CARAT

CARbon Agroforestry Tool

CARAT is a digital decision support tool developed by ILVO, Fornalab and the Soil Service of Belgium (Belgium – Consortium Agroforestry Flanders). The latest version (in Python) was launched in collaboration with RegenFarmer (Denmark) . CARAT helps farmers and advisors explore the contribution of agroforestry systems to carbon storage in tree biomass and soil

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Introduction

Agroforestry can play an important role in climate change mitigation due to the ability to sequester carbon in trees and soil. Quantifying this carbon sequestration enables financial carbon valuation in agroforestry systems and can provide an economic incentive for land managers to adopt agroforestry. Ex-ante simulations of carbon sequestration can also support the design of climate-effective agroforestry systems. The CARAT tool (CARbon Agroforestry Tool) was developed to quantify this carbon sequestration in agroforestry systems.

CARAT can be applied to a selection of high-stemmed tree species commonly found in temperate agroforestry systems, and is widely applicable to any type of tree configuration (e.g. alley cropping, silvopastoral systems, etc.). Carbon storage in plant biomass is quantified using tree-species-specific allometric relationships and growth data from literature. Annual leaf litter is quantified using a validated leaf litter distribution model developed by Ferrari and Sugita (1996). This model is spatially explicit and predicts annual leaf litter around trees based on an exponential decrease in leaf biomass with increasing distance from the tree and also utilizes species-specific allometric equations.

The leaf litter model was subsequently coupled with the RothC model (Coleman and Jenkinson 1996). This model was developed to simulate the conversion of organic carbon in the topsoil of non-waterlogged agricultural plots. By combining these two models, the user can estimate the effect of leaf fall on the organic carbon content in the soil. CARAT is an interactive tool that allows the user to modify various input parameters (e.g. the design of the agroforestry system, the initial organic carbon content in the soil, crop rotation, tree species).

This tool was developed as a dynamic product that can be continuously improved using in-situ measurements and extended to other agroforestry systems (tree species, planting pattern, tree form, …) This tool supports scientists, policymakers and land managers in quantifying above- and below-ground carbon stocks in agroforestry systems, and in predicting how these stocks will develop over time. In this context, CARAT can be a powerful tool for financial carbon valuation.

Selection of the agroforestry field

CARAT predicts carbon sequestration in trees and in the soil for a plot of your choice. The tool offers two options for selecting a plot, you can either select/draw an actual field on the map, or enter the dimensions of a rectangular plot manually. Fields in agricultural use in Flanders, The Netherlands, France, Ireland, parts of Northern Germany, Denmark, Finland, Czechia, Austria and Portugal are included in the tool and can be selected. Otherwise it is possible to draw a field on the map. Alternatively, a rectangular plot can be defined with a width and height (in meters) of your choice. After selecting or defining a plot, the plot is represented as a grid with cells.

For each of these cells, leaf fall and the corresponding carbon input to the soil are calculated. This calculation is repeated for each time step (1 year) over a fixed period (e.g. 30 years). For each of these time steps, CARAT stores the leaf litter distribution and corresponding carbon inputs on the plot as a matrix. When the values in all cells of these individual matrices are summed, the total annual leaf litter and carbon input on the plot are obtained.

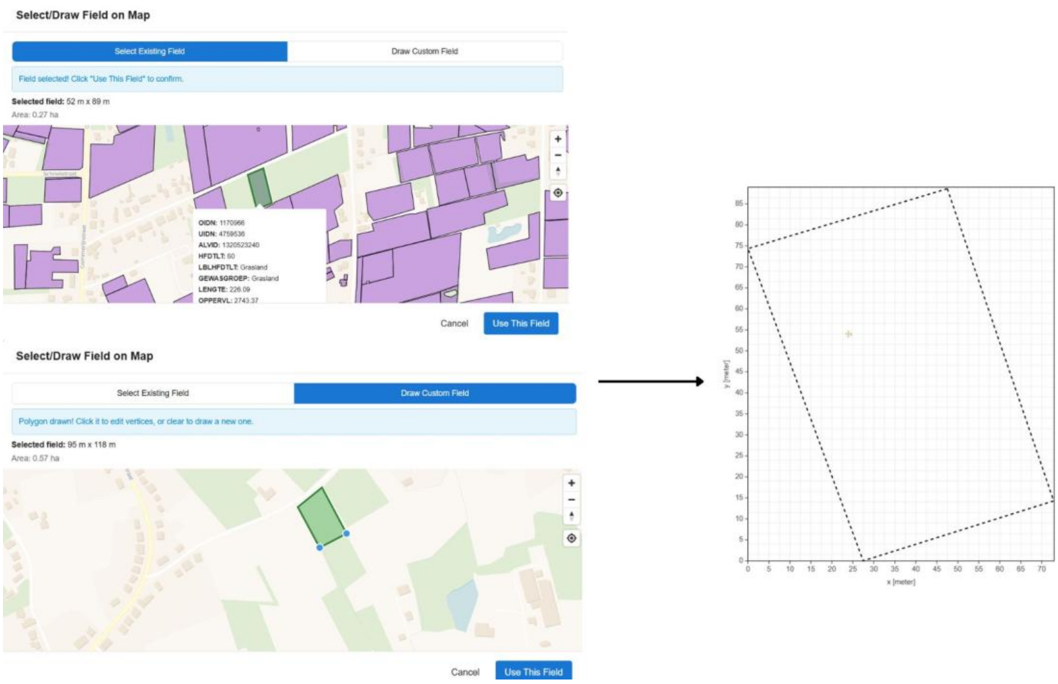


Figure 1: Selection of the plot for which the simulation is to be carried out, by selecting/drawing an actual field on the map.

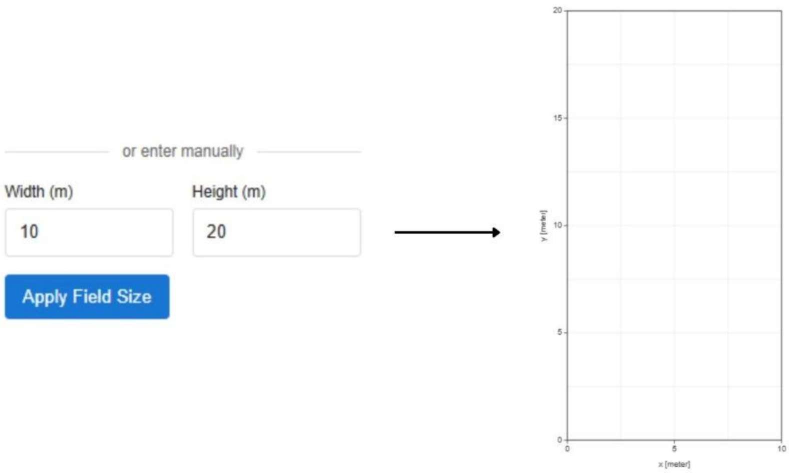


Figure 2: Selection of the plot for which the simulation is to be carried out, by entering the dimensions of the plot manually.

Tree species

CARAT was developed for 19 tree species typically found in an agroforestry context: sycamore maple (Acer pseudoplatanus), black alder (Alnus glutinosa), horse chestnut (Aesculus hippocastanum), hazel (Corylus avellana), ash (Fraxinus excelsior), walnut (Juglans regia), wild apple (Malus domestica), poplar (Populus × canadensis), wild cherry (Prunus avium), wild pear (Pyrus communis), sessile oak (Quercus petraea), pedunculate oak (Quercus robur), black locust (Robinia pseudoacacia), willow (Salix sp.), rowan (Sorbus aucuparia), wild service tree (Sorbus torminalis), small-leaved lime (Tilia cordata), large-leaved lime (Tilia platyphyllos) and elm (Ulmus sp.). In addition, a ‘standard tree’ may be used, this was compiled based on the average of the tree species listed above.

Evolution of the DBH

Both woody biomass and the amount of leaf litter are expressed in the underlying models as a function of the Diameter as Breast Height (DBH) of the tree. This varies with their age, thereby adding a temporal component to the models. The relationship between DBH and age is, species-specific and is estimated here on the basis of a number of references: Van Den Berge et al. (2021) for trees in hedgerows in Flanders, Lukaszkiewicz & Kosmala (2008) for urban trees in Poland, Monteiro et al. (2017) for urban trees in the UK, and finally Carton (2022) and Pardon (2018) for poplars in Flanders (see Figure 3, Table 1)

The raw data (DBH as a function of age) were extracted from each of these studies. A logistic relationship was then fitted to these individual datasets (Eq. 1). This relationship is often used in ecology to approximate tree growth.

$$DBH = \frac{a}{e^{b-c\,t}} \quad \textbf{[Eq. 1]}$$

Where *a, b* and *c* are specific model parameters and *t* is the age of the tree [in years]. The model parameters are estimated for each tree species and each study by minimising the *Root Mean Square Error* (RMSE). Tree species for which no relationship was available from the literature were included by comparing their growth rate with that of other tree species for which a relationship was available. If two or more growth relationships were available for a particular tree species, the curve that best reflected growth in an isolated context (e.g. urban trees) was selected (see Figure 3 and Table 1).

