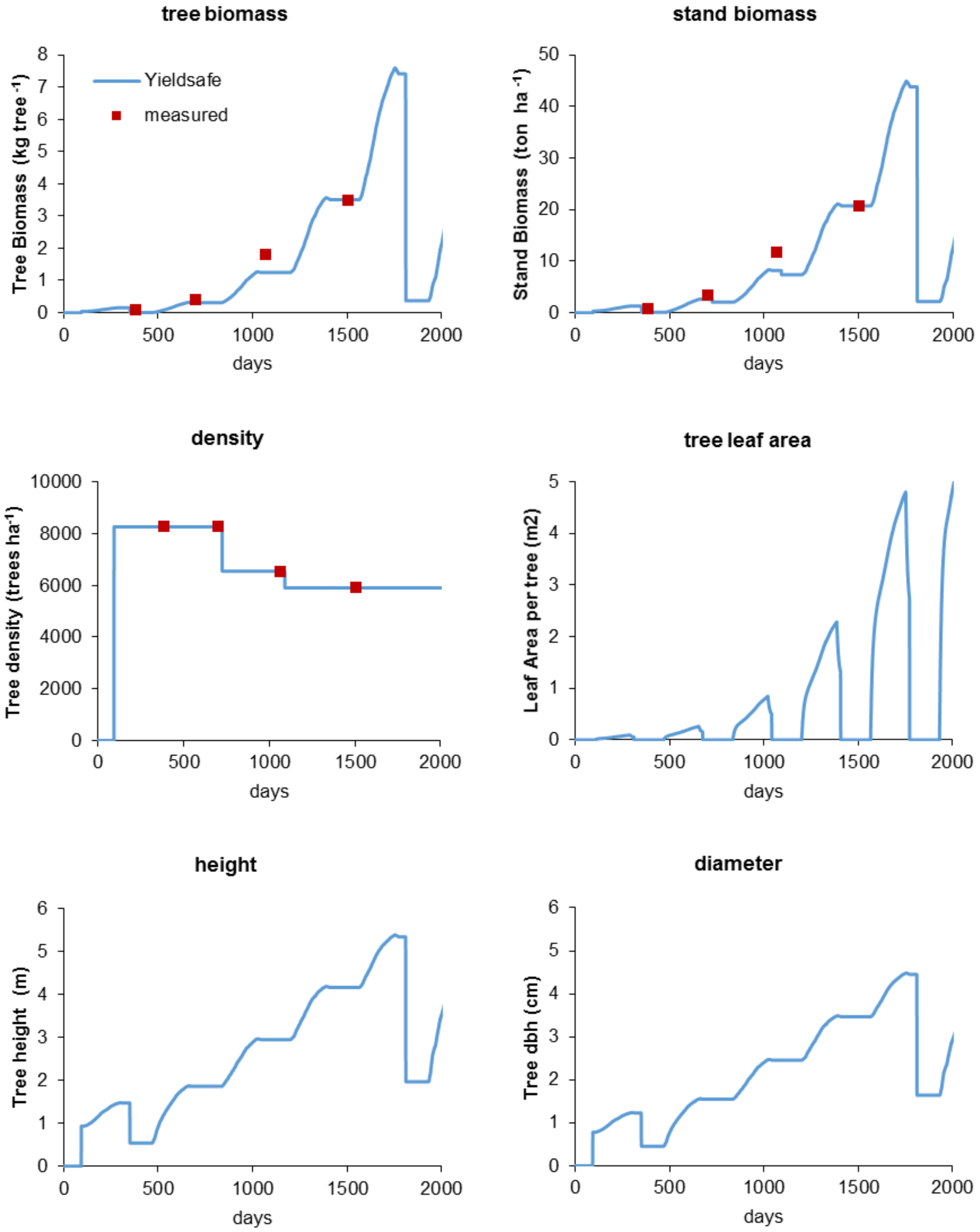


Figure 48. Observed and Yield SAFE estimation for poplar growth in SRC in Cottbus

Related to the 2nd rotation and following rotations, the same parameters values were used as for the first rotation. Even if (Auclair and Bouvarel 1992) suggested that biomass production is greater after coppicing and (Herve and Ceulemans 1996; Abdi 2010) had found better intrinsic growth performance on coppiced trees, (Lamerre et al. 2015) did not find any difference in yearly yields comparing a 6 year rotation cycle to a 2 rotation 3 year rotation cycle.

10.8.9.2 Poplar calibration (UK)

The values obtained from Yield-SAFE are very similar to those derived from the consulted experts. Effectively after poplar calibration of Yield-SAFE using (Tallis et al. 2013) data values obtained in the Danish are around 12.5 kg tree^{-1} for the first 2-year-rotation with an increase in the following rotations with values ranging between 14 and 18 kg tree^{-1} (similar to those expected of 13 kg.tree^{-1} and 16 kg.tree^{-1} for the first and following rotations respectively). The results are shown in Figure 49.

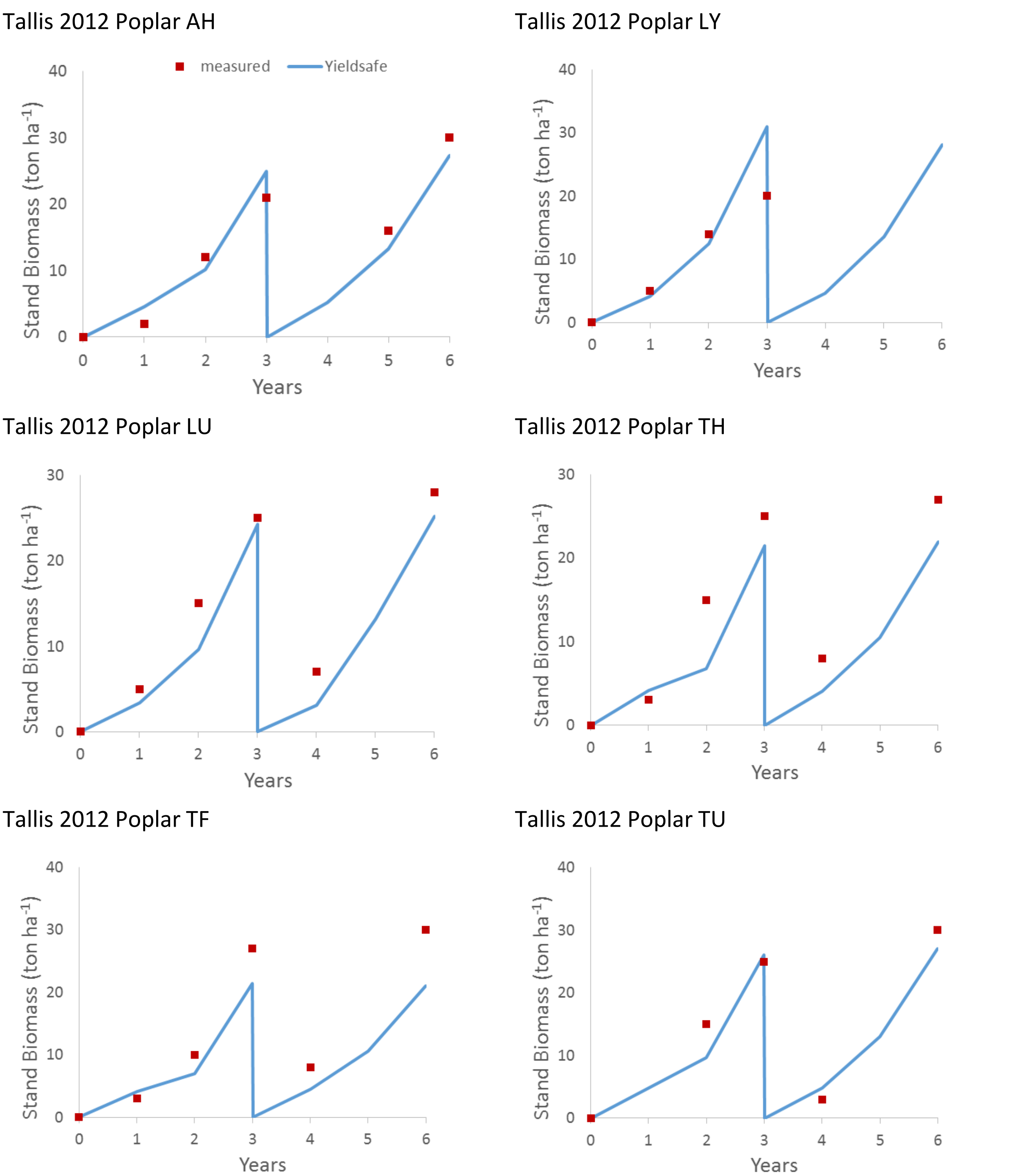


Figure 49. Comparison of Yield-SAFE simulation of Poplar SRC with observations from UK SRC trial sites (see Table for site codes)

10.8.9.3 Willow calibration

Results obtained from the pure willow SRC (with a 5533 trees.ha^{-1} tree density and 100% covered with willow) do not seem to differ vastly and are consistent with the values observed on the trial sites. Pure SRC coppice tree yields varied between 1.1 and 1.5 kg tree^{-1} after a 2-year rotation representing tree yields of between 6 and 8.2 t DM ha^{-1}. The results are shown in Figure 50.

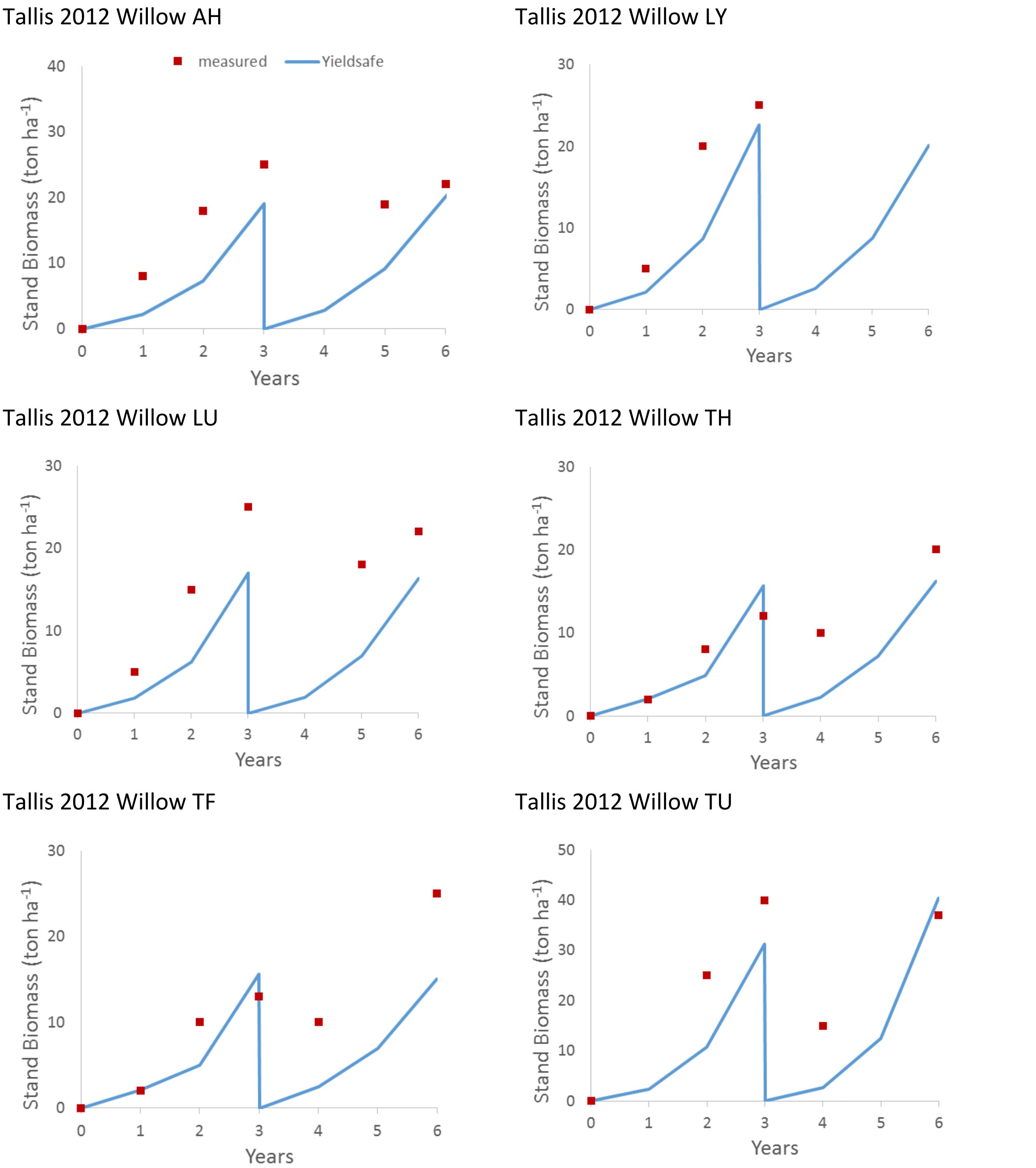


Figure 50. Comparison of Yield-SAFE simulation of Willow SRC with observations from UK SRC trial sites (see Table for site codes)

