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Regular Article

# Temperate agroforestry for tree carbon storage in Switzerland: 10 years of biophysical and social monitoring

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ABSTRACT

Agroforestry, the integration of woody structures in agricultural land, has high potential for climate protection and resilience, since trees are active carbon sinks. Yet, there is only limited empirical evidence on the actual performance of temperate agroforestry systems in this respect, nor on its acceptance by farmers. We monitored four silvoarable agroforestry systems in Switzerland (apple, sour cherry, poplar, wild cherry) over ten years and measured tree growth and carbon storage performances. We compared the measured data to outcomes of the Yield-SAFE model. We regularly interviewed farmers on their observations of their agroforestry systems. Individual growth of agroforestry trees varied between species and location, with differences between the smallest and largest tree ranging from 44 % to 97 %. Consequently, the carbon sequestration potential varied substantially between 0.4 and 2.5 t $CO_{2eq}$ per year and hectare. The modelling approach showed a good fit for apples and wild cherries and – after (re)calibration with local data – also for poplars and sour cherries. Tree mortality was up to 20 % in the first years but if replaced, this did not influence the overall outcome after ten years. Farmers' evaluations differed, depending on the motivation of individual farmers. They changed only slightly with time, indicating that their expectations had been realistic. The study highlights the usefulness of long-term empirical data for model calibration and of monitoring farmers' satisfaction. Realistic model predictions and management of farmers' expectations will facilitate the implementation of agroforestry.

## 1. Introduction

Mitigate and adapt to climate change is one of the major challenges for today's society [1]. Many states and international institutions are therefore formulating goals and strategies to mitigate and adapt to this threat. For example, the Climate Law of the European Union as well as the Climate Strategy of Switzerland aim at climate neutrality by 2050 [2,3]. The agricultural sector is the 5th biggest emitter in Europe with around 12 % of all greenhouse gas (GHG) emissions [4]. Both, the potential for GHG emission reduction and removal, are being investigated in the context of the European "carbon farming" initiatives and regulations [5]. Herein agroforestry systems, the combination of trees with crops or grassland, are highlighted as active carbon sinks. Agroforestry for carbon storage has been promoted since the turn of the century (e.g. Refs. [6,7]). Carbon is sequestered by the trees and fixed in the leaves, branches, stems, and roots. Leaf fall and root decay lead to an increase of the organic matter (higher carbon content) in the soil [8]. The parts of the wood that are used for construction or furniture remove carbon from the atmosphere as long as they stay in use [9,10]. Measured data on carbon storage in temperate agroforestry are still limited, but are gradually increasing [11,12]. For Europe, Kay et al. [13] estimated that implementing agroforestry on 10 % of European farmland would compensate between 0.09 and 7.29 t C $ha^{-1}$ $yr^{-1}$, which is up to 43 % of the GHG emissions of the European agricultural sector and is therefore touted as one of the possible mitigation measures for climate change in Europe.

About nine per cent of European farmland are still managed as agroforestry systems [14,15], namely traditional systems such as orchards in Central Europe [16] or wooded pasture systems in the Mediterranean region (i.e. Dehesa, Montado) [17,18]. From the late 1990ies onwards also modern agroforestry systems started to be introduced, notably by pioneer farmers. Modern systems are designed for management with today's farm machinery, and they differ in type and density of the woody species planted and the products produced. Accordingly, different systems have different growth pattern and thus a different potential for carbon storage [13]. Predictions about the long-term storage potential have to account for the specifics of the location and system

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characteristics. Actual field data on growth, management, and mortality of trees and plants in temperate agroforestry systems are scarce [12], yet this needs to be evaluated, if agroforestry is to contribute significantly to climate mitigation.

In the case of agroforestry, decision makers (farmers, landowners, administrators, policy makers) need to rely on models to predict both the productivity (biomass, fruits, etc.) and the climate and environmental impacts (carbon sequestration, soil health, biodiversity, etc.) that these systems can have over their lifetime in a specific place [19,20]. The development of such models is still ongoing [21–23]. At present, there are very few models that allow to simulate different types of agroforestry systems (including different tree and crop species) in various locations (including different climate, soil, and water conditions). User-friendly, easy-to-use models, which still yield valid results and can account for the complexity of agroforestry systems, are rare. Yield-SAFE, a parameter sparse, process-based dynamic model, is one of these few tools. It accounts for climate, soil and agronomic parameters and informs about tree-growth and crop-yields over the life cycle of an agroforestry system, based on the resource use and competition between trees and crops or grass [24]. It is also available as an online dashboard with an user interface, making it accessible to researchers, policy makers and practitioners [25].