For each tree on the plot and for each time step, the model will calculate the DBH based on the corresponding formulas. These DBH values are then used as input for the leaf fall model. This model predicts the total annual leaf fall per 1 m² on the plot as the sum of the leaf fall from all individual trees on the plot. This calculation is repeated for a specific time period (e.g. 30 years).

Table 1: Diameter at breast height (DBH) [cm] as a function of age (t) [years] for the various agroforestry tree species.

Tree species	Growth rate	Equation	Reference
Acer pseudoplatanus	Fast	= 61/(1+exp(2-0.059*t))	Monteiro et al. (2017)
Alnus glutinosa	Fast	= 728/(1+exp(4.62-0.035*t))	Van De Berge et al. (2021)
Aesculus hippocastanum	Medium	= 52.8/(1+exp(2.02-0.069*t))	Lukaszkiewicz & Kosmala (2008)
Corylus avellana	Medium	89.9/(1+exp(2.28-0.04*t))	Lukaszkiewicz & Kosmala (2008)
Fraxinus excelsior	Fast	68.7/(1+exp(2.7-0.072*t))	Lukaszkiewicz & Kosmala (2008)
Juglans regia	Medium	= 89.9/(1+exp(2.28-0.04*t))	Lukaszkiewicz & Kosmala (2008)
Malus domestica	Medium	= 89.9/(1+exp(2.28-0.04*t))	Lukaszkiewicz & Kosmala (2008)
Populus × canadensis	Very fast	= 6.47185+16.32306*log(t)	Carton (2022)
Prunus avium	Fast	= 89.9/(1+exp(2.28-0.04*t))	Lukaszkiewicz & Kosmala (2008)
Pyrus communis	Medium	= 89.9/(1+exp(2.28-0.04*t))	Lukaszkiewicz & Kosmala (2008)
Quercus petraea	Slow	= 60.2/(1+exp(2-0.061*t))	Van De Berge et al. (2021)
Quercus robur	Slow	= 60.2/(1+exp(2-0.061*t))	Van De Berge et al. (2021)
Robinia pseudoacacia	Fast	= 1452.5/(1+exp(5.66-0.041*t))	Van De Berge et al. (2021)
Salix sp.	Fast	= 1452.5/(1+exp(5.66-0.041*t))	Van De Berge et al. (2021)
Sorbus aucuparia	Medium	= 89.9/(1+exp(2.28-0.04*t))	Lukaszkiewicz & Kosmala (2008)
Sorbus torminalis	Medium	= 89.9/(1+exp(2.28-0.04*t))	Lukaszkiewicz & Kosmala (2008)
Tilia cordata	Medium	= 89.9/(1+exp(2.28-0.04*t))	Lukaszkiewicz & Kosmala (2008)
Tilia platyphyllos	Medium	= 89.9/(1+exp(2.28-0.04*t))	Lukaszkiewicz & Kosmala (2008)
Ulmus sp.	Fast	= 61/(1+exp(2-0.059*t))	Monteiro et al. (2017)

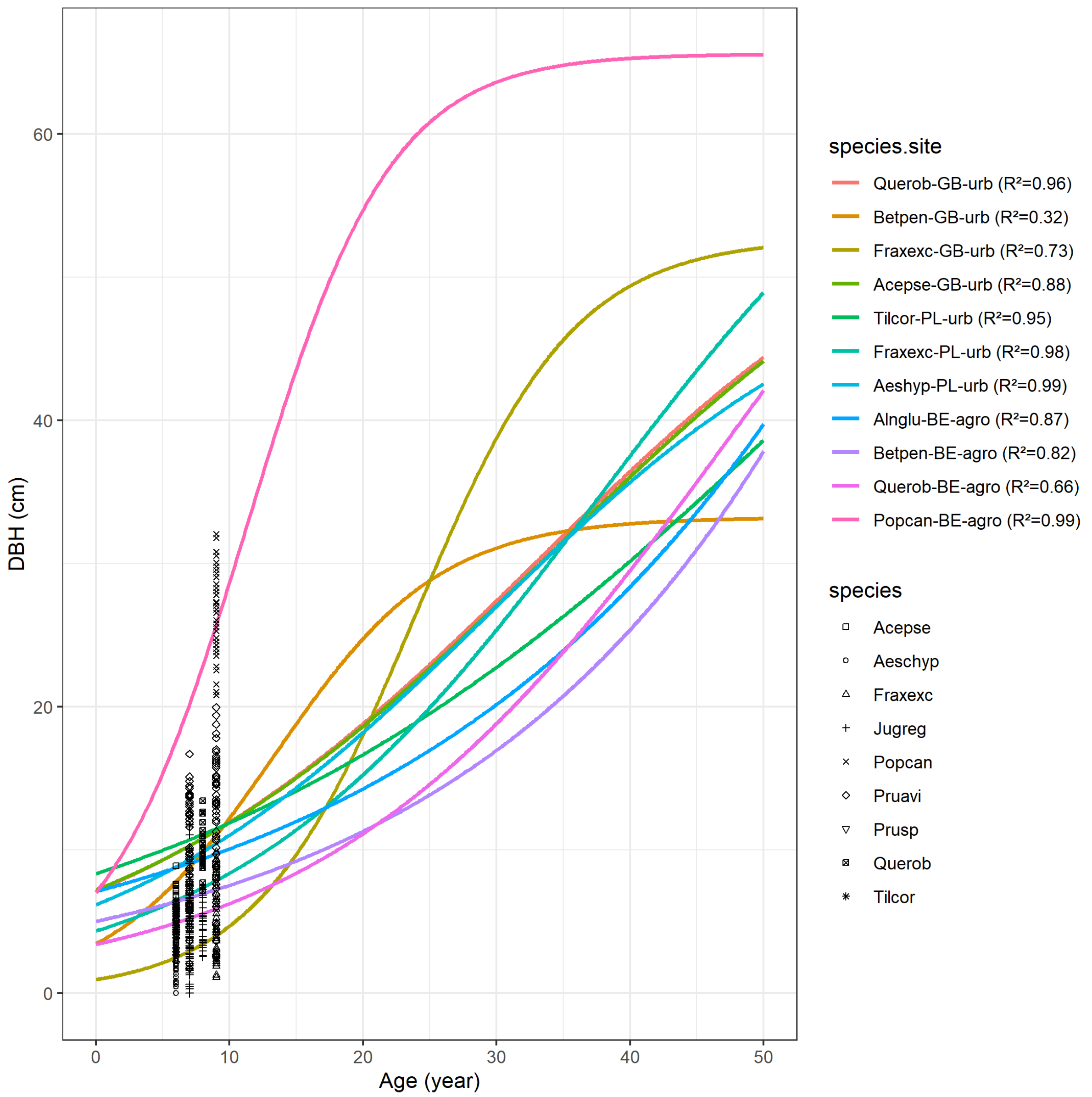


Figure 3: Diameter at breast height (DBH) [cm] as a function of age (t) [years] for various tree species in urban and agricultural contexts. The relationships were determined by fitting a logistic curve [$DBH = \frac{a}{e^{b-ct}}$] to the raw data from four different studies [Monteiro et al. (2017) – GB-urb, Lukaszkiewicz & Kosmala (2008) – PL-urb, Van den Berge et al. (2021) – BE-agro and Pardon (2018) – BE-agro]. The goodness-of-fit (R^2) is also reported for each curve. In addition, the raw measurement points (DBH as a function of age) for a number of typical agroforestry tree species are shown on the graph. We can see that these measurements exhibit a relatively wide spread but overlap to a certain extent with the predicted growth curves (e.g. for poplar).

Carbon storage in woody biomass

To quantify the above-ground woody biomass of the various trees on the plot, allometric relationships based on DBH were again used. These relationships were derived for each tree species from the literature: Shafer et al. (2019) with biomass equations for trees in food forests, McPherson et al. (2016) with volume equations for urban trees in the USA, and Hjelm & Johansson (2012) with volume equations for poplars in Sweden. Tree species for which no allometric relationship was available were estimated based on tree species with a similar growth rate (see Table 2). If only an allometric relationship for above-ground volume was available, the wood density was also looked up in the *Global Wood Density Database* (Zanne et al. 2009). By multiplying the wood density by the volume, the total above-ground biomass can then be determined. The carbon content is ultimately determined by multiplying the total above-ground biomass by a factor of 47% (a typical value used for trees in temperate forests; IPCC 2006).

Table 2: Allometric relationships for above-ground biomass based on diameter at breast height (DBH) for the 19 tree species in CARAT. The equations were derived from the literature for corresponding tree species in an urban forest or food forest context.