10.9 Radiata pine and sheep

10.9.1 Brief description of the experiment where data was measured

The parameter calibration of the Yield-SAFE model was performed with tree data from a silvopastoral system established in Castro Riberas de Lea (Lugo, Galicia, NW Spain, European Atlantic Biogeographic Region). The experiment was initiated in 1995 when land ploughing was carried out and the experimental plots were established. The experimental design was a randomised block with twelve treatments and three replicas. We selected two of twelve treatments consisted of the evaluation of *Pinus radiata* D. Don (transplanted in soil from paper pots) that was established at two densities: (a) 2500 trees ha^{-1}, with a planting distance of 2m×2m and an area of 64 m^2 per replicate, and (b) 833 trees ha^{-1}, with a planting distance of 3m×4m and an area of 192 m^2 per replicate. In each experimental unit, 25 trees were planted with an arrangement 5×5 stems. After plantation, the plots were sown with a mixture of *Dactylis glomerata* L. var. Saborto (25 kg ha^{-1}), *Trifolium repens* L. var. Ladino (4 kg ha^{-1}) and *Trifolium pratense* L. var. Marino (1 kg ha^{-1}). Fertiliser was not applied to replicate traditional reforestation practices for agricultural land in this area. A low pruning was performed on *Pinus radiata* D. Don at the end of 2001.

The calibration procedure for the pasture component is described below in section B – Pasture (*Pinus radiata*) - 80% *Dactylis glomerata*

10.9.2 Literature review of tree parameters

Table 73. Tree parameter values for *Pinus radiata* D. Don growth obtained from literature review

Parameter	Value	Reference
Pheight	2.2	(Carson et al. 2014)
LA0	0-8	(Waghorn et al. 2015)
Epst	0.19-0.88	(Álvarez et al. 2013)
F	0.33-0.76	(Kimberley and Beets 2007)
LA max	83-337	(Teskey and Sheriff 1996)
Wood density	400000-450000	(Mead 2013)
Sigmaheight	<70	(Mead 2013)

10.9.2.1 Measured data for calibration

For parameter calibration of the Yield-SAFE model, the height and diameter of the trees measured from 1995 to 2013 were used. Measurements were taken from nine inner trees in each plot. In the case of the trees established at low density (833 trees ha^{-1}), tree biomass was also determined via the implementation of allometric equations based on diameter (Montero et al. 2005) and used for parameter calibration of the model. However, the tree biomass was considered as estimated data and therefore its standard deviation was increased by 70%, when calculating likelihood. It is important to be aware that the equations defined by Montero et al. (2005) were determined for tree densities similar to 833 trees ha^{-1} and for this reason the equations were not used to estimate the tree biomass in the case of the trees established at high density (2500 trees ha^{-1}).

The following thinning regimes for forest and agroforestry plantations were used, with year of thinning (Y) and residual density (RD) left in the stand:

Table 74. Measured data for calibration of radiata pine

	Planting density	Y	RD	Y	RD	Y	RD	Y	RD	Y	RD	Y	RD	Y	RD
Agro-forestry	2500	4	2407	13	2314	14	2221	15	2036	16	1851	17	1758	18	1388
Agro-forestry	833	2	832	3	763	5	428	6	659	14	590	16	555		
Forest (Sánchez et al. 2003)	2000	10	1188	15	859	20	574	25	384	30	267	35	193	40	145

10.9.3 Calibration results

Tree parameter calibration of the Yield-SAFE model was made with a Python version of the model prepared to use an optimization module with the L-BFGS-B algorithm (Byrd et al. 1995).

The Yield-SAFE calibration procedure was done, in a first step, for data of potential growth of trees (Castedo Dorado et al. 2003) and pasture (Yepes V 2011) in Galicia (NW Spain) and assuming that light and temperature, but not water, limited growth within the model.

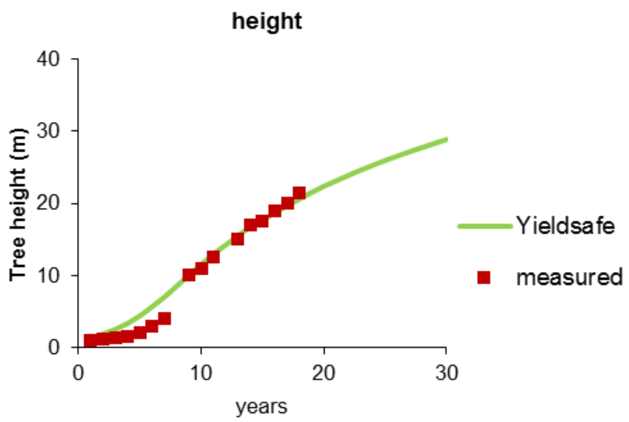
Table 75. Yield-SAFE parameter values found for *Pinus radiata* D. Don growth

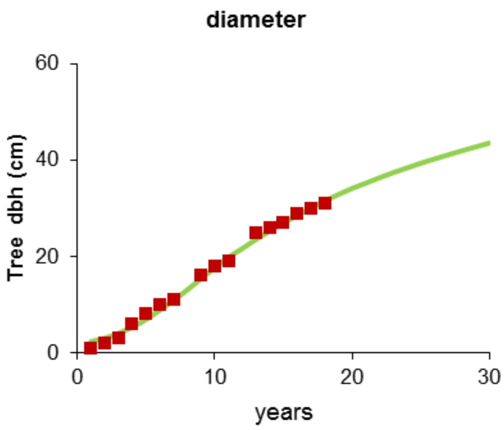
Parameter	Description	Unit	Value	Reference from literature
nShoots0	Initial number of shoots	shoots tree^{-1}	0.67	
Biomass0	Initial biomass per tree	g tree^{-1}	54.33	
LA0	Initial leaf area	m^2	0.25	0-8
ap	function describing tree height and diameter relationship		0.25	
epst	Radiation use efficiency	g MJ^{-1}	1.04	0.19-0.88
F	Tree form factor		0.41	0.33-0.76
gammat	water needed to produce 1 g of biomass	m^3 g^{-1}	0.000001	
kmain	Maintenance coefficient		0.000013719	
LAMax	Maximum leaf area of a tree	m^2	225	83-337
LAsbMax	Maximum leaf area	m^2	0.025	
ratiobranch	Proportion of above ground biomass that forms timber	0-1	0.35	
WoodDensity		g m^3	400000	400000-450000
pFCritt	Critical pF value for tree growth	(log cm)	3.84	
PWPt	Permanent wilting point	(log cm)	4.2	
SigmaHeight	Ratio of tree height	(log cm)	60.15	<70

	to tree diameter			
dsigma_density	The change in SigmaHeight with density		150.02	
canopyWidthDepth	Ratio of canopy with to canopy depth		0.9	
TreeTau	number of days after bud-burst at which the leaf area reached 63.2% of its maximum area		10	
$DOY_{leaffallstart}$	DOY when leaves no longer grow and start to fall	1-365	300	
$Leaf_{LeafFallEnd}$	DOY when leaves no longer fall	1-365	330	
*f*LeafFall	Proportion of leaf area that will fall (1=deciduous)	0-1	0.1	
	Weight of a single leaf	g	0.1	
	Area of a single leaf	cm2	30	
SLA	Specific Leaf Area	cm2/g	300	

10.9.4 Observed vs predicted

Results for *Pinus radiata* growth in Galicia in a situation of low (833 trees ha^{-1}) and high (2500 trees ha^{-1}) density are presented in Figure 51 and Figure 52, respectively, with the measured data used for calibration.





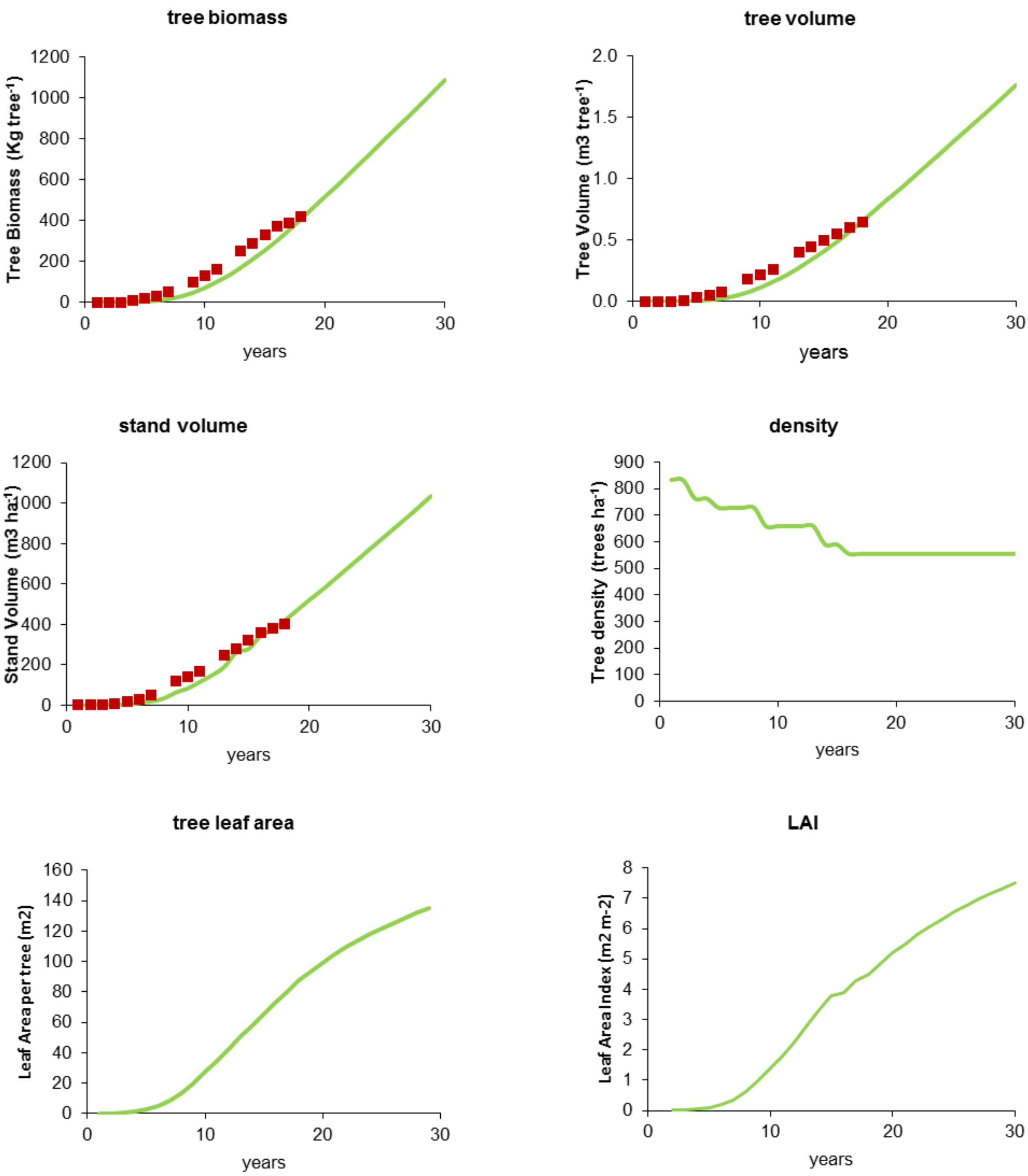


Figure 51:Measured and Yield-SAFE estimation for *Pinus radiata* D. Don established at low density (833 trees ha^{-1}) in Galicia (NW Spain)