However, despite the potential of agroforestry for supporting the agroecological transition [26] and the efforts made by researchers to provide reliable models to support agroforestry knowledge, there is a discrepancy between the attention agroforestry gets from researchers and policy makers and the actual uptake by farmers (e.g. Ref. [27]). The latter still is disappointingly low and lags behind expectations. The uptake of modern agroforestry systems is still largely limited to pioneer farmers. There have been surveys and questionnaires on farmers' perception and motivations to adopt – or not adopt – agroforestry [28–30], but these are always snapshots in time. Little is known about how the farmers' evaluation of agroforestry systems evolves in the years after planting an agroforestry plot on their farm: to what extent the original expectations were met, which additional challenges they perceived and what their learnings are.

In summary, whereas agroforestry systems are heralded to be promising land use systems in terms of their environmental impact, little is known about their growth behaviour nor about their specific impact on or interactions between natural resources and the environment [31]. While there are good data on tree growth under forestry conditions [32–34], there is little empirical knowledge on the performance of trees in an agroforestry context and on the fulfilling of farmer's expectations.

Here we present an interim report on the evolution of four agroforestry systems in Switzerland over ten years. We tested field measurements against modelled predictions using the Yield-SAFE model, including (re)calibration of the model using local data on tree growth, and used the model to evaluate their carbon storage. Lastly, we analysed how the farmers' perception of the strengths and weaknesses of the systems, which they planted ten to fifteen years ago, evolved over time. Our research objectives were to generate empirical data on tree growth and mortality in agroforestry systems, to make the data available for model validation and improvement and to conduct a first evaluation of the carbon storage achieved until now. We also wanted to report on the farmers' own evaluations of how the systems work in order to facilitate extension and farmer advice.

## 2. Material and methods

### 2.1. Agroforestry plots

This study analysed four modern Swiss agroforestry systems (AF1–4, Fig. 1, Table 1) planted by pioneer farmers between 2007 and 2013. The sites are different in size, tree species, management and number of trees