Tree species	Equation	Reference
Acer pseudoplatanus	= 520*(0.0019421*DBH^1.785)	McPherson et al. (2016)
Alnus glutinosa	= 0.00079*DBH^2.28546	Shafer et al. (2019)
Aesculus hippocastanum	= 580*(0.0002431*DBH^2.415)	McPherson et al. (2016)
Corylus avellana	= exp(-2.2118+2.4133*ln(DBH))	Shafer et al. (2019)
Fraxinus excelsior	= 530*(0.0005885*DBH^2.206)	McPherson et al. (2016)
Juglans regia	= exp(-2.2118+2.4133*ln(DBH))	Shafer et al. (2019)
Malus domestica	= exp(-2.2118+2.4133*ln(DBH))	Shafer et al. (2019)
Populus × canadensis	= 374*(exp(-2.14+2.26*ln(DBH)))	Hjelm & Johansson (2012)
Prunus avium	= exp(-2.2118+2.4133*ln(DBH))	Shafer et al. (2019)
Pyrus communis	= exp(-2.2118+2.4133*ln(DBH)))	Shafer et al. (2019)
Quercus petraea	= 580*(0.0002431*DBH^2.415)	McPherson et al. (2016)
Quercus robur	= 580*(0.0002431*DBH^2.415)	McPherson et al. (2016)
Robinia pseudoacacia	= 4.13741*DBH^2.17752	McPherson et al. (2016)
Salix sp.	= 0.454*10^(0.8856+2.0552*log(2.54*DBH))	Shafer et al. (2019)
Sorbus aucuparia	= exp(-2.2118+2.4133*ln(DBH))	Shafer et al. (2019)
Sorbus torminalis	= exp(-2.2118+2.4133*ln(DBH))	Shafer et al. (2019)
Tilia cordata	= exp(-2.6788+2.4542*ln(DBH))	Shafer et al. (2019)
Tilia platyphyllos	= exp(-2.6788+2.4542*ln(DBH))	Shafer et al. (2019)
Ulmus sp.	= 460*(0.0018*DBH^1.869)	McPherson et al. (2016)

Leaf fall model

The spatial distribution of leaf litter around the various trees on the plot is quantified using the model developed by Ferrari and Sugita (1996) (Eq. 2). This model was implemented here in the R software package (R Core Team 2023). The amount of leaf litter [g dry matter m^{-2} $year^{-1}$] produced by tree species j at a given point i on the plot is calculated as follows:

$$LF_{ij} = \frac{\alpha_j \gamma_j^2}{2\pi} \sum_k DBH_{jk}^{\beta_j} \exp\left(-\gamma_j d_{ijk}\right) \quad \textbf{[Eq. 2]}$$

Where α_j, β_j and γ_j are the specific parameters for tree species j, DBH_{jk} is the diameter at breast height (1.3 m) of the k^{th} individual of tree species j, and d_{ijk} is the distance from point i to the k^{th} individual of tree species j [in m].

According to this model, leaf litter decreases exponentially as a function of distance from a tree. At any given distance, the amount of leaf fall is calculated based on an allometric relationship with the DBH [cm]. The model contains three tree-species-specific parameters (α, β and γ). For each of the tree species in this model, these parameters were determined based on Ishihara and Hiura (2011). This study reports the estimated parameters for 17 tree species in temperate deciduous forests in Japan. By comparing the leaf shape and size of the agroforestry tree species with those in the Japanese database, corresponding parameters were supplemented (see Table 3).

Table 3: Tree-species-specific parameter values (α, β and γ) for the leaf fall model by Ferrari & Sugita (1996). For each of the agroforestry tree species included in CARAT, leaf size and shape were compared with one of the tree species from the Japanese study by Ishihare & Hiura (2011). Based on the similarities with these Japanese tree species, the parameter values for the agroforestry trees were further refined.

Agroforestry tree species	Tree species from Ishihara & Hiura (2011)	α	β	γ
Acer pseudoplatanus	*Acer mono*	41.4	1.5	0.21
Alnus glutinosa	*Sorbus alnifolia*	0.9	3	0.16
Aesculus hippocastanum	*Magnolia obvata*	28.1	1.5	0.3
Corylus avellana	*Ostrya japonica*	77.9	1.5	0.17
Fraxinus excelsior	*Fraxinus lanuginosa*	14.2	2.03	0.16
Juglans regia	*Fraxinus lanuginosa*	14.2	2.03	0.16
Malus domestica	*Carpinus cordata*	36.8	1.5	0.3
Populus × canadensis	*Tilia maximowicziana*	18.8	1.5	0.3
Prunus avium	*Prunus ssiori*	19.8	1.5	0.3
Pyrus communis	*Carpinus cordata*	36.8	1.5	0.3
Quercus petraea	*Quercus robur**	0.55	2.1	0.13
Quercus robur	*Quercus robur**	0.55	2.1	0.13
Robinia pseudoacacia	*Fraxinus lanuginosa*	14.2	2.03	0.16
Salix sp.	*Carpinus cordata*	36.8	1.5	0.3
Sorbus aucuparia	*Fraxinus lanuginosa*	14.2	2.03	0.16
Sorbus torminalis	*Morus australis*	11.9	1.5	0.3
Tilia cordata	*Tilia janopica*	0.9	2.44	0.19
Tilia platyphyllos	*Tilia americana*	3.2	2.35	0.21
Ulmus sp.	*Ulmus davidiana*	0.3	2.87	0.3

*More accurate parameter values were already available for the pedunculate oak (Q. robur) in Jonard et al. (2006).

Carbon in leaf material and division into different fractions

To determine the total organic carbon in the leaf biomass, a conversion factor of 47% is used (IPCC 2006). Once fallen to the ground, the carbon from the leaves will, over time, be converted into soil. In this process, the organic carbon content in the leaves is divided into different fractions: labile (f_{DPM}), recalcitrant (f_{RPM}) and humified (f_{HUM}) organic matter.

The method described by Peltre et al. (2012) is used to determine these fractions. First, the I_{ROC} indicator value is calculated, which reflects the amount of organic matter that can be retained in the soil for several decades (Eq. 3).

$$I_{ROC} = 44.5 + 0.5\,SOL - 0.2\,CEL + 0.7\,LIC - 2.3\,C_{3d} \textbf{[Eq. 3]}$$

Where *SOL*, *CEL* and *LIC* represent the soluble, cellulose and lignin fractions [%] in the leaf material, respectively (Van Soest 1991). C_{3d} is the fraction of organic matter that has mineralised after three days of incubation in the laboratory. This variable is strongly related to the lignin fraction in the leaf material. Consequently, based on the measurement data in Peltre et al. (2012), a linear regression was established between the C_{3d} and *LIC* values (Eq. 4). This equation can then be used to calculate the C_{3d} fractions for other leaf material as well, provided the Van Soest fractions are known.

$$C_{3d} = -0.2716\, LIC + 10.769 \textbf{ [Eq. 4]}$$

Finally, the regressions from Peltre et al. 2012 are used to calculate the fractions of labile (f_{DPM}) and recalcitrant (f_{RPM}) organic matter in the leaves (Eq. 5 and 6).

$$f_{DPM} = -1.254\, I_{ROC} + 115.922 \textbf{ [Eq. 5]}$$

$$f_{RPM} = 0.979\, I_{ROC} - 8.928 \textbf{ [Eq. 6]}$$

The above method was used to determine the DPM:RMP ratio for a number of tree species from Schrijver et al. (2012) (*Alnus glutinosa, Fagus sylvatica, Tilia cordata, Quercus rubra, Prunus avium, Populus × euramericana and Fraxinus americana*) (Eq. 7 and Table 4).

$$DPM{:}RPM = \frac{f_{DPM}}{f_{RPM}} \textbf{ [Eq. 7]}$$

Table 4: Calculation of the DPM:RPM ratios for the tree species in Schrijver et al. (2012) based on the Van Soest fractions [soluble (SOL), cellulose (CEL) and lignin (LIC), expressed as a percentage]. The method of Peltre et al. (2012) was applied to determine the fractions of labile (f_{DPM})) and recalcitrant (f_{RPM}) organic matter in the leaves of the tree species.

Tree Species	SOL	CEL	LIC	C_{3d}	I_{ROC}	f_{DPM}	f_{RPM}	**DPM:RMP**
Alnus glutinosa	44.33	15.37	21.23	5.00	66.95	31.97	56.61	0.57
Fagus sylvatica	43.46	20.60	20.94	5.08	65.08	34.31	54.79	0.63
Tilia cordata	43.58	21.09	20.53	5.19	64.50	35.04	54.22	0.65
Quercus rubra	41.83	17.17	20.40	5.23	64.24	35.37	53.96	0.66
Prunus avium	51.34	14.60	13.73	7.04	60.67	39.84	50.47	0.79
Populus x *euramericana*	48.70	17.23	15.04	6.68	60.55	39.99	50.35	0.79
Fraxinus americana	51.88	17.20	13.62	7.07	60.27	40.34	50.08	0.81

Based on the values in Table 4, a distinction was made between 'fast decomposers' (DPM:RPM = 0.6) and 'slow decomposers' (DPM:RPM = 0.8). Finally, based on the decomposition rate of their leaf litter (from the literature and expert knowledge), the DPM:RPM ratios for the tree species in CARAT were supplemented (see Table 5). These values are then fed into the RothC model (Coleman and Jenkinson 1996) so that the transfer of organic carbon from the leaf litter to the soil over time can be modelled (see below).