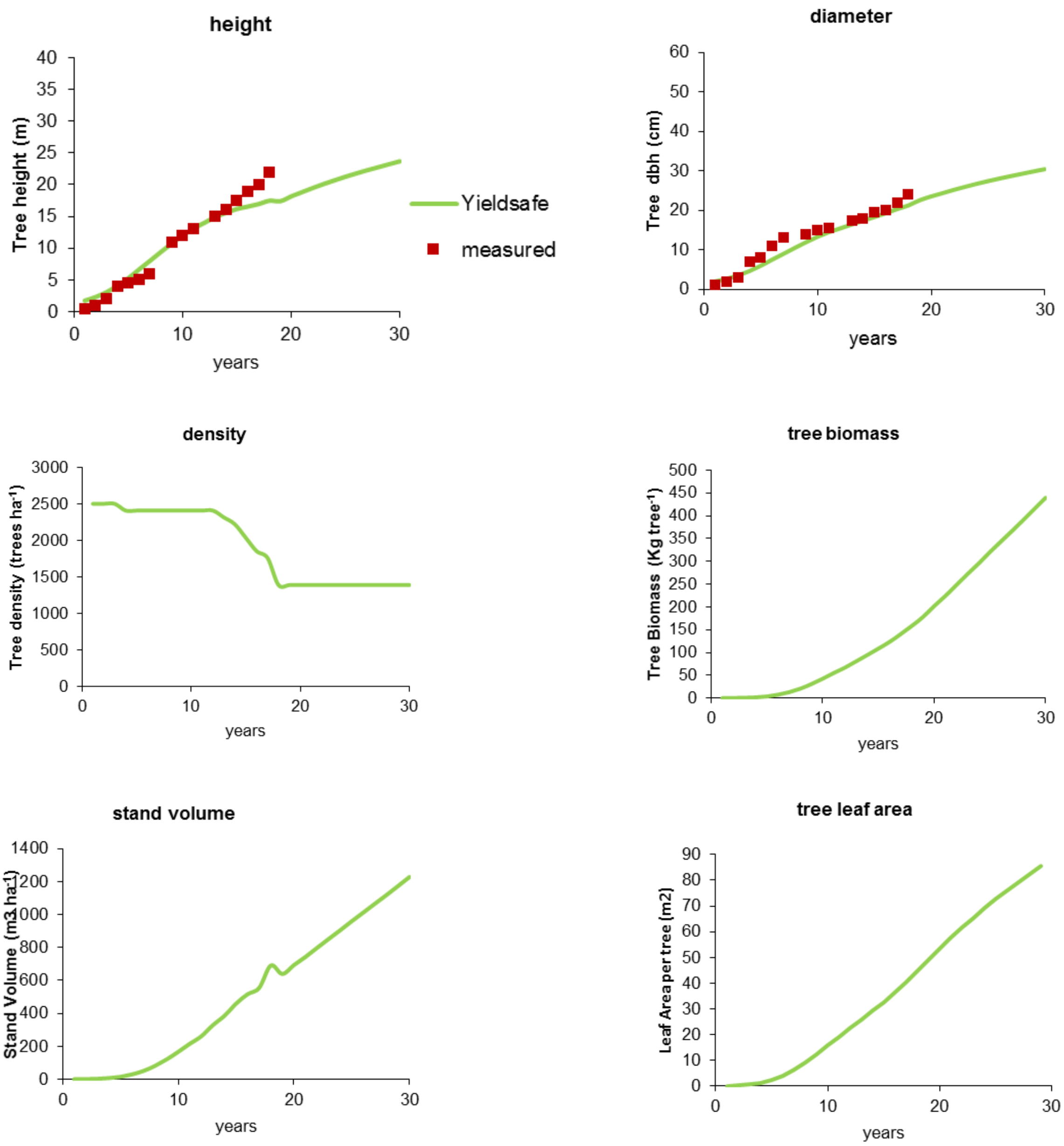


Figure 52. Measured data (points) and Yield-SAFE estimation for *Pinus radiata* D. Don established at high density (2500 trees ha^{-1}) in Galicia (NW Spain).

10.10 Chestnut

Chestnut (*Castanaea sativa* Miller) agroforestry is a traditional land use system in O Courel, Galicia (NW Spain) to produce chestnuts. The chestnuts are recognized under the label of Protected Geographical Indication (PGI), and are mainly exported to selective markets in Europe.

10.10.1 Measured data for calibration

Measured data was used for the tree calibration (Table 76).

Table 76. Measured data for chestnut growth

Year	Tree height (m)	Tree diameter (cm)	Tree biomass (kg tree^{-1})	Stand biomass (ton ha^{-1})	Tree volume (m^3 tree^{-1})	Stand volume (m^3 ha^{-1})
10	13.1	10.1	33.68984	113.4	0.047475	159.8
15	17.5	14.2	67.60369	146.7	0.118341	256.8
20	20.9	17.8	108.9308	173.2	0.213522	339.5
25	23.6	21	155.609	194.2	0.379808	407.4
30	25.7	23.8	205.6585	210.8	0.450927	462.2
35	27.5	26.4	258.5928	224.2	0.584083	506.4
40	29	28.7	312.9161	235	0.721704	542
45	30.3	30.9	368.8351	243.8	0.863389	570.7
50	31.4	32.9	425.4237	251	1.00661	593.9
55	32.4	34.8	482.8947	256.9	1.151504	612.6
60	33.2	36.6	540.9091	261.8	1.297107	627.8

10.10.2 Calibration results

Parameter set found for values for chestnut growth:

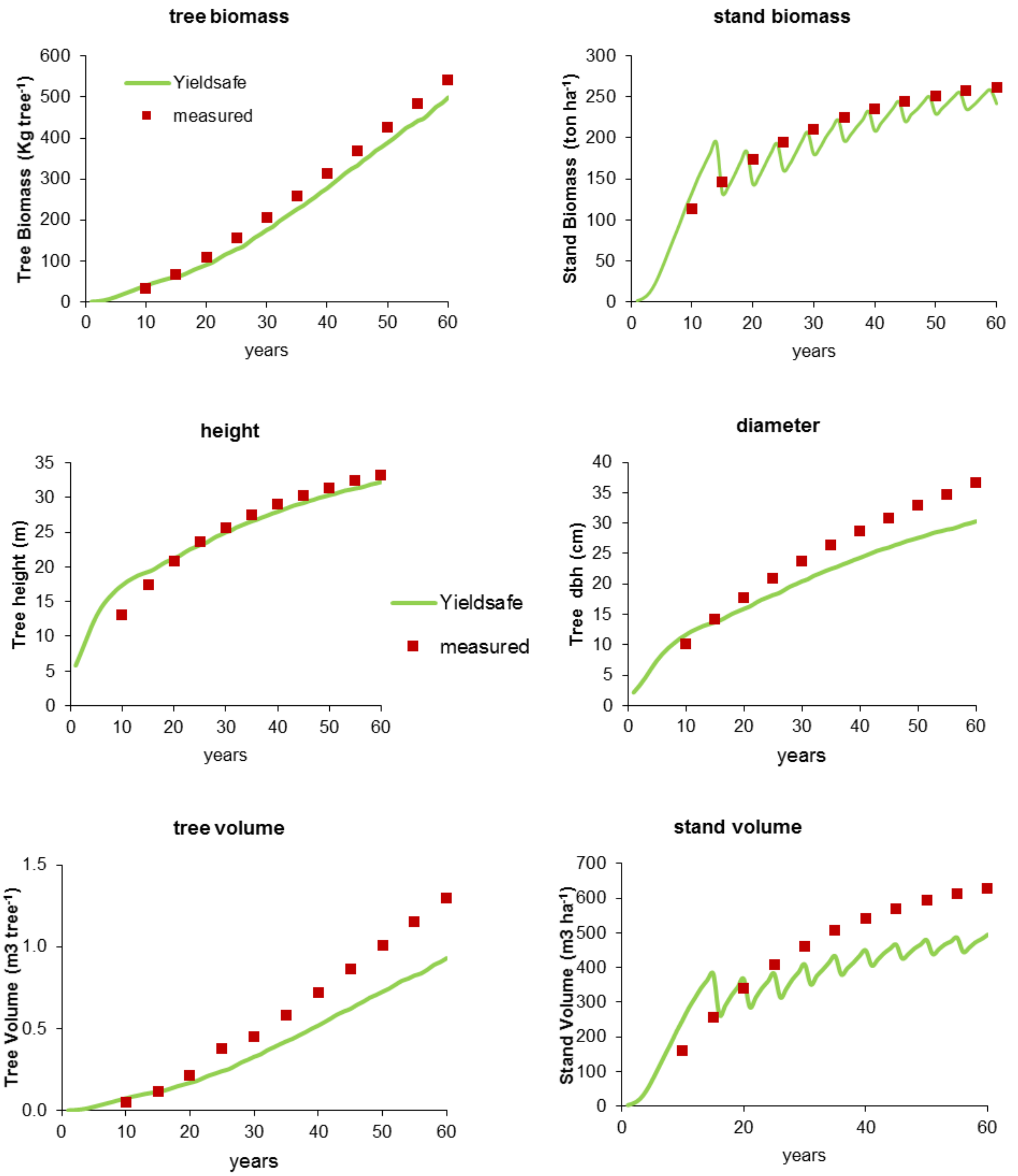
Table 77. YIELD-SAFE parameter values for chestnut growth

Parameter	Description	unit	Value
DOYplanting	DOY = Day Of Year	J. day	2
DOYpruning		J. day	350
Pruning height		m	0
Pbiomass	Proportion of biomass removed per prune		0
Pshoots	Proportion of shoots removed per prune		0.2
	Maximum proportion of bole		0.6
Bheight	Maximum bole height	m	6
DOYthining			330
Site factor			1
nShoots0 =		tree^{-1}	4
Biomass0 =		g tree^{-1}	150
Boleheight0		m	0
LA0 =		m^2 tree^{-1}	0.2
ap		0.0055	0.65
DOYbudburst	Time of bud burst		60
epst	Radiation use efficiency	g MJ^{-1}	0.76
F	form factor		0.4
gammat	water needed to produce 1 g of tree biomass	m3 g^{-1}	0.0004

kt	Extinction coefficient		0.8
Kmain	Fraction of Biomass needed for maintenance respiration		0.0002
LA max	Maximum leaf area	m^2	110
LAsbMax	Maximum leaf area for a single bud	m^2	0.02
NshootsMax	Maximum number of buds on a tree		5500
ratiobranch	ratio of branches to total biomass		0.2
ratiotimber	ratio of timber to total biomass		0.75
Wood density	wood density	$g\ m^{-3}$	400000
pFcritt	Critical pF value for tree	(log cm)	4
PWPt	Permanent Wilting Point for Trees	(log cm)	4.2
Sigmaheight	Ratio of height to diameter		70
dsigma/density	Response of Ht/diameter to density		0.8
Canopywidth/depth	Ratio of maximum width ro canopy depth		1.1
TreeTau	Number of days after BudBurst to reach 63.2% of final leaf area		10
$DOY_{leaffallstart}$	DOY when leaves no longer grow and start to fall	1-365	100
$Leaf_{LeafFallEnd}$	DOY when leaves no longer fall	1-365	140
fLeafFall	Proportion of leaf area that will fall (1=deciduous)	0-1	0.2
	Weight of a single leaf	g	0.15
	Area of a single leaf	cm^2	10
SLA	Specific Leaf Area	cm^2/g	66.66667
RSR	Root to Shoot Ratio (IPCC broadleaves=0.25; conifers=0.2)	0-1	0.25
f^{FR}	Proportion of fine roots from root biomass	0-1	0.1
fCCL	Ratio of Carbon Content in Leaves	0-1	0.5
$fCCR_t$	Ratio of Carbon Content in tree roots	0-1	0.5
Pi_{SR}	Ratio of structural root mass to aboveground biomass	0-1	0.22
r	Length of fine roots per unit of structure root	m/g	50000
K_r	Extinction coefficient governing the absorption of water per unit of root length	0-1	0.0007
	Horizontal pruning	years	80
	Horizontal prune percentage	%	0
	Pruned shoots %	%	0
$Leaf_{UME}$	Utilizable Metabolizable Energy from leaves	MJ/t DM	0
$Branch_{UME}$	Utilizable Metabolizable Energy from branches	MJ/t DM	0
Fru_{UME}	Utilizable Metabolizable Energy from fruit	MJ/t DM	8912
$Fruit_{Name}$	fruit name		chestnut
Fru_p	Fruit productivity g per canopy area	g / m2 LAI	190
$Fruit_{FallingDays}$	Nr of days when 95% of fruit falls	days	60
$Fruit_{DOYPeak}$	DOY when fruit fall peak occurs	DOY	304
$Fruit_{Weight}$	weight of a single fruit	$g\ piece^{-1}$	15
Kta	a parameter for Kt		10
Ktb	b parameter for Kt		0.4

10.10.3 Observed vs predicted

The simulation results for chestnut growth in Asturias are presented in Figure 51, with the measured data used for calibration.