Table 5: DPM:RMP ratio of tree species in CARAT.

Agroforestry tree specie	**DPM:RPM**
Acer pseudoplatanus	0.8
Alnus glutinosa	0.62
Aesculus hippocastanum	0.62
Corylus avellana	0.8
Fraxinus excelsior	0.8
Juglans regia	0.62

Malus domestica	0.8
Populus × canadensis	0.8
Prunus avium	0.8
Pyrus communis	0.8
Quercus petraea	0.62
Quercus robur	0.62
Robinia pseudoacacia	0.8
Salix sp.	0.8
Sorbus aucuparia	0.8
Sorbus torminalis	0.8
Tilia cordata	0.8
Tilia platyphyllos	0.8
Ulmus sp.	0.8

Soil carbon model

The leaf fall model was linked to the RothC model (Coleman and Jenkinson 1996) to calculate the effect of leaf fall on the organic carbon content in the soil. The total organic carbon in the leaf biomass of the various trees is first converted into the amount of DPM and RPM in the leaf biomass, as this is the input for RothC. For a typical Flemish crop rotation, it is possible to compare carbon storage in the soil under conventional agriculture with the same rotation in an agroforestry context.

RothC is a model that calculates the conversion of organic carbon in unsaturated soil layers and takes into account the effects of soil type, temperature, moisture content and crop cover. The organic carbon in the soil is divided into five compartments (see Figure 4). The four active compartments are *Resistant Plant Material* (RPM), *Decomposable Plant Material* (DPM), *Microbial Biomass* (MB) and *Humified Organic Matter* (HUM). Each compartment is converted at a specific rate via first-order kinetics. *Inert Organic Matter* (IOM) is resistant and is not converted.

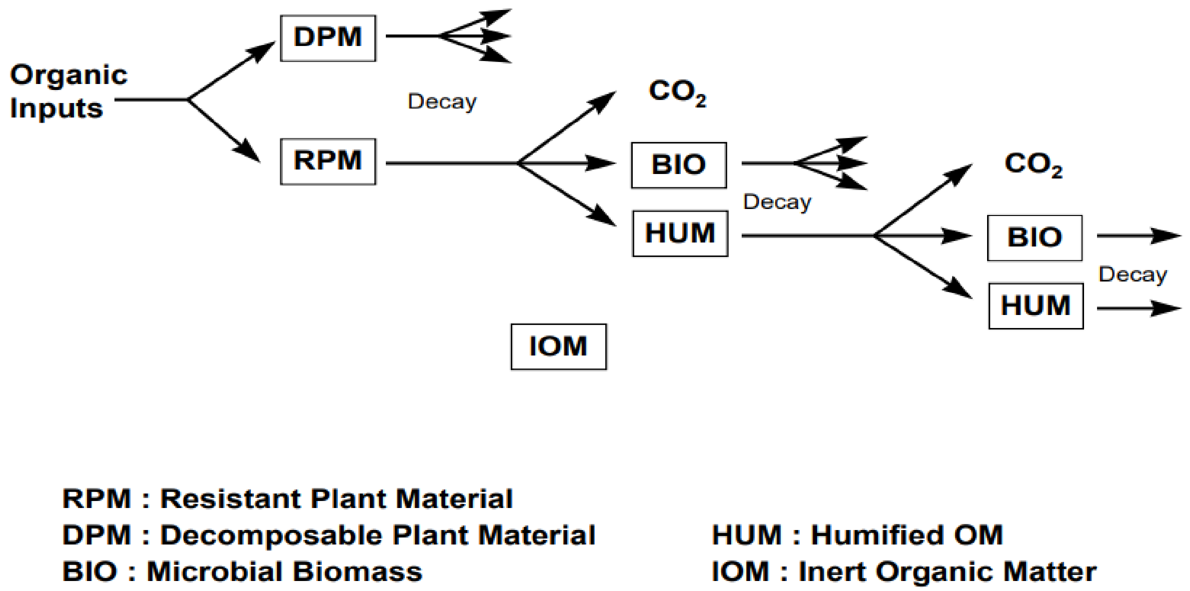


Figure 4: Structure of the RothC model. Organic carbon is divided into five compartments: Resistant Plant Material (RPM), Decomposable Plant Material (DPM), Microbial Biomass (MB), Humified Organic Matter (HUM) and Inert Organic Matter (IOM). With the exception of IOM, each of these fractions is converted according to first-order kinetics (Coleman and Jenkinson, 1996).

Carbon from organic matter (e.g. crop residues, leaves and organic manure) is divided into DPM and RPM according to the specific DPM/RPM ratio. DPM and RPM are both converted into CO2, BIO and HUM. The clay content of the soil determines the proportion that is converted into CO2 and the proportion of BIO + HUM. The BIO + HUM fraction is split into 46% BIO and 54% HUM.

If an active compartment contains a quantity of Y t C ha^{-1} , this quantity decreases at the end of the month in accordance with Eq. 8.

$$Y\ e^{-abckt}\ t\ C/ha \quad \textbf{[Eq. 8]}$$

Where a is the influence factor for temperature, b is the influence factor for moisture content, c is the influence factor for crop cover, k is the decomposition rate constant for the compartment, and t is equal to 1/12 (k is based on an annual decomposition rate). These factors are calculated on the basis of a number of input parameters such as temperature, clay content, precipitation, etc. The calculation is described in the RothC user guide: RothC - A model for the turnover of carbon in soil (Coleman and Jenkinson, 1996). The k-values for the various compartments were taken from RothC (Table 6).

Table 6: Decomposition rate constants for the various active compartments of RothC: Resistant Plant Material (RPM), Decomposable Plant Material (DPM), Microbial Biomass (MB) en Humified Organic Matter (HUM (Coleman en Jenkinson,1996).

Decomposition rate constants	(-)
DPM	10.0
RPM	0.3
BIO	0.66
HUM	0.02

Crop rotation: the effect of crop residues and fertilisation

In agricultural fields, organic carbon is added through crop residues on the one hand and the application of organic fertilisers on the other. The model focused only on organic fertilisers because mineral fertilisers do not introduce organic carbon and therefore have no influence on carbon accumulation in the soil. The crop rotations currently included in the model are perennial grassland, grass-maize rotation and arable farming comprising grain maize, sugar beet, potato, winter wheat and mustard. For each rotation, the most common fertilisation practices and crop rotation in Flanders were selected. Values for carbon input and the DPM/RPM ratio of crop residues were obtained from the CLSIM web application (Belgian Soil Science Service). In time, more crop rotations will be available and eventually the user will be able to enter their own rotations and fertilisation practices.

For permanent grassland, an annual application of 25 tonnes of cattle slurry per hectare in April was assumed. Cattle slurry has a DPM/RPM ratio of 1.15. Grass introduces carbon into the soil on a daily basis. Based on the calculated grass growth, a previous BDB project called NEMO calculated an annual crop residue amount of 2187 kg DM/ha. On a monthly basis, this gives an input of 182 kg DM/ha and, multiplied by a conversion factor of 48%, a carbon input of 87 kg C/ha/month. Grass has a DPM/RPM ratio of 1.37; based on this, there is a monthly input of DPM and RPM equal to 51 and 37 kg C/ha/month respectively.

In arable crop rotations, the crops grown alternate between potatoes for consumption, winter wheat, sugar beet and grain maize. Prior to 1995, mustard was not sown as a green cover crop between the main crops. After that, mustard was added to the rotation wherever possible. Following a late crop, such as grain maize, it is not possible to sow mustard, and the rotation was left fallow. At the start of each main crop, 25 tonnes of pig slurry per hectare (DPM/RPM ratio of 1.15) was applied if this fell within the fertiliser application period. For consumption potatoes, winter wheat, sugar beet, grain maize and mustard, a DPM/RPM ratio of 1.52, 1.35, 1.54, 1.35 and 1.37 respectively was used.

Validation

Alley cropping Zottegem

Part of this calculation tool (namely the leaf fall model by Ferrari and Sugita 1996) has already been validated on the basis of leaf fall measurements taken on an agroforestry plot in Zottegem. On this 248 m × 64 m plot, five rows of trees consisting alternately of poplar (Populus alba) and sweet cherry (Prunus avium) were planted 14 years ago. The rows of trees are 16 m apart and the spacing between trees within each row is 2 m. The rows are oriented east-west. The southernmost row of trees is a double row. The plot has a slope that runs perpendicular to the rows of trees. Leaf fall measurements were taken between the rows of trees on the plot along eight different transects, four of which are located on the higher (southern) part of the plot and four on the lower (northern) part (see Figure 5).