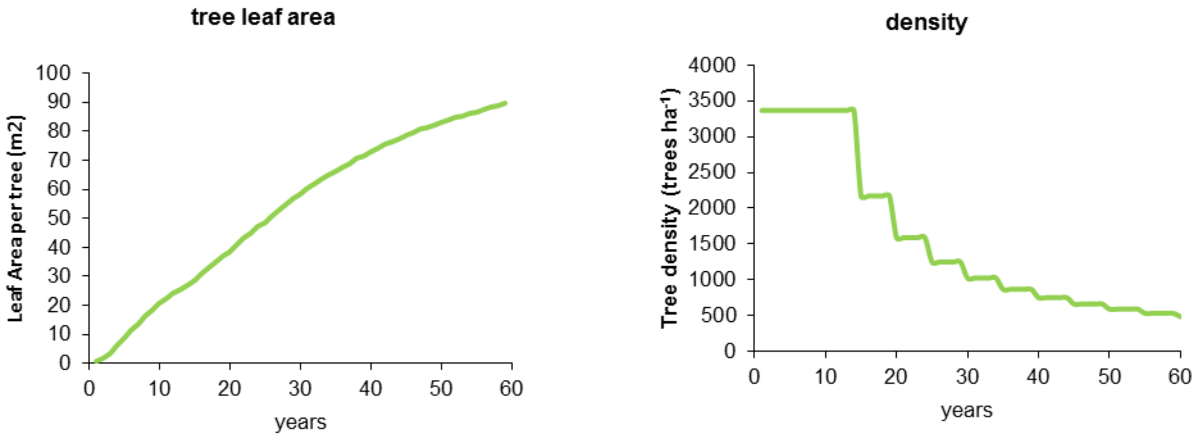


Figure 53. Calibration results of the Yield-SAFE model for *Castanea sativa* established in Galicia (NW Spain).

11. Annex VIII – Crop calibration

The following pages refer to a calibration process which is still ongoing with constant interaction between researchers' interest in modelling with Yield-SAFE. In some cases they might be close to final parameter sets, but others the calibration is in an earlier stage requiring further improvement. Most importantly they store a relatively intensive bibliography review regarding physiological thresholds for needed parameters and as much validation as possible.

The following pages present the follow up of the newest undergoing calibrations for different tree species:

- Natural Mediterranean pasture/grass (Portugal)
- Pasture (80% *Dactylis glomerata*) (Spain)
- Wheat (Spain)
- Barley (Spain)
- Barley – Rothamsted (RothC)
- Grassland (Switzerland)
- Winter rye (Switzerland)
- Sugar beet (Italy)
- Asparagus (Italy)

11.1 Natural Mediterranean pasture/grass (Portugal)

11.1.1 Description of the experiment where data was measured

A natural pasture – grass – was selected and the parameters validated using information from (Potes 2011). This work shows grazed pasture production values from a pasture improvement trial that was conducted from 1998 to 2004 in Herdade da Contenda, located near Barrancos (latitude 38.1 N, longitude 7.2 W). Climate data from 1999 to 2004 was retrieved for that location using the Clipick tool (Palma 2015; Palma 2017) and the results from the model compared with the published values and considering also as reference the average values of grass yield of 1-1.8 t ha^{-1} from the work of (Cubera et al. 2009), also developed in Portugal in an open woodland with Quercus ilex trees.

11.1.2 Literature review of crop parameters

The literature review produced the following set of parameter for grass growth:

Table 78. Literature values for grass growth parameters

Parameter	Value	Reference
epsc	0.23 - 2.05	(Bat-Oyun et al. 2012)
gammac	0.0006 m3/g of C for pastures	(Lozano-Parra et al. 2014)
CropSLA	0.015 m2/g of C for pastures	(Lozano-Parra et al. 2014)

11.1.3 Calibration Results

Table 79. Yield-SAFE parameter set for grass growth in Barrancos, South Portugal

Parameter	Description	unit	Value	Reference from literature
doysowing	DayofSowing	-365 to 365	-110	
doyharvest	Day of harvest if tsum is not reached	1-365	1000000	
t0	Temperaturethreshold for growth	°C	10	
tsumemerge	Temperature sum untilemergence	°C	0	
tsumrb	Temperature sum at which partitioning starts to decline	°C	500	
tsumre	Temperature sum at which partitioning starts to decline	°C	1500	
tsumharvest	Temperature sum untilharvest	°C	1000000	
bc0	Initialbiomass	g	0.4	
la0	Initialleafarea	m2/m2	1	
croppartition2leaves	Partitioning to leaves at emergence	0-1	1.00	
epsc	Potential growth (Light use efficiency)	g/MJ	0.00030	0.23 - 2.05
gammac	water needed to produce 1 gram of crop biomass when VPD=1kPa	m^3/g	0.98000	0.0006
hicrop1	Harvestindex	0-1	*0.02000*	
hicrop2	Harvest index 2(e.g. straw)	0-1	0.7	
kc	RadiationExtinctionCoefficient	0.5-1	2.90	
pfcritc	Critical pF value for crop, above which crop starts to drought induction	log(-h)	4.2	
pwpc	pF for permanent wilting point	log(-h)	0	

thetacrop1	Moisture content of the crop 1 (wet basis)	0-1	0	
thetacrop2	Moisture content of the crop 2 (wet basis)	0-1	0.0015	
cropsla	Specific Leaf Area	m2 g^{-1}	1.00000	0.015
sitefactor	Site factor	0-1.5	1	
RSR_c	root-to-shoot ratio - proportion of belowground to above ground biomass	0-1	0.4	
$fCCR_c$	Ratio of carbon content in crop roots	0-1	0.1	
CCAGstraw	Ratio of carbon content in crop straw	0-1	0.5	
CCAGgrain	Ratio of carbon content in crop grain	0-1	0.5	
StrawResidue	Above ground residue left afer harvest	0-1	0.1	
$Crop_{UME}$	Utilizable Metabolizable Energy	MJ/t DM	12700	
$Straw_{UME}$	Utilizable Metabolizable Energy	MJ/t DM	7000	
Crop2Livestock	Use crop harvest to feed livestock	1=yes 0=no	1	
DE	Digestibility energy (usually 45-55 for low quality forages)	%	50	
Kmainc_m	Maintenance respiration coefficient (fraction of biomass)	g g^{-1}	0.037	
Kmainc_g	Amount of carbon respired to maintain existing biomass	g g^{-1}	0.54	
Pasture/Grass?	Controller for crop manager to pick crop yield	1=yes	1	

11.1.4 Observed vs Predicted

The set of parameters adjusted with the calibration and validation procedures provided results consistent with the measured data and also the existing references. The average daily values of pasture production from 1999 to 2004 in Figure 54 are close to the values referred by (Potes 2011) and are also consistent with the values from (Cubera et al. 2009) regarding pasture production in open-areas in 2001-2002.

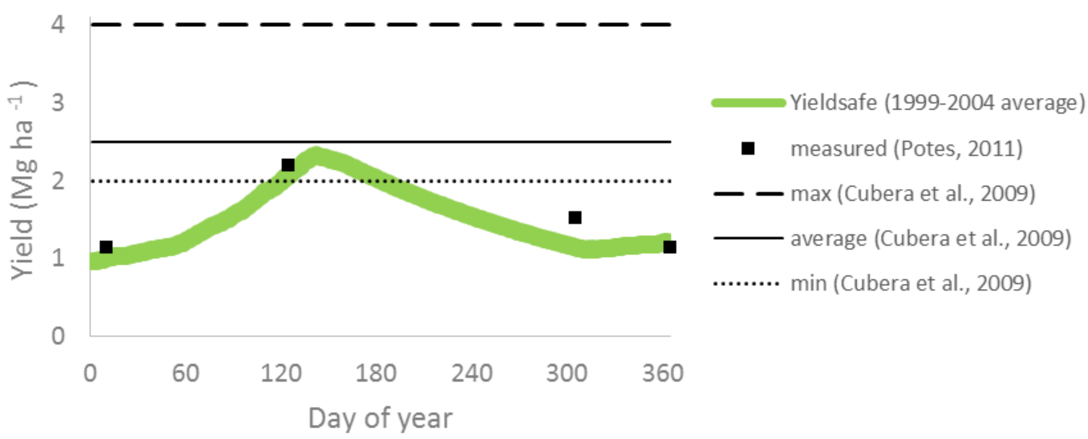


Figure 54. Average daily values of Yield-SAFE estimation of grass yield in Barrancos in Mg ha^{-1} from 1999 to 2004 with measured values from Potes(2011) and minimum, maximum and average values from Cubera et al. (2009)

Figure 55 shows the results of a 20 years simulation of pasture growth in Barrancos, Portugal and the minimum and average reference values from (Cubera et al. 2009).

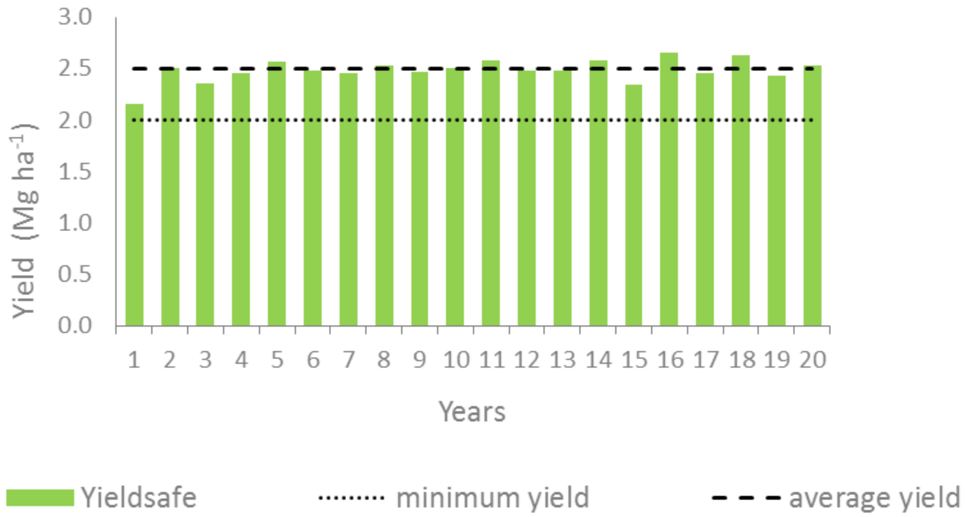


Figure 55. Calibration results of Yield-SAFE model for mediterranean grass with minimum and average yield values from Cubera et al.(2009)

11.2 Pasture (80% *Dactylis glomerata*)

11.2.1 Description of the experiment where data was measured

As described above in Annex VII, Item 10.9 (*Pinus radiata* and sheep), the parameter calibration of the Yield-SAFE model was performed with pasture data from a plot established in Lugo (Galicia, NW Spain, European Atlantic biogeographic region) at an altitude of 452 m above sea level. The experiment was conducted in a soil with a pH in water of 6.5 and a low percentage of organic matter (2.63%). The field experiment was located in the Atlantic biogeographic region where the climate is influenced by Atlantic climatic patterns, with long cool moist winters and warm dry summers. Soil moisture becomes a limiting factor in late summer.

The study was initiated in 1997 when land ploughing was carried out and the experimental plots were established. The experimental design was a randomised block with twenty two treatments and four replicas (8 m^2 per replicate). We selected one of twenty two treatments consisted of sowing with a mixture of *Dactylis glomerata* L. var. Artabro (25 kg ha^{-1}) and *Trifolium repens* L. var. Huia (3 kg ha^{-1}) without fertilisation. This treatment was selected due to the high proportion of *Dactylis glomerata* L. in the botanic composition of the pasture (above 80% in some harvests) because the Yield-SAFE model is not yet prepared to work with a multispecific pasture composition with different light and humidity requirements.