The amount of leaf litter was collected at fixed distances (1m, 4m, 8m, 12m and 15m) from the rows of trees along the transects in 40 cm × 40 cm trays. The trays were emptied on 29 September, 6 October, 13 October, 20 October, 30 October, 5 November and 18 November 2014. The poplar leaves and cherry leaves were collected separately. The leaves were then dried in an oven at 70 °C for at least 48 hours. The dry weight of the leaves was then determined and added up for the different time points to determine the total annual leaf fall.

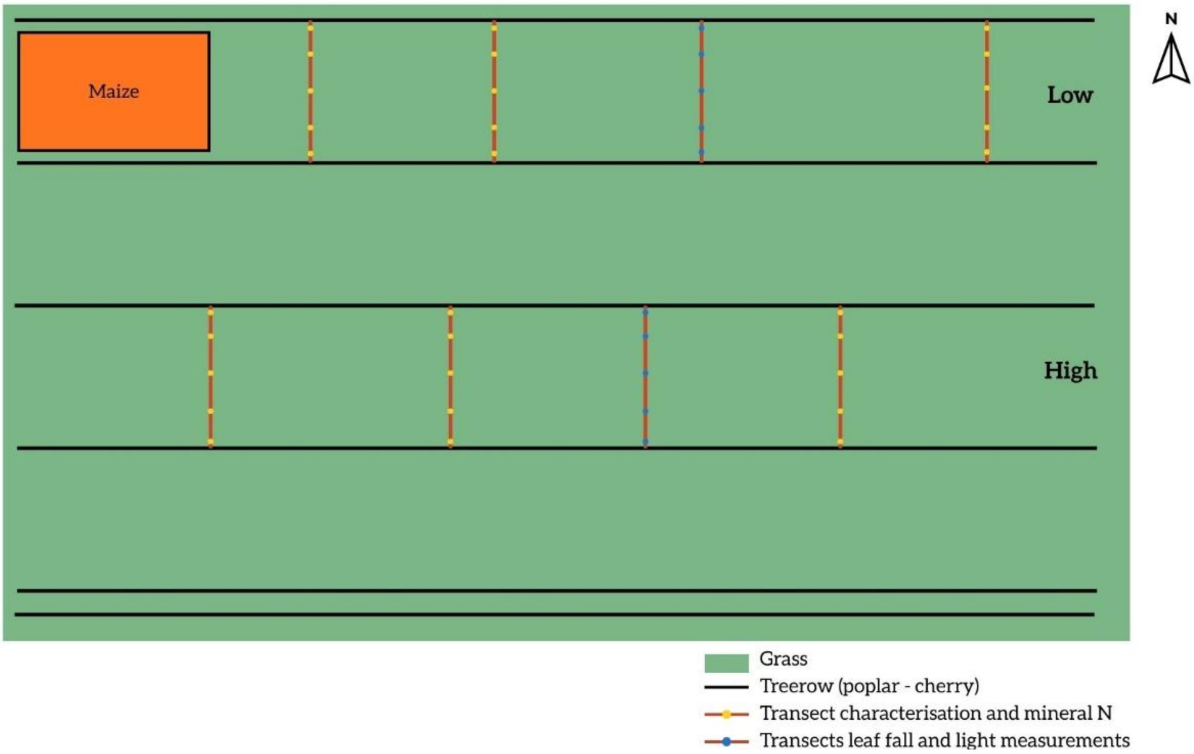


Figure 5: Schematic representation of the agroforestry plot in Zottegem, showing the locations of the eight transects along which the leaf fall measurements were carried out.

The leaf fall model developed by Ferrari and Sugita (1996) was then used to predict leaf fall for this same plot. The plot was divided into a grid of 248 × 64 cells of 1 m². For each cell, annual leaf fall was modelled over a period of 30 years. In this case, the leaf fall values were extracted after 14 years for the corresponding locations of the leaf fall measurements. The modelled values were finally compared with the measured values using a Bootstrap Cross-Validation method (see Figure 6 and Table 7). This validation was carried out in the R software package using the *caret* package (Kuhn 2021). The result of this validation was an RMSE and Pearson R^2 of 46.6 and 0.20, respectively. Overall, we observe that the leaf fall model (significantly) overestimates the measured values in the field. However, it should be noted that a number of assumptions were made regarding the implementation of the plot (dimensions estimated based on GIS) and the location of the transects (estimated based on a sketch). A more accurate approximation of the plot and the position of the transects could lead to a better agreement between the measurements and model estimates. However, further research will be required to achieve this.

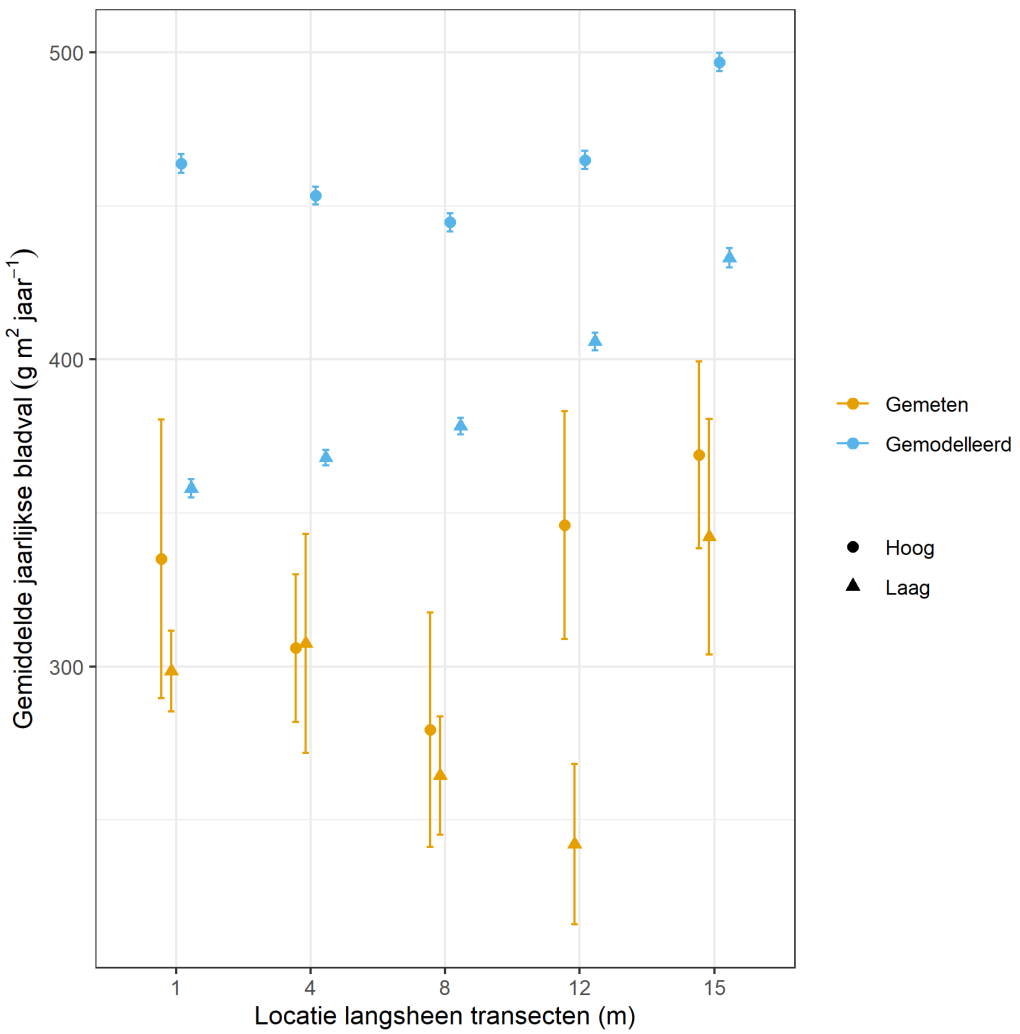


Figure 6: Measured (orange) and modelled (blue) values for average annual leaf fall at fixed locations along the four transects in the upper section (circles) and the four transects in the lower section (triangles) of the agroforestry plot at Zottegem. The error bars indicate the standard error of the mean for the four transects in the upper and lower sections of the plot.

Table 7: Measured and modelled leaf fall at the five locations along the eight transects between the rows of trees on the plot in Zottegem.

Transect	Section	Location	Measured annual leaf fall (g m^{-2} $year^{-1}$)	Modelled annual leaf fall (g m^{-2} $year^{-1}$)
T1	Upper	1 m	326.25	454.66
T1	Upper	4 m	271.13	444.75
T1	Upper	8 m	204.50	435.93
T1	Upper	12 m	334.69	456.07
T1	Upper	15 m	362.00	487.88
T2	Upper	1 m	401.31	466.03
T2	Upper	4 m	304.50	456.31
T2	Upper	8 m	343.19	447.71
T2	Upper	12 m	420.44	468.03
T2	Upper	15 m	451.38	499.92
T3	Upper	1 m	402.56	468.99
T3	Upper	4 m	374.56	456.35
T3	Upper	8 m	347.38	447.74

T3	Upper	12 m	381.19	468.05
T3	Upper	15 m	357.44	500.03
T4	Upper	1 m	210.06	465.60
T4	Upper	4 m	273.88	455.87
T4	Upper	8 m	222.63	447.27
T4	Upper	12 m	247.75	467.58
T4	Upper	15 m	304.75	499.48
T1	Lower	1 m	336.75	360.96
T1	Lower	4 m	293.50	370.40
T1	Lower	8 m	279.06	380.91
T1	Lower	12 m	252.00	408.63
T1	Lower	15 m	327.69	436.09
T2	Lower	1 m	289.75	361.06
T2	Lower	4 m	241.56	370.51
T2	Lower	8 m	212.19	381.03
T2	Lower	12 m	165.75	408.76
T2	Lower	15 m	248.31	436.22
T3	Lower	1 m	277.50	361.06
T3	Lower	4 m	409.00	370.50
T3	Lower	8 m	263.44	381.03
T3	Lower	12 m	270.63	408.75
T3	Lower	15 m	359.75	436.22
T4	Lower	1 m	289.81	348.95
T4	Lower	4 m	285.94	360.57
T4	Lower	8 m	303.19	370.21
T4	Lower	12 m	280.19	397.17
T4	Lower	15 m	433.44	423.62

Rows of Populus x canadensis in Flanders

A second set of validation measurements was carried out by Carton (2022), in which the soil carbon content near poplars was compared with the values predicted using CARAT (Figure 7). On a plot of arable land and a plot of grassland bordered by a row of poplar trees, four composite samples were taken from the 0-30 cm soil layer at varying distances from the row of trees. The planting plan for these plots was simulated in CARAT and, for the relevant tree age, these measured values were compared with the values obtained via CARAT. On average, CARAT was found to (slightly) overestimate the soil carbon content; for certain plots, these discrepancies were quite significant. An overestimation of the amount of leaf litter, as mentioned above, may be the reason for these higher simulated values.

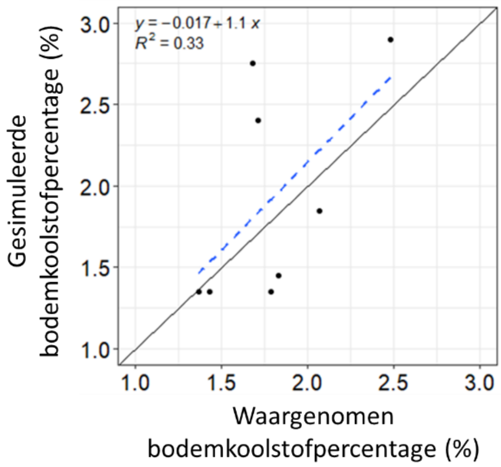


Figure 7: Comparison between measured (x-axis) and modelled (y-axis) soil carbon percentages. No significant difference was found between the measured values (M=1.795, SD=0.355) and the modelled values (M=1.925, SD=0.663) (t14=0.633, p=2.14).

Future steps

An important next step in the validation of CARAT is to collect measurements of DBH, leaf fall, soil organic carbon, and core samples for age determination, etc., across a wide range of agroforestry plots with different combinations of tree species. Based on this extensive collection of measurements, the various components of the model can be better parameterized and validated separately. This will also enable us to better assess the predictive power and applicability of this model.

A second important step is the implementation of CARAT in a user-friendly software package with a user interface, with the long-term aim of automating the input of plot and parameter data. This will enable the various target groups (e.g. farmers, policymakers, etc.) to easily specify any plot and tree location and predict the above- and below-ground carbon storage on that plot over time. Furthermore, it enables users to simulate various scenarios (e.g. number of trees, distance between rows, different combinations of tree species, etc.).

A practical user guide

The tool can be opened with the internet link: https://agroforestry.ilvo.be/carat/

The CARAT tool should automatically open on its first tab ‘About’.

To start working with the tool, go to the second tab ‘Field’.

1. Configuration of the field

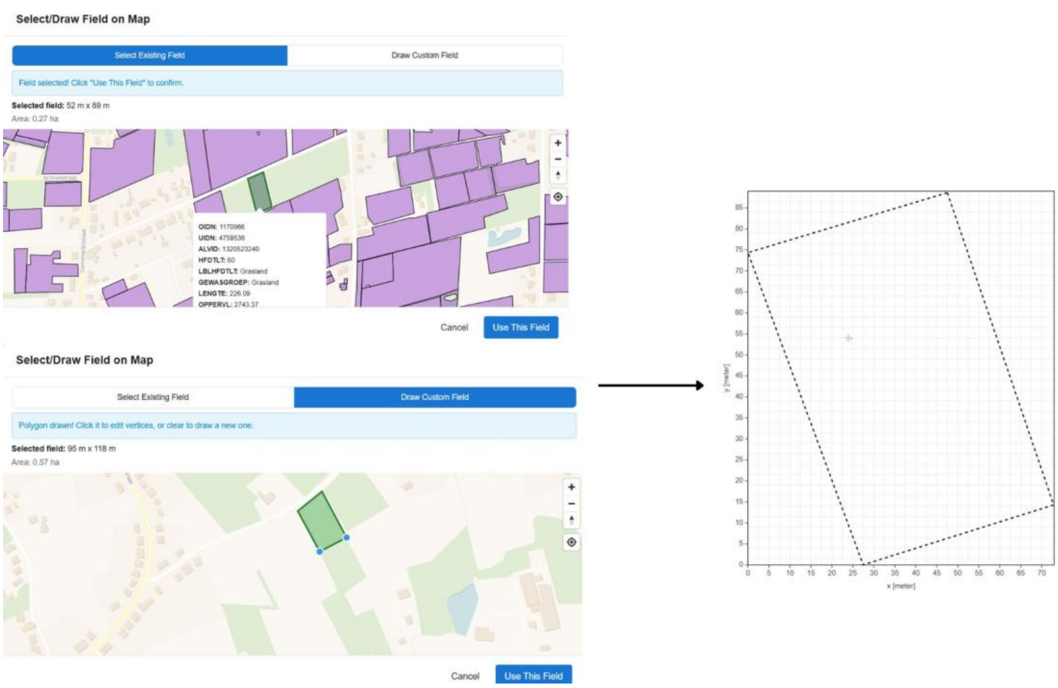
1.1 Choose field dimensions

The first step is to choose the field dimensions. You can either select/draw an actual field on the map, or enter the dimensions of a rectangular plot manually.

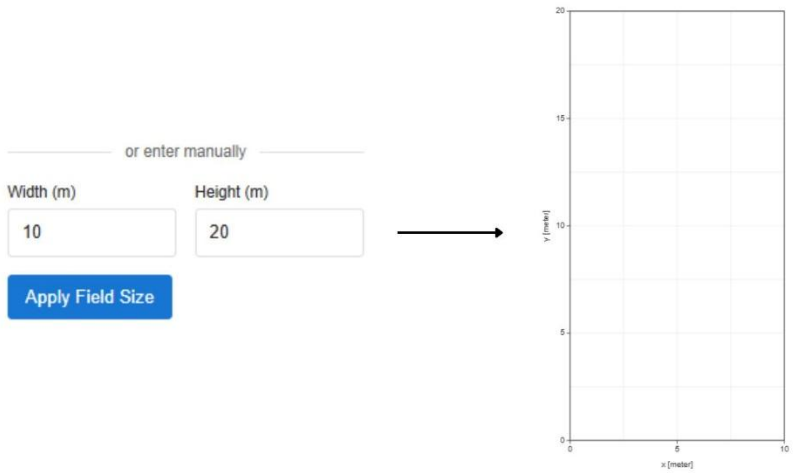
Fields in agricultural use in Flanders, The Netherlands, France, Ireland, parts of Northern Germany, Denmark, Finland, Czechia, Austria and Portugal are included in the tool and can be selected. Zoom in on the location of the field and by hovering your mouse over a field, detailed information about the fields will be displayed. Click the desired field to select it and press the ‘Use This Field’ button.

Otherwise it is possible to draw a field on the map. Zoom in on the location and click to define the corners of the field. Then click ‘Use This Field’ to confirm.

Once you selected a field, on the map, it will be displayed on the grid, as shown below. The dashed line represents the field boundaries.