11.2.2 Measured data for calibration

For parameter calibration of Yield-SAFE model, pasture production was determined in each plot from 1999 to 2006. The pasture was harvested using a hand harvester in May, June, July and December, as is traditional for the area, when the pastures reached about 20 cm. Fresh pasture was weighed in situ and a representative subsample was taken to the laboratory. Once in the laboratory, the subsamples (100 g each) were dried (72 hours at 60ºC) and weighed to estimate dry matter production. Annual pasture production was calculated by summing the consecutive harvests of the pasture production in that year.

11.2.3 Literature review of crop parameters

Table 80. Parameter values for pasture (*Dactylis glomerata* L.) growth obtained from literature review

Parameter	Value	Reference
TsumRE	1100	(Al Haj Khaled et al. 2005)
(Bc)0	0-35	(Moreno et al. 2006)
LA	0.8	(Pogacar and Kajfez-Bogataj 2015)
epsc	1-2	(Feldhake and Belesky 2009)
gammac	0.34-0.39 (50% FC) 0.60-0.75 (100% FC)	(Moreno et al. 2006)
HIcrop1	0.7-0.8	(Larcher 2003)
kc	0.8	(Jovanovic and Annandale 1998)
SLA	0.0257-0.027	(Milla et al. 2008)
$Crop_{UME}$	10-12	(Fernández et al. 2008)(Fernández et al. 2008)
DE	63.3	(Rocalba 2016)
Kmainc_m	0.024-0.03	(Peri 2005)
Kmainc_g	0.45	(Press et al. 1998)

11.2.4 Calibration results

The Yield-SAFE calibration procedure was done, in a first step, for data of potential growth of trees (Castedo Dorado et al. 2003) and pasture (Yepes V 2011) in Galicia (NW Spain) and assuming that light and temperature, but not water, limited growth within the model. The resulting values of the parameters are in the following Table.

Table 81. YIELD-SAFE parameter values for pastures (*Dactylis glomerata* L.) after calibration

ColumnName	Unit	Description	Value
doysowing	-365 to 365	DayofSowing	Not used
doyharvest	1-365	Day of harvest if tsum is not reached	100000
t0	^oC	Temperaturethreshold for growth	5
tsumemerge	^oC	Temperature sum untilemergence	0
tsumrb	^oC	Temperature sum at which partitioning starts to decline	300
tsumre	^oC	Temperature sum at which partitioning starts to decline	400
tsumharvest	^oC	Temperature sum untilharvest	1000000
bc0	g	Initialbiomass	20
la0	m2/m2	Initialleafarea	0.8
croppartition2leaves	0-1	Partitioning to leaves at emergence	0.8
epsc	g/MJ	Potential growth (Light use efficiency)	1.5
gammac	m3/g	water needed to produce 1 gram of crop biomass when VPD=1Kpa	0.00075
hicrop1	0-1	Harvestindex	0.9
hicrop2	0-1	Harvest index 2(e.g. straw)	0.1
kc	0.5-1	RadiationExtinctionCoefficient	0.8
pfcritc	log(-h)	Critical pF value for crop, above which crop starts to drought induction	3.0
pwpc	log(-h)	pF for permanent wilting point	4.2
thetacrop1	0-1	Moisture content of the crop 1 (wet basis)	0
thetacrop2	0-1	Moisture content of the crop 2 (wet basis)	0
cropsla	m2 g^{-1}	Specific Leaf Area	0.02
sitefactor	0-1.5	Site factor	1

11.2.5 Observed vs predicted

Figure 56 shows that in the most harvests the Yield-SAFE calibration procedure was successfully performed for pasture production (*Dactylis glomerata* L.) and it allows us to predict pasture response to different situations. However, in some harvests, the model did not estimate adequately the pasture yields probably due to the increase of the proportion of other spontaneous species in these harvests with different light and humidity requirements than *Dactylis glomerata* L. Therefore, the adaptation of model structure for multiple arable component species is needed to improve estimations.

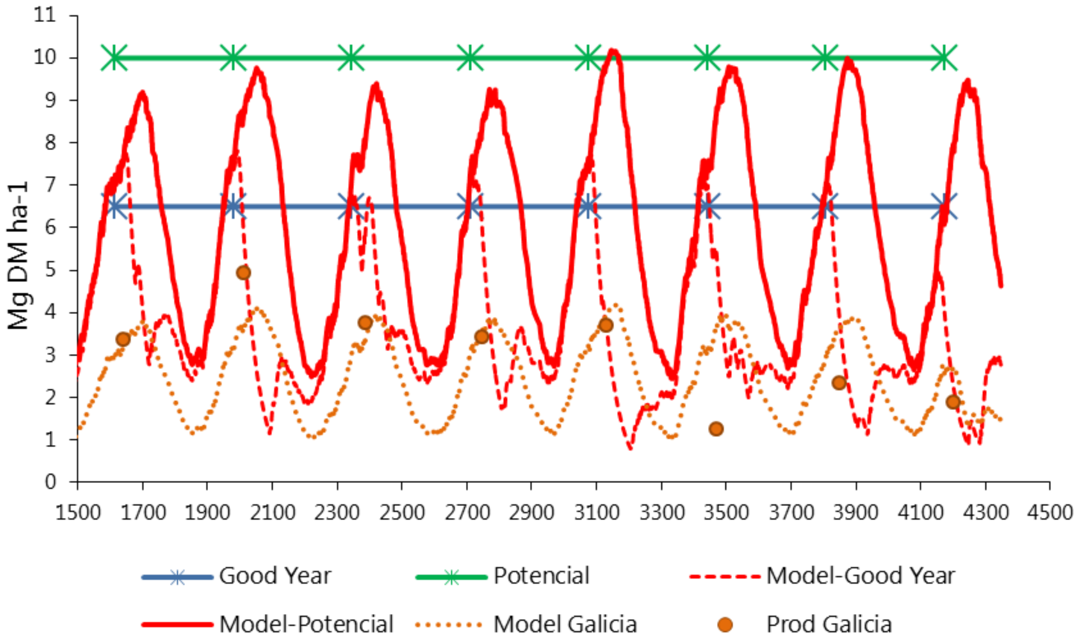


Figure 56. Calibration results of Yield-SAFE model for pasture production (*Dactylis glomerata* L.) for reference potential yield (filled red line) and water limited (dotted red line) where a site factor of 0.5 allowed to adjust the yield a non fertilized pasture with observed data (orange dotted line)

11.3 Wheat- Toledo

11.3.1 Description of the experiment where data was measured

The study was carried out in an experimental silvoarable plantation that combine hybrid walnut (hybrid Mj209xRa Juglans major that comes of the pollination from J. major with pollen of J. regia planted in 2007 for quality timber with annual crops (winter cereals: wheat, barley and triticale). The experiment includes the respective control plots of cereal without trees, and of walnuts without intercrops. The experiment is located at El Carpio de Tajo (Toledo, Spain; coordinates: ETRS 89 UTM 30 N = 374444 W; 4411877 N), at 411 m of altitude, mean annual temperature of 15,3 °C and 437.6 mm of mean annual precipitation (data from 1961-2002 from the 3303E weather station at Carpio de Tajo, accessed from website

http://sig.magrama.es/93/ClienteWS/siga/Default.aspx?nombre=CH_ESTACIONES&claves=DGA.CH_ESTACIONES.CLAVE&valores=3303E).

The soil is a Fluvisol, > 140 cm depth, pH ~ 6. The management is intensive with irrigation and fertilization. The plot has a total area of 68.4 ha, of which 0.5 ha were under study

Three replicated plots of 20x4 m were selected as pure plantation control. There were 5 replicated plots of 20 x 4 m with the silvoarable combination. In 2013-2014 growing season 2 varieties of wheat (Kilopondio and Bologna) and 2 of barley (Azara y Doña Pepa) were tested. In 2014-2015 the cultivars were Ingenio, Sublim and Nogal for wheat and Basic, Lukhas, Hispanic and Dulcinea for barley. This second year, a local variety of triticale (Verato) was also tested. The agriculture control plots consisted of 4 replicate plots of a size of 2 x 2 m for each cultivar. The study started in autumn 2013 where all plots were fertilized with 600 kg ha^{-1} of NPK 8:12:12. In spring 2014, 120 kg urea (46%) ha^{-1} was applied. The same doses were applied in 2014 and 2015.

11.3.2 Measured data for calibration

Crop yield was measured through 3-4 herbage samples (50 cm x 50 cm) per plot, which were taken using hand clippers at a height of 2.5 cm in June 2014 and 2015. The following Table describes the measurements made.

Table 82. Brief description of measured data for wheat

	Wheat biomass production (t/ha)		Wheat grain production (t/ha)	
Year 2014	Wheat in arable system	8.15	Wheat in arable system	1.16
	Wheat in silvoarable system	8.26	Wheat in silvoarable system	1.39
Year 2015	Wheat in arable system	6.67	Wheat in arable system	1.16
	Wheat in silvoarable system	7.19	Wheat in silvoarable system	1.39

11.3.3 Literature review of crop parameters

The parameter values for Wheat growth obtained from literature review are detailed in the Table below.

Table 83. Crop parameter values for Wheat obtained from literature review

Parameter	Value	Reference from literature
name	Wheat	
doysowing	- 45	(Taken from own data)
doyharvest	165	(Taken from own data)
t0	5	(Bonciarelli 1987)
tsumemerge	150	(Bonciarelli 1987)
tsumrb	1300	(Bonciarelli 1987)
tsumharvest	2400	(Bonciarelli 1987)
bc0	0.2773 g / plant 45 days after germination	(Hentz et al. 2012)
epsc	1.46 – 2.93 1.79 – 2.33 (BARLEY)	(Muurinen and Peltonen-Sainio 2006)
hicrop1	0.347	(Asif et al. 2012)
kc	0.65	(Lunagaria and Shekh 2006)
cropsla	272	(Rebetzke et al. 2004)

11.3.4 Calibration results

The resulting values of the parameters that resulted from the calibration procedure are in the following Table.

Table 84. Set of parameter values found for wheat growth

Parameter	Description	unit	Value	Reference from literature
doysowing	DayofSowing	-365 to 365	-45	- 45
doyharvest	Day of harvest if tsum is not reached	1-365	165	165
t0	Temperaturethreshold for growth	°C	5	5
tsumemerge	Temperature sum untilemergence	°C	150	150
tsumrb	Temperature sum at which partitioning starts to decline	°C	1300	1300
tsumre	Temperature sum at which partitioning starts to decline	°C	1500	
tsumharvest	Temperature sum untilharvest	°C	2400	2400
bc0	Initialbiomass	g	10	0.2773
la0	Initialleafarea	m2/m2	0.1	
croppartition2 leaves	Partitioning to leaves at emergence	0-1	0.8	
epsc	Potential growth (Light use efficiency)	g/MJ	1.34	1.46 – 2.93
gammac	water needed to produce 1 gram of crop biomass when VPD=1Kpa	m3/g	0.0005	
hicrop1	Harvestindex	0-1	0.5	0.347
hicrop2	Harvest index 2(e.g. straw)	0-1	0.4	
kc	RadiationExtinctionCoefficient	0.5-1	0.7	0.65

pfcritc	Critical pF value for crop, above which crop starts to drought induction	log(-h)	3.2	
pwpc	pF for permanent wilting point	log(-h)	4.2	
thetacrop1	Moisture content of the crop 1 (wet basis)	0-1	0	
thetacrop2	Moisture content of the crop 2 (wet basis)	0-1	0	
cropsla	Specific Leaf Area	$m2\ g^{-1}$	0.005	272
sitefactor	Site factor	0-1.5	1	

11.3.5 Observed vs predicted

Figure 57 shows the simulation result for crop yield on a 20 year cycle of wheat production in Toledo.