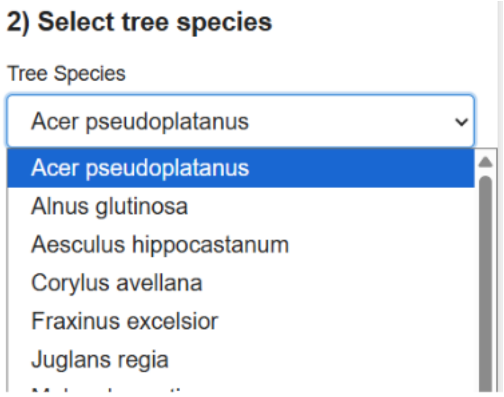
The other option is to enter your field dimensions directly. Enter the Width and Height (in meters), then click ‘Apply Field Size’. Your field will be displayed as a rectangular grid, where the edges of the grid represent the boundaries of your field.



1.2 Select tree species

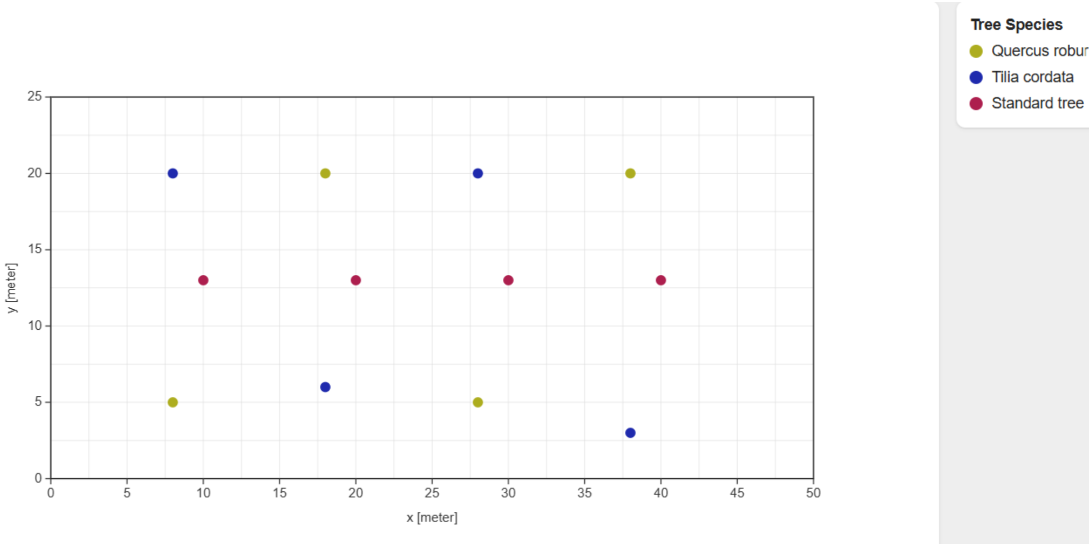
The next step is to select the tree species that you want to add to the grid. You can choose a species from the drop-down list.

If you do not want to specify the tree species, you can select the "Standard tree", whose models were designed to represent the general reactions of a tree in an agroforestry system.

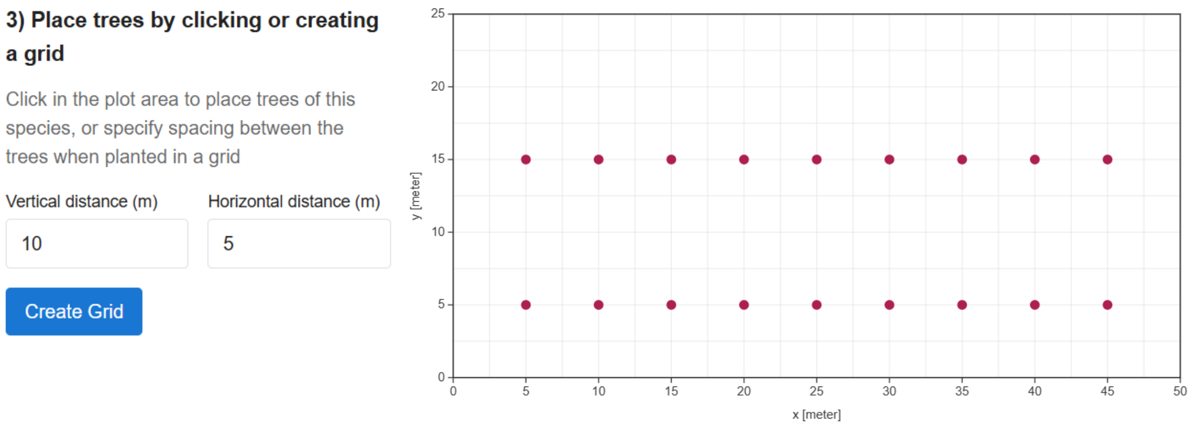


1.3 Place trees by clicking or creating a grid

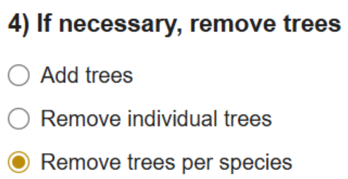
The selected tree species can now be added to the field. The first option is to place the trees one by one: simply click directly on the grid where you want to position a tree. To add a different species, change your selection in the list.



The second option is to create a regular grid of trees. Choose the vertical distance and horizontal distance between the trees and click ‘Create grid’. The trees will automatically appear on the field.



1.4 If necessary, remove trees



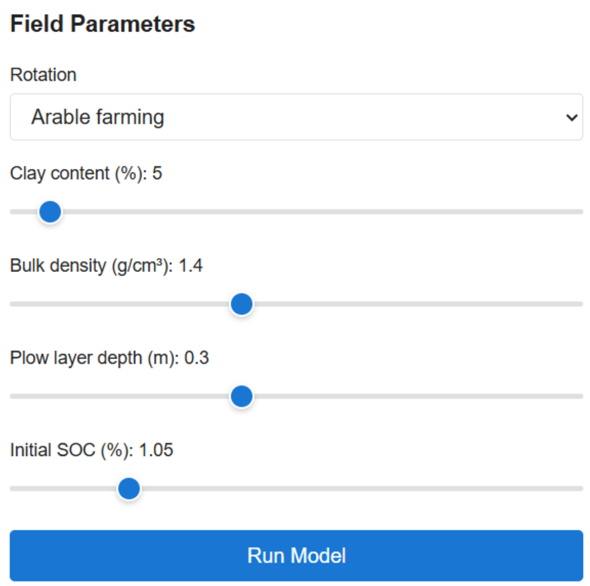
Adding trees is the default action when clicking on the field grid. You can change this action to ‘Remove individual trees’ to delete trees by clicking on them. It is also possible to remove all trees of a specific species by selecting ‘Remove trees per species’ and clicking on one of the trees of that species.

Once your field design matches your requirements, proceed to the next step by opening the third tab, ‘Timeseries’.

2. Timeseries

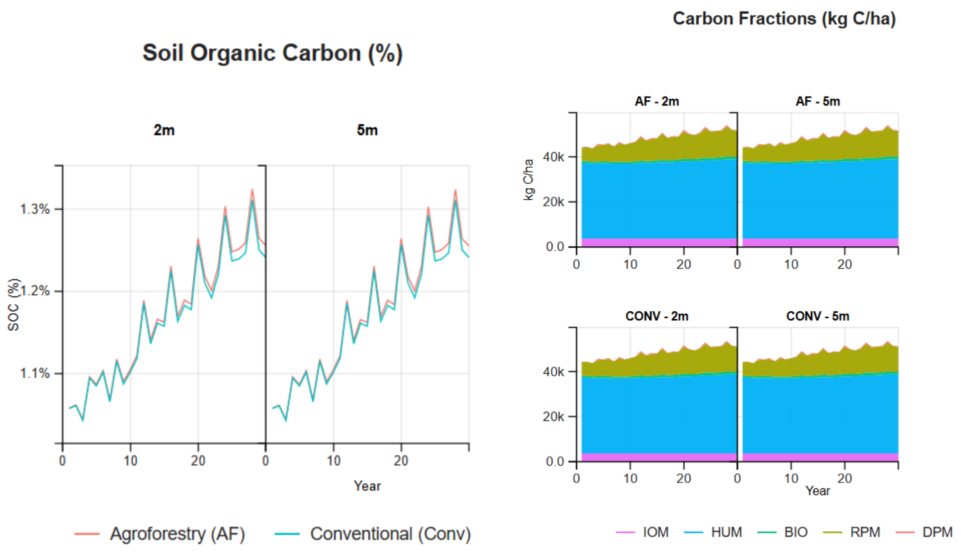
2.1 Field parameters

The model has five parameters that you can adjust to match your field characteristics. They have default values, which are considered to represent the average for each parameter, which will be used if no changes are made. You can adjust the following parameters by moving the sliders:



- Rotation: Choose between Arable farming, Grass-maize and Grassland.
- Clay content: choose a value between 0% and 100%.
- Bulk density: Choose a value between 1 g/cm^3 and 2 g/cm^3.
- Plow layer depth: Choose a depth between 0.1 and 0.6 m.
- Initial Soil Organic Carbon (SOC): Choose a value between 0.1 and 5%.