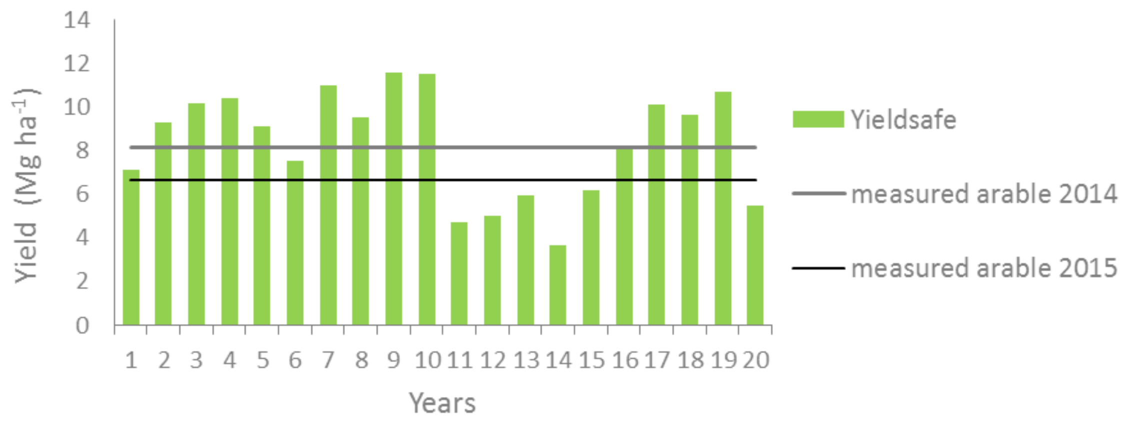


Figure 57. Calibration result of Yield-SAFE model for wheat production in Toledo (Spain)

11.4 Barley- Toledo

11.4.1 Description of the experiment where data was measured

The study was carried out in an experimental silvoarable plantation that combine hybrid walnut (hybrid Mj209xRa Juglans major that comes of the pollination from J. major with pollen of J. regia planted in 2007 for quality timber with annual crops (winter cereals: wheat, barley and triticale). The experiment includes the respective control plots of cereal without trees, and of walnuts without intercrops. The experiment is located at El Carpio de Tajo (Toledo, Spain; coordinates: ETRS 89 UTM 30 N = 374444 W; 4411877 N), at 411 m of altitude, mean annual temperature of 15,3 °C and 437.6 mm of mean annual precipitation (data from 1961-2002 from the 3303E weather station at Carpio de Tajo, accessed from website http://sig.magrama.es/93/ClienteWS/siga/Default.aspx?nombre=CH_ESTACIONES&claves=DGA.CH_ESTACIONES.CLAVE&valores=3303E).

The soil is a Fluvisol, > 140 cm depth, pH ~ 6. The management is intensive with irrigation and fertilization. The plot has a total area of 68.4 ha, of which 0.5 ha were under study.

Three replicated plots of 20x4 m were selected as pure plantation control. There were 5 replicated plots of 20 x 4 m with the silvoarable combination. In 2013-2014 growing season 2 varieties of wheat (Kilopondio and Bologna) and 2 of barley (Azara y Doña Pepa) were tested. In 2014-2015 the cultivars were Ingenio, Sublim and Nogal for wheat and Basic, Lukhas, Hispanic and Dulcinea for barley. This second year, a local variety of triticale (Verato) was also tested. The agriculture control plots consisted of 4 replicate plots of a size of 2 x 2 m for each cultivar. The study started in autumn 2013 where all plots were fertilized with 600 kg ha^{-1} of NPK 8:12:12. In spring 2014, 120 kg urea (46%) ha^{-1} was applied. The same doses were applied in 2014 and 2015.

11.4.2 Measured data for calibration

Crop yield was measured through 3-4 herbage samples (50x50 cm) per plot, which were taken using hand clippers at a height of 2.5 cm in June 2014 and 2015. The description of the measured data is presented in the Table below.

Table 85. Brief description of measured data for barley

	Barley biomass production (t/ha)		Barley grain production (t/ha)	
Year 2014	Barley in arable system	6.32	Barley in arable system	1.06
	Barley in silvoarable system	7.82	Barley in silvoarable system	1.85
Year 2015	Barley in arable system	5.69	Barley in arable system	3.00
	Barley in silvoarable system	6.72	Barley in silvoarable system	3.47

11.4.3 Literature review of crop parameters

Table 86. Crop parameter values for Barley obtained from literature review

Parameter	Value	Reference from literature
name	Barley	
doysowing	-45	(Taken from own data)
doyharvest	165	(Taken from own data)
t0	5	(Bonciarelli 1987)
tsumemerge	109-145	(Miller et al. 2001)
tsumrb	1434-1556	(Miller et al. 2001)

tsumharvest	1538-1665	(Miller et al. 2001)
bc0	45 g/m2	(Mollah and Paul 2008)
la0	0.61	(Mollah and Paul 2008)
epsc	1.79 – 2.33	(Muurinen and Peltonen-Sainio 2006)
gammac	0.00034	(Saied and Ashraf 2014)
hicrop1	0.55	(Peltonen-Sainio et al. 2008)
kc	0.43	(Kemanian et al. 2004)
Cropsla	0.03	(Gunn et al. 1999)

11.4.4 Calibration results

Table 87. Yield-SAFE parameters for Barley growth after calibration

Parameter	Description	Unit	Value	Reference from literature
DOYsowing	Day of sowing	1-365	80	-45
DOYharvest	Day of harvest (if threshold not reached)	1-365	210	165
To	Temperature threshold	°C	5	5
Tsumemerge	Temperature sum to emergence	°Cd	50	109-145
TsumRB	Tsum at which partitioning starts to decline	°Cd	456	1434-1556
TsumRE	Tsum at which partitioning to leaves = 0	°Cd	464	
Tsumharvest	Temperature sum to harvest	°Cd	2000	1538-1665
BiomassCrop0	Initial Biomass	g	10	45
Initial leaf area	Initial leaf area	m2 m-2	0.1	0.61
CropPartition 2leav	Partition to the leaves at emergence	0-1	0.8	
epsc	Potential growth	g MJ^{-1}	1.34	1.79 – 2.33
gammac	water needed to produce 1 gram of crop biomass when VPD=1Kpa	m3 g^{-1}	0.00025	0.00034
HIcrop1	Harvest index	g g^{-1}	0.5	0.55
HIcrop2	Harvest index	g g^{-1}	*0.4*	
kc	Radiation Extinction Coefficient		0.7	0.43
pFcritc	Critical pF value for crop	log(cm)	3.20	
PWPc	Permanent Wilting Point for Crop	log(cm)	4.2	
Thetacrop1	Moisture content of the crop (wet basis)		0	
Thetacrop2	Moisture content of the crop (wet basis)		0	
CropSLA	Specific Leaf Area	$m^2 g^{-1}$	0.005	0.03
RSR_c	root-to-shoot ratio - proportion of belowground to above ground biomass	0-1	0.4	
$fCCR_c$	Ratio of carbon content in crop roots	0-1	0.1	
CCAGstraw	Ratio of carbon content in crop straw	0-1	0.5	
CCAGgrain	Ratio of carbon content in crop grain	0-1	0.5	

StrawResidue	Above ground residue after harvest	0-1	0.1	
$Crop_{UME}$	Utilizable Metabolizable Energy	MJ/t DM	12000	
$Straw_{UME}$	Utilizable Metabolizable Energy	MJ/t DM	7000	
Crop2Livestock	Use crop harvest to feed livestock	1=yes 0=no	0	
DE	Digestibilty energy (usually 45-55 for low quality forages)	%	50	
Kmainc_m	Maintenance respiration coefficient (fraction of biomass)	$g\ g^{-1}$	0	
Kmainc_g	Amount of carbon respired to maintain existing biomass	$g\ g^{-1}$	0	

11.4.5 Observed vs Predicted

Figure 58 shows the simulation result of crop yield for a 20 year cycle of Barley production in Toledo.

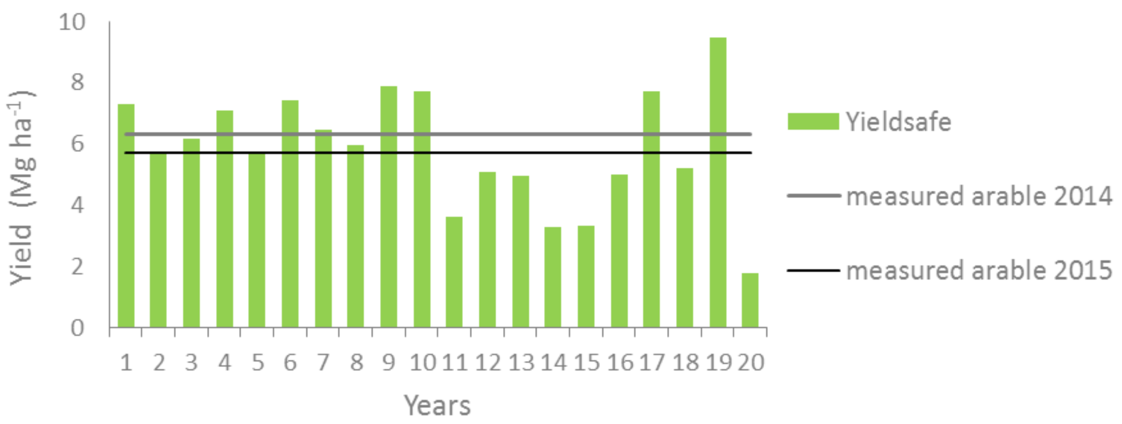


Figure 58. Yield-SAFE yield estimation for Barley production in Toledo (Spain)

11.5 Barley – Rothamsted (RothC)

Table 88. Crop parameters used to simulate barley growth in Rothamsted (UK)

Parameter	Description	Unit	Value
DOYsowing	Day of sowing		80
DOYharvest	Day of harvest (if threshold not reached)	DOY	210
To	Temperature threshold	°Cd	5
Tsumemerge	Temperature sum to emergence	°Cd	50
TsumRB	Tsum at which partitioning starts to decline	°Cd	456
TsumRE	Tsum at which partitioning to leaves = 0	°Cd	464
Tsumharvest	Temperature sum to harvest	°Cd	2000
Initial conditions			
BiomassCrop0	Initial Biomass	g	10
Initial leaf area	3,24	m^2 m^{-2}	0,1
CropPartition2leav	Partition to the leaves at emergence		0,8
Parameters			
epsc	Potential growth	g MJ^{-1}	3
gammac	water needed to produce 1 gram of crop biomass when VPD=1Kpa	m3 g^{-1}	0,00020
HIcrop1	Harvest index	g g^{-1}	0,50000
HIcrop2	Harvest index	g g^{-1}	*0,40000*
kc	Radiation Extinction Coefficient		0,7
pFcritc	Critical pF value for crop	log(cm)	3,20
PWPc	Permanent Wilting Point for Crop	log(cm)	4,2
Thetacrop1	Moisture content of the crop (wet basis)		0
Thetacrop2	Moisture content of the crop (wet basis)		0
CropSLA	Specific Leaf Area	m^2 g^{-1}	0,008
Site factor			1,00000
RSR	root-to-shoot ratio - proportion of belowground to above ground biomass	0-1	0,4
CCRc	Ratio of carbon content in crop roots	0-1	0,130
CCAGstraw	Ratio of carbon content in crop straw	0-1	0,5
CCAGgrain	Ratio of carbon content in crop grain	0-1	0,5
StrawResidue	Above ground residue left after harvest	0-1	0,100

11.6 Grassland (Spruce) in Switzerland

11.6.1 Description of the experiment where data was measured

As already described above in section D - Spruce and Grassland in Switzerland, the daily climate data was retrieved from the tool Clipick, an online tool developed under AGFORWARD project to ease the access to climate data for modelling (Palma 2015). The information was collected for the municipality Muriaux, Switzerland (Lat: 47.2299 Lon: 6.9943) for the years 1960-1990 and was duplicated for modelling 1990 to 2020.

The area is located at approximately 1000 m elevation on Karst Mountains (Barbezat et al. 2008) . The barren landscape with calcareous rocky elements and crevices is not yet suitable for arable cropping. The trees typically grows on the ridges and the pasture is located on the deeper stands with deep marly colluvial soils (Chételat et al. 2013). The soil is classified by the FAO standard as very fine.

11.6.2 Measured data for calibration

Table 89. Measurements for the grassland in Switzerland calibration

	Agroscope	Monitoring program Swiss (2015)
Extensive grassland	2 - 4 t DM / ha	
Wytweiden		1 - 2 t DM /ha
Wytweiden		6 -10 t /ha

11.6.3 Literature review of crop parameters

The performance of grassland was calibrated by data from Kiniry et al. (1999), Hendrickson et al. (2013) and Garnier et al. (1997). Regional Swiss data comes from Sereke et al. (2015). The parameter values for Grass obtained from literature review are in the following table.

Table 90. Values for Yield-SAFE calibration for grassland in Switzerland derived from literature

Parameter	Value	Reference
Name	Grass	
Epsc	1.1 – 4.4	(Kiniry et al. 1999)
Gammac	1 – 4 g biomass/ mm water → (1 mm of rain = 1 litre, and 1000 mm = 1000 L or 1 m^3) 1g/0.001m^3 = 0.001	(Hendrickson et al. 2013)
Kc	0.4	(Kiniry et al. 1999)
cropsla	15 – 29 m^2/kg => 0.0015	(Garnier et al. 1997)

11.6.4 Calibration results

The set of parameters values that resulted from the calibration procedure of Grass growth can be found in Table 91.

Table 91. Yield-SAFE parameter values used for grass after calibration

Parameter	Description	Unit	Value	Reference from literature
Name	The name of the crop	unitless	Grass	
Doysowing	Day of Sowing	-365 to 365	Permament (1)	
Doyharvest	Day of harvest if tsum is not reached	1-365	Permanent (365)	
t0	Temperature threshold for growth	°C	5	
tsumemerge	Temperature sum until emergence	°C	0 (default)	
Tsumrb	Temperature sum at which partitioning starts to decline	°C	1000 (default)	
Tsumre	Temperature sum at which partitioning starts to decline	°C	1100 (default)	
tsumharvest	Temperature sum until harvest	°C	1000000 (default)	
bc0	Initial biomass	g	10 (default)	
la0	Initial leaf area	m2/m2	0.18	
Croppartition 2leaves	Partitioning to leaves at emergence	0-1	0.8	
Epsc	Potential growth (Light use efficiency)	g/MJ	1.1	1.1 – 4.4
Gammac	water needed to produce 1 gram of crop biomass when VPD=1Kpa	m3/g	0.001	0.001
hicrop1	Harvest index	0-1	0.9	
hicrop2	Harvest index 2(e.g. straw)	0-1	0	
Kc	Radiation Extinction Coefficient	0.5-1	0.4	0.4
pfcritc	Critical pF value for crop, above which crop starts to drought induction	log(-h)	3.2	
pwpc	pF for permanent wilting point	log(-h)	4.2	
thetacrop1	Moisture content of the crop 1 (wet basis)	0-1	0.6	
thetacrop2	Moisture content of the crop 2 (wet basis)	0-1	Not used	
cropsla	Specific Leaf Area	$m2\ g^{-1}$	0.0015	0.0015
sitefactor	Site factor	0-1.5	1	
Kmainc_m	Maintenance respiration coefficient (fraction of biomass)	$g\ g^{-1}$	0.037	
Kmainc_g	Amount of carbon respired to maintain existing biomass	$g\ g^{-1}$	0.54	

11.6.5 Observed vs predicted

Figure 59 shows the simulation result for 20 years of grass growth in Switzerland and the reference and measured values used for the calibration procedure.

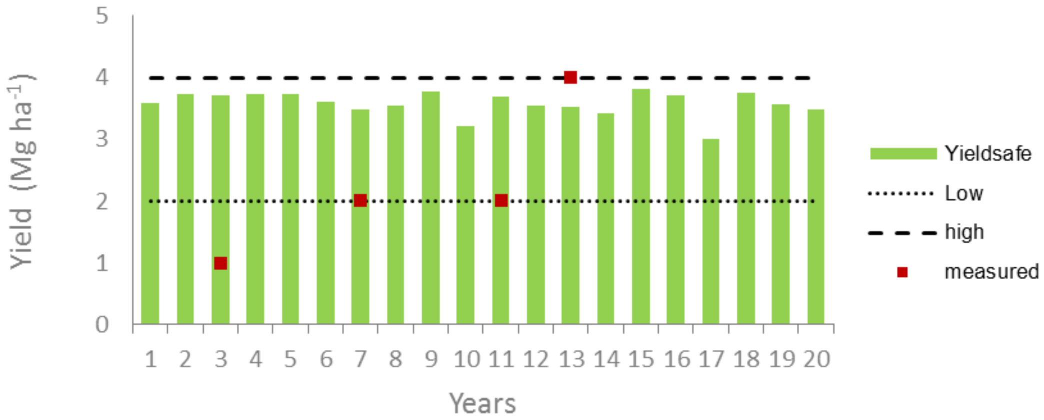


Figure 59. Calibration result of Yield-SAFE model for Grass production in Switzerland

11.7 Winter rye (apple tree) in Switzerland

11.7.1 Description of the experiment where data was measured

The agroforestry system consists of apple trees with mainly winter wheat and is located in canton of Lucerne, central Switzerland. The experiment takes place on 50 hectare. Herein 545 apple trees (varieties Boskoop and Spartan) were planted. The fruits are used for juice and cider production. The cropland is used for winter wheat, rapeseed, strawberries and sown flower strips.

The model was calibrated using climate data for Sursee (Lat: 47.1715, Lon: 8.1111, Alt: 500) from Clipick for the years 1960-1990. Herein the area is characterized by an average annual temperature of 8.9 °C. The average annual rainfall is 967 mm of which monthly falls between 65 mm (October) and 135 mm (August). As input parameter the minimum and maximum temperature, humidity, rainfall, wind speed and solar radiation were used.

The soil type is an eutric camisole, with a soil depth of > 100 cm. The soil texture is sandy-loam and the field is north-west orientated. As input into the model the European soil maps classification (Wösten et al. 1999; Hiederer 2013a; Hiederer 2013b) was used.(Wösten et al. 1999; Hiederer 2013a; Hiederer 2013b) was used.

11.7.2 Measured data for calibration

Rye yields typically range from 3 to 8 t per ha (Schlegel, 2013). In 2015 in Switzerland 3 and 9 t per ha were harvested. Field measurements described in the research and development protocol of WP4 (Herzog, 2015) were started in June and July 2011, and a second assessment was carried out in 2014, when the trees were measured for the second time and soil properties were assessed. Winter rye field data comes from the annual regional statistic and the research plots at Freiburg University (Germany), as described in the underneath table.

Table 92. Brief description of measured data for winter rye

	University Freiburg (Agroforestry plot 2006)	Monitoring program Swiss (2015)
Winter rye	3 – 4 t / ha	
Winter rye		3.4 – 9 t /ha

11.7.3 Literature review of crop parameters

The rye model was mainly based on the existing wheat model for Switzerland. Adaptations were made for the temperature threshold for growth radiation, potential growth (Light use efficiency), and water needed to produce one gram of crop biomass, the harvest index and the extinction coefficient. The data comes Beckmann et al.(2001), Sánchez et al. (2015), Mekonnen and Hoekstra (2011), Kaltschmitt et al. (2009), Hatfield and Stewart (1997) and Amanullah (2015). The set of parameter values for winter rye obtained from literature review are described in Table 93.

Table 93. Values for Yield-SAFE calibration for winter rye derived from literature

Parameter	Value	Reference
name	Winter Rye	
t0	1-5	(Beckmann et al. 2001)
tsumemerge	50	(Feyereisen et al. 2006)
tsumrb	2050	(Feyereisen et al. 2006)
tsumharvest	1700-2000	(Beckmann et al. 2001)
epsc	2.3-2.7 2.74 ± 0.17 to 3.95 ± 0.19 g C MJ^{-1} 2.8 kg DM ha^{-1} MJ^{-1} m^2	(Sánchez et al. 2015) (Feyereisen et al. 2006)
gammac	0,0004 - 0,0005 m3/g (400-500 l / kg DM) 1930 m3/t	 (Beckmann et al. 2001) (Mekonnen and Hoekstra, 2011)
hicrop1	0.52 (corn-straw relationship 1:0.9 8t rye/ 7.2 t straw)	(Kaltschmitt et al. 2009)
hicrop2	0.48	(Kaltschmitt et al. 2009)
kc	0.3 0.0046	(Allen et al. 1998) – FAO cereals (Hatfield and Stewart, 1997)
thetacrop1	0.14 (-0.2)	(Beckmann et al. 2001)
cropsla	0.008-0.02 0.04-0.08 m^2/g (0.4-0.8 cm^2/mg)	(Paponov et al. 1999) (Amanullah, 2015)

http://ucanr.org/sites/asi/db/covercrops.cfm?crop_id=12

11.7.4 Calibration results

The Yield-SAFE calibration procedure was done, and the resulting values of the parameters are in the following Table.

Table 94. Yield-SAFE parameter values found for winter rye after calibration

Parameter	Description	Unit	Value	Reference from literature
name	The name of the crop	unitless	Winter Rye	
doysowing	Day of Sowing	-365 to 365	-80	
doyharvest	Day of harvest if tsum is not reached	1-365	210	
t0	Temperature threshold for growth	^{o}C	5	1-5
tsumemerge	Temperature sum until emergence	^{o}C	50	50
tsumrb	Temperature sum at which partitioning starts to decline	^{o}C	500	2050
tsumre	Temperature sum at which partitioning starts to decline	^{o}C	500	2050
tsumharvest	Temperature sum until harvest	^{o}C	1700	1700-2000
bc0	Initial biomass	g	10	

			(default)	
la0	Initial leaf area	m^2/m^2	0.05	
Croppartition 2leaves	Partitioning to leaves at emergence	0-1	0.8	
epsc	Potential growth (Light use efficiency)	g/MJ	2.3	2.3-2.7 2.74 ± 0.17 to 3.95 ± 0.19
gammac	water needed to produce 1 gram of crop biomass when VPD=1Kpa	m^3/g	0.0004	0,0004 - 0,0005
hicrop1	Harvest index	0-1	0.52	0.52
hicrop2	Harvest index 2(e.g. straw)	0-1	0.48	0.48
kc	Radiation Extinction Coefficient	0.5-1	0.3	0.3
pfcritc	Critical pF value for crop, above which crop starts to drought induction	log(-h)	2.9	2.9
pwpc	pF for permanent wilting point	log(-h)	4.2	4.2
thetacrop1	Moisture content of the crop 1 (wet basis)	0-1	0.15	0.14 (-0.2)
thetacrop2	Moisture content of the crop 2 (wet basis)	0-1	0.15	
cropsla	Specific Leaf Area	$m^2\ g^{-1}$	0.008	0.008-0.02 0.04-0.08
sitefactor	Site factor	0-1.5	1	

11.7.5 Observed vs predicted

Figure 60 shows the Yield-SAFE estimated values for 20 years of winter rye growth in Switzerland and the reference and measured values used for the calibration procedure.

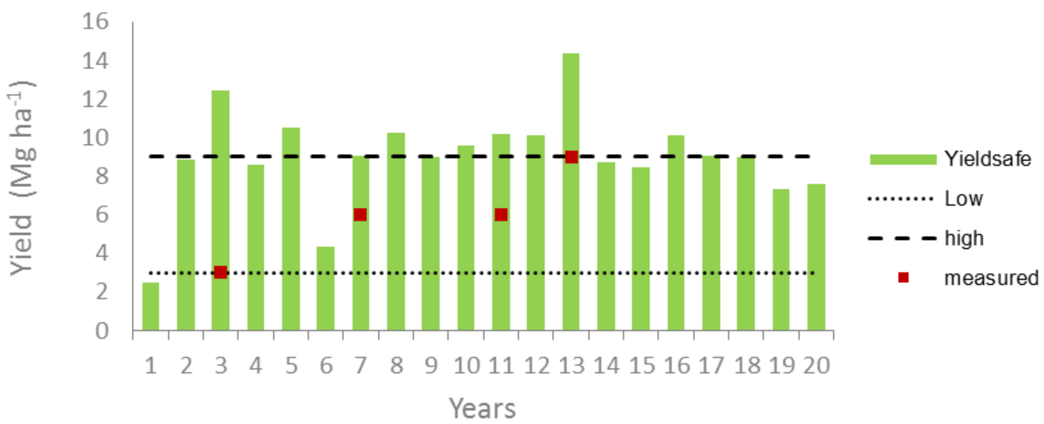


Figure 60. Observed data (points from Swiss Monitoring Programme) and Yield-SAFE (green) estimation for potential yield of winter rye in CH

11.8 Sugar beet

11.8.1 Literature review of crop parameters

The set of parameter values for sugar beet obtained from literature review are detailed in the underneath Table.