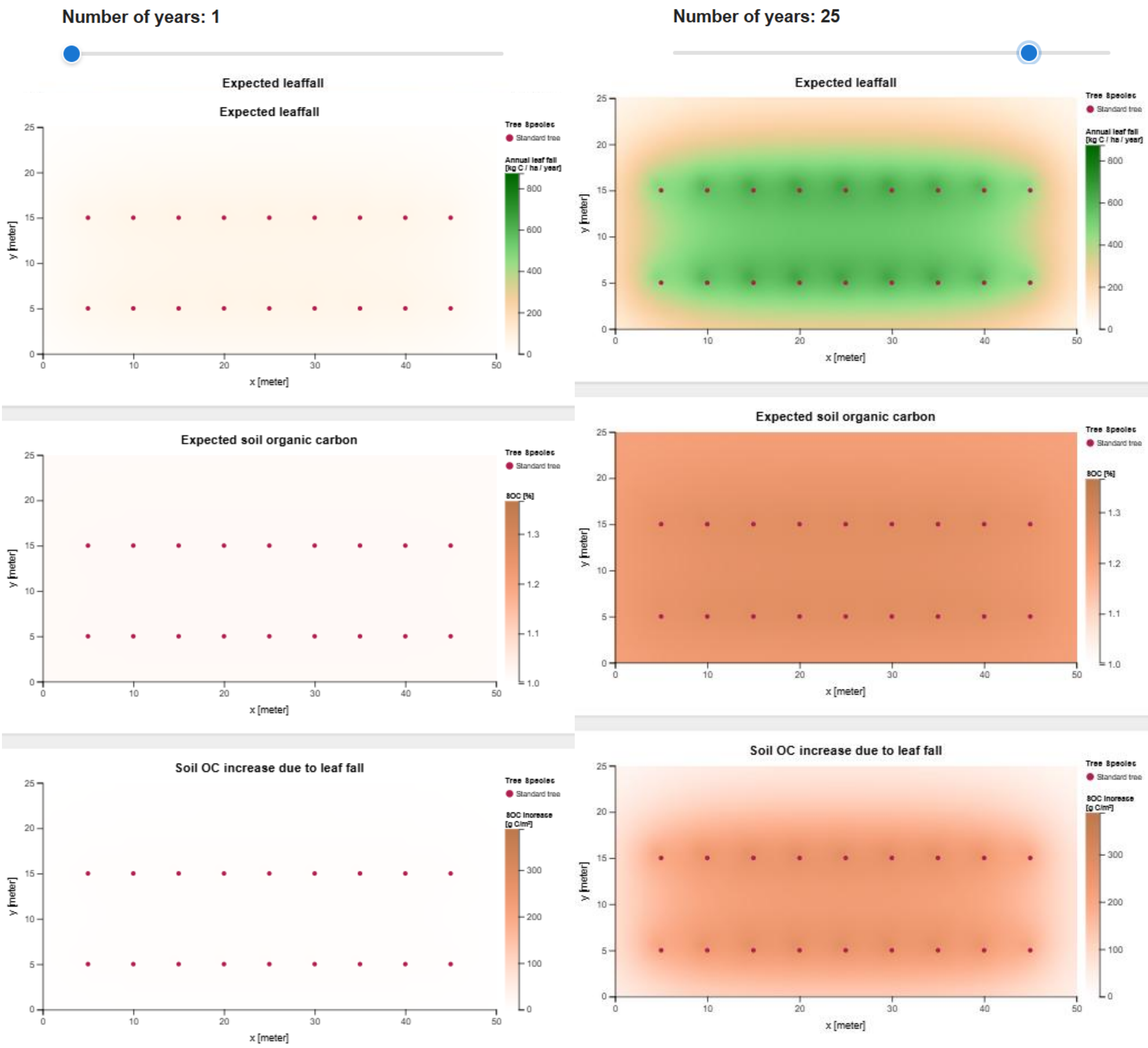
When all the parameters are set, click on the 'Run Model' button. After the simulation finishes, the results for Soil Organic Carbon (%) and Carbon Fractions (kg C/ha) will be displayed.



To see more results open the third tab of the tool, titled 'Raster output'.

3. Raster output

This tab shows the expected impact of tree growth on carbon sequestration in the field over time. Three different rasters are displayed: leaf fall, expected soil organic carbon and the proportion of carbon, which would be due to the leaf fall. The year of projection can be selected between the first and 30th, by moving the slider.



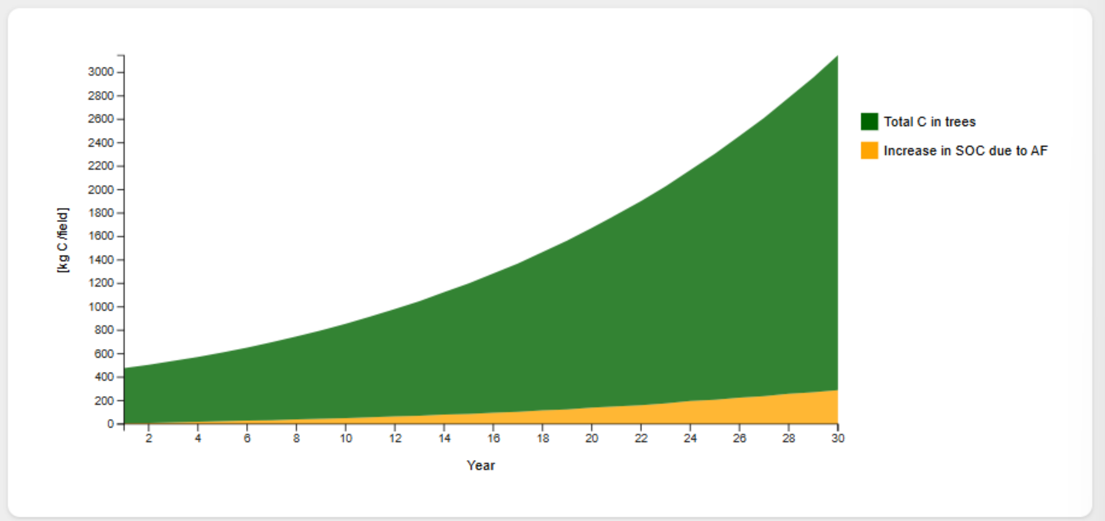
Number of years: 1
Number of years: 25
Expected leaffall
Expected soil organic carbon
Soil OC increase due to leaf fall
Tree Species
Standard tree
Annual leaf fall [kg C / ha / year]
SOC [%]
SOC increase [g C/m²]
x [meter]
y [meter]

4. Summarizing table

The next tab displays the summary table. This table shows, in 5-years intervals, the increase in SOC, the total carbon in the trees, and the total carbon increase due to agroforestry, both for the entire field and per hectare. Additionally, a figure illustrates the total carbon increasing over time, divided by total carbon in trees and increase in SOC due to agroforestry.

About Field Timeseries Raster output Summarizing table Report

Years	Increase in SOC due to AF [kg C / field]	Increase in SOC due to AF [kg C / ha]	Total C in trees [kg C / field]	Total C in trees [kg C / ha]	Total C increase due to AF [kg C / field]	Total C increase due to AF [kg C / ha]
1	5.76	46.07	472.07	3776.55	477.83	3822.62
5	23.56	188.50	588.24	4705.94	611.81	4894.44
10	51.55	412.39	805.15	6441.18	856.70	6853.57
15	87.49	699.94	1113.79	8910.32	1201.28	9610.26
20	139.69	1117.55	1534.29	12274.29	1673.98	13391.84
25	207.85	1662.81	2098.63	16789.01	2306.48	18451.81
30	289.92	2319.33	2856.42	22851.38	3146.34	25170.71



5. Report

The last tab of the tool is the report. You can see the report directly on this page or you can download it. The report contains the field configuration and parameters, timeseries figures, raster outputs and the summarizing table.

5.1 Download the report

To download the, click the ‘Save as HTML’ button. This will generate an .HTML file of the report, which you can save in a folder and rename it.

This file is a web version of the report, by transforming this HTML file into a .pdf file, an internet connection is not required anymore.

5.2 Save the report as a .pdf file

Click on the downloaded .html report. The report will open in a new window or tab in your web browser.

Once you see the report in your web browser, click on the menu icon in the top right corner of the page. Generally, it looks like *3 points* (e.g. on Google Chrome) or *3 lines* (e.g. on Firefox).

Then choose ‘Print’. A new window will open to configure the printing options. Click on the drop-down ‘Destination’ list to choose if you want to: print the report (select a printer) or to convert it into a .pdf file with ‘Save to pdf’. If you choose to save it, a window will appear where you have the option to choose the name and folder where you want to save this report.

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