Table 95. Values for Yield-SAFE calibration for sugar beet derived from literature

Parameter	Value	Reference
Root/shoot ratio (R/S)	3.2	(De Temmerman et al. 2007)
Radiation Use Efficiency (RUE)	3-3.8 g/MJ	(Lemaire et al. 2008)
Water use Efficiency (WUE)	2.3-5.8 g/kg	(Rinaldi and Vonella 2006)
Specific Leaf Area (SLA)	15.1 m^2/kg	(Rinaldi 2003)
Leaf Area Index (LAI)	3 to 4	(Tsialtas and Maslaris 2007)
Sugar grade	15-18%	(Draycott 2006)
Potential yield (sugar)	8 to 18 t/ha	(Draycott 2006)
Potential yield (root)	50 - 100 t/ha	(Draycott 2006)
Root moisture	75%	Italian guide to sugar beet cultivation

11.8.2 Calibration results

The resulting values of the parameters found for sugar beet growth after the calibration procedure are the ones presented in the following Table.

Table 96. Yield-SAFE parameter values found for sugar beet after calibration

Parameter	Description	Unit	Value	Reference from literature
name	The name of the crop	unitless	Sugar beet	
DOYsowing	Day of sowing		60	
DOYharvest	Day of harvest (if threshold not reached)		260	
Override DOYHarvest by calendar (0=Use above rules; 1=Use Calendar)			0	
To	Temperature threshold	°C	5	
Tsumemerge	Temperature sum to emergence	°Cd	57	
TsumRB	Tsum at which partitioning starts to decline		456	
TsumRE	Tsum at which partitioning to leaves = 0		800	
Tsumharvest	Temperature sum to harvest	°Cd	1000000	
BiomassCrop0	Initial Biomass	g	50	
Initial leaf area	#N/A	m^2 m^{-2}	0.075	
CropPartition2leav	Partition to the leaves at emergence		0.5	
epsc	Potential growth	g MJ^{-1}	0.7	3-3.8

gammac	water needed to produce 1 gram of crop biomass when VPD=1Kpa	m^3 g^{-1}	0.00045	2.3-5.8 g/kg
HIcrop1	Harvest index	g g^{-1}	1.00000	
HIcrop2	Harvest index	g g^{-1}	*0.00000*	
kc	Radiation Extinction Coefficient		0.7	
pFcritc	Critical pF value for crop	log(cm)	3.15	
PWPc	Permanent Wilting Point for Crop	log(cm)	4.2	
Thetacrop1	Moisture content of the crop (wet basis)		0	
Thetacrop2	Moisture content of the crop (wet basis)		0	
CropSLA	Specific Leaf Area	m^2 g^{-1}	0.09	15.1
RSR	root-to-shoot ratio - proportion of belowground to above ground biomass	0-1	3.0	3.2
CCRc	Ratio of carbon content in crop roots	0-1	0.3	
CCAGstraw	Ratio of carbon content in crop straw	0-1	0.5	
CCAGgrain	Ratio of carbon content in crop grain	0-1	0.5	
StrawResidue	Above ground residue left afer harvest	0-1	0.10	
CropEnergy	Utilizable Metabolizable Energy	MJ/t DM	12000.0	
Straw Energy	Utilizable Metabolizable Energy	MJ/t DM	4500.0	
Crop2Livestock	Use crop harvest to feed livestock	1=yes 0=no	0	
DE	Digestible energy (usually 45-55 for low quality forages)	%	50	
Kmainc_m	Maintenance respiration coefficient (fraction of biomass)	g g-1	0	
Kmainc_g	Amount of carbon respired to maintain existing biomass	g g-1	0	
Pasture/Grass?	Controller for crop manager to pick crop yield	1=yes 0=no	0	
Tuber	Controller for crop manager to harvest below ground biomass	1=yes 0=no	1	

11.8.3 Observed vs predicted

Figure 61 represents the production values predicted by the Yield-SAFE model for sugar beet growth in the city of Masi (PD), Italy for the year of 2015, together with reference production values for sugar beet from Draycott (2006).

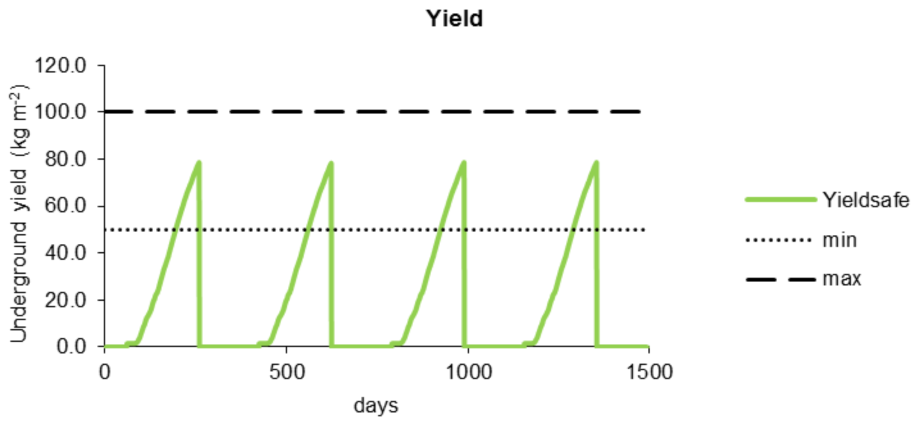


Figure 61. Average daily sugar beet production with maximum and minimum values from Draycott (2006)

11.9 Asparagus

11.9.1 Measured data for calibration

The data used for the calibration procedure, for a 2 years growth period, is described in Table 97.

Table 97. Brief description of measured data for asparagus

Date	Year	Simulation day	Yield (t/ha)	Post harvest yield (t/ha)
2014/08/08	1	515	0.073	0.073
2015/03/10	2	820	0.212	0.066
2015/06/17	2	910	0.313	0.101

11.9.2 Calibration results

The resulting set of parameter values found for asparagus growth after the calibration procedure are the ones presented in Table 98.

Table 98. Yield-SAFE parameter values found for asparagus after calibration

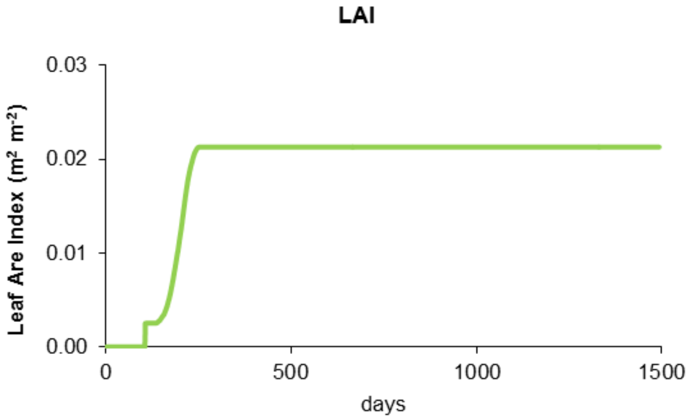
Parameter	Description	Unit	Value	Reference from literature
name	The name of the crop	unitless	Asparagus	
DOYsowing	Day of sowing		-30	
DOYharvest	Day of harvest (if threshold not reached)		20000	
Override DOYHarvest by calendar	0=Use above rules; 1=Use Calendar		1	
To	Temperature threshold	°C	5	
Tsumemerge	Temperature sum to emergence	°Cd	100	
TsumRB	Tsum at which partitioning starts to decline		1200	
TsumRE	Tsum at which partitioning to leaves = 0		2500	
Tsumharvest	Temperature sum to harvest	°Cd	2E+12	
BiomassCrop0	Initial Biomass	g	13	
Initial leaf area	4.34	$m^2\ m^{-2}$	0.0025	
CropPartition2leav	Partition to the leaves at emergence		0.8	
epsc	Potential growth	$g\ MJ^{-1}$	0.48	
gammac	water needed to produce 1 gram of crop biomass when VPD=1Kpa	$m^3\ g^{-1}$	0.00020	
HIcrop1	Harvest index	$g\ g^{-1}$	0.50000	
HIcrop2	Harvest index	$g\ g^{-1}$	*0.70000*	
kc	Radiation Extinction Coefficient		0.8	
pFcritc	Critical pF value for crop	log(cm)	2.60	
PWPc	Permanent Wilting Point for Crop	log(cm)	4.2	
Thetacrop1	Moisture content of the		0.14	

	crop (wet basis)			
Thetacrop2	Moisture content of the crop (wet basis)		0	
CropSLA	Specific Leaf Area	$m^2 g^{-1}$	0.021	
RSR	root-to-shoot ratio - proportion of belowground to above ground biomass	0-1	0.4	
CCRc	Ratio of carbon content in crop roots	0-1	0.3	
CCAGstraw	Ratio of carbon content in crop straw	0-1	0.5	
CCAGgrain	Ratio of carbon content in crop grain	0-1	0.5	
StrawResidue	Above ground residue left afer harvest	0-1	0.1	
CropEnergy	Utilizable Metabolizable Energy	MJ/t DM	12000.0	
Straw Energy	Utilizable Metabolizable Energy	MJ/t DM	7000.0	
Crop2Livestock	Use crop harvest to feed livestock	1=yes 0=no	0	
DE	Digestible energy (usually 45-55 for low quality forages)	%	50	
SPD	shrub prunning doy		120	
SHI	shrub harvest index		0.40	
yesShrub	Is it a shrub	1=yes 0=no	1	

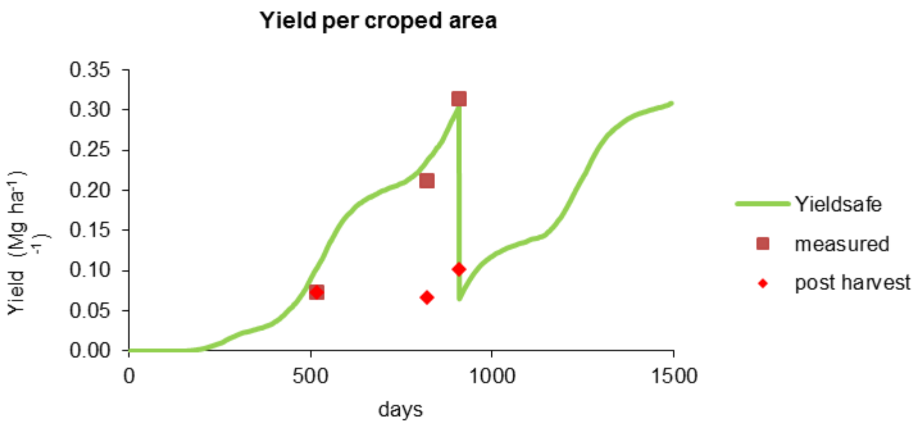
11.9.3 Observed vs predicted

Figure 62 represents the simulation results for Asparagus growth in Castel Rittaldi (Italy). Figure 82 A shows the Yield-SAFE estimation of asparagus LAI; B represents the observed and predicted values of production considering harvests on day 90 of the second year of growth and C the same production value, but with harvest on day 180 of the second year of growth.

A



B



C

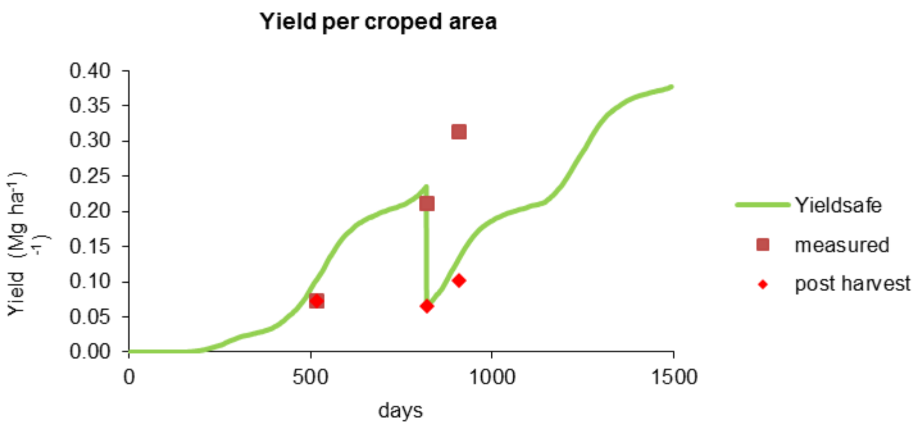


Figure 62. Yield-SAFE (green) estimation of asparagus LAI a) and observed and predicted values of production considering harvests on day 90 b) and 180 c) of the second year of growth