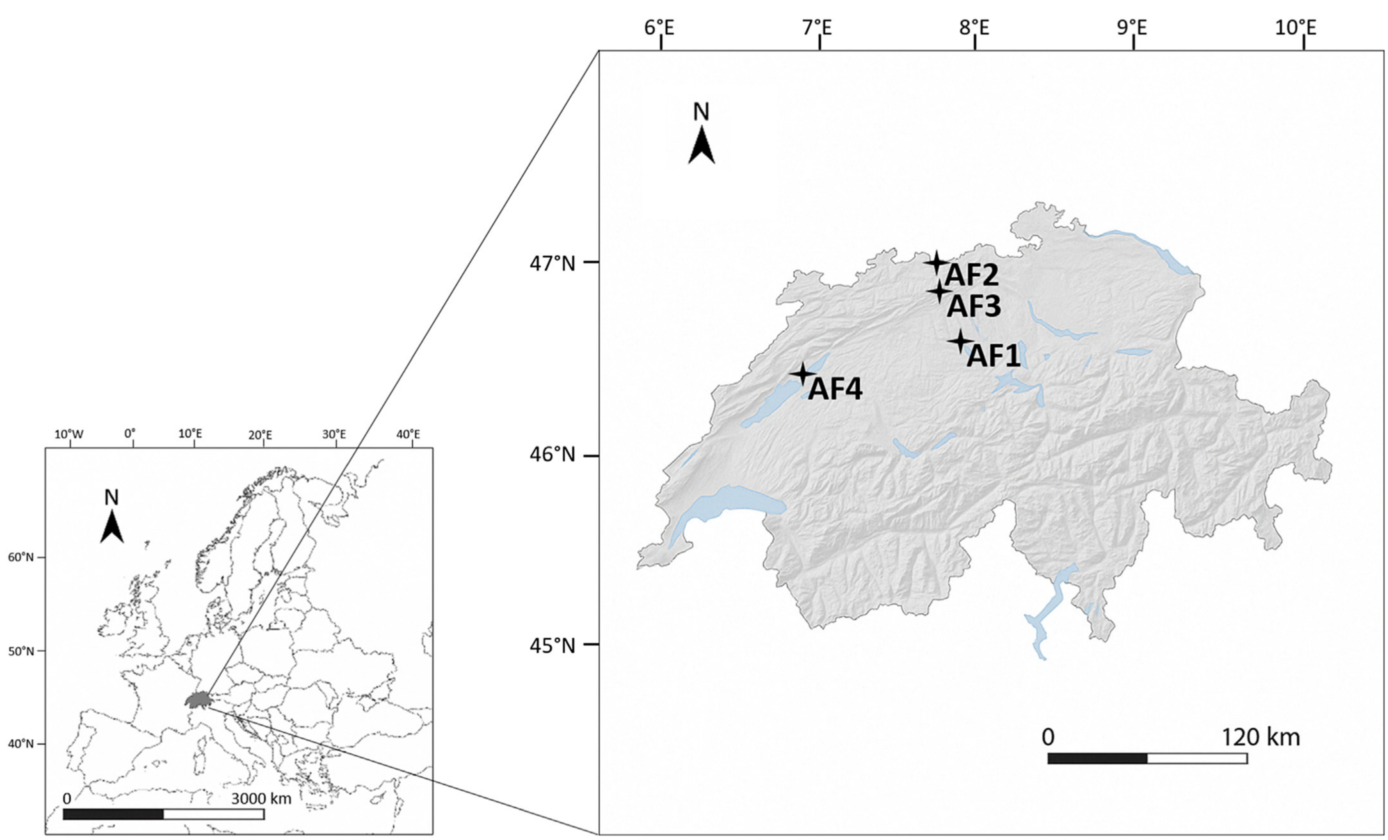


**Fig. 1.** Location of the four agroforestry monitoring sites AF1, AF2, AF3 and AF4 in the Swiss lowlands. AF1: Apple intercropped; AF2: Sour cherry and vegetables; AF3: Poplar intercropped; AF4: Wild cherry intercropped. Source: ezilon maps www.ezilon.com.

**Table 1**
Summary of the four monitoring sites.

| Test site | AF1: Apple intercropped | AF2: Sour cherry and vegetables | AF3: Poplar intercropped | AF4: Wild cherry intercropped |
|---|---|---|---|---|
| Description | Apple trees (*Malus domestica*) planted in 15 two meters wide grassy strips, with a distance of 15 m between lines. Conventionally managed with a crop-rotation. The apples are used for juice. | Sour cherry (*Prunus cerasus*) and apple trees (*Malus domestica*) on 2 m wide grassy strips, intercropped with vegetables on 2.5 ha. The distance between the four tree-lines ranges from 15 to 50 m. | Three lines of poplars (*Populus tremula*) on 2 m wide grassy strips in a distance of 27 m. When there is ley in the rotation, the tree lines are sometimes fenced and the ley is grazed. | Three lines of wild cherry (*Prunus avium*), apple (*Malus domestica*) and pear (*Pyrus communis*) 24 m apart. |
| Coordinates ( ± 5 km) | 47°13′N, 8°09′E | 47°32′N, 7°50′E | 47°30′N, 7°52′E | 47°02′N, 7°01′E |
| Elevation (m a.s.l.) | 504 | 310 | 445 | 436 |
| Surface (ha) | 5.6 | 2.5 | 1.0 | 2.0 |
| Management | Conventional | Organic | Conventional | Conventional |
| Installation | 2007 | 2009 | 2011 | 2013 |
| Number of trees | 545 | 87 | 52 | 54 |
| Tree species | *Malus domestica* | *Prunus cerasus* and *Malus domestica* | *Populus tremula* | *Prunus avium, Malus domestica, Pyrus communis* |
| Monitored trees | 70 | 36 | 16 | 37 |
| Monitored species | *Malus domestica* | *Prunus cerasus* | *Populus tremula* | *Prunus avium* |
| Crop rotation | Strawberries, winter wheat, maize, fallow land | Vegetables | Ley, fodder crops | Winter wheat, maize, sugar beet, ley |
| Farm characteristics at moment of planting | Family-owned mixed farm of 50 ha with arable crops, vegetable & fruit production. | Family owned 15 ha farm with fruit and vegetable production. Occasional collaboration with sheep farmer for grazing. Partly integrated in socially supporting farming approach. | Family-owned mixed farm of 18 ha with arable crops and suckler cows. | The agroforestry system is managed by a farmer who provides this service to the corporate land owner. |

m a.s.l.: m above sea-level.

planted, but have a similar structure (high stem trees with about 50–100 trees per ha) and are all silvoarable intercropping agroforestry systems.

The initial status of the systems was recorded (parcel and individual trees located in Geographic Information System (GIS), description of soil profile) and a monitoring concept was established with the goal of regularly evaluating their performance by means of tree measurements and farmer questionnaires [35]. For the actual monitoring, we selected trees inside the agroforestry systems, avoiding the outer tree rows and the first and last trees of the rows to be monitored. The number of trees investigated was roughly in proportion to the number of trees of the respective agroforestry system.

### 2.2. Measuring and calculating tree biomass and carbon stock

Starting in 2014, the trees were measured every three years. The monitoring was limited to the above ground biomass. Diameter at breast height (DBH) was measured using a slide gauge and the location of the measurement was marked with a paint spray. Tree height was measured using triangulation with a “Vertex 5” tool. Exactly the same trees were measured in each sampling round.

Based on this field data collected, tree biomass and carbon content were calculated using the following equations:

$$B_{ab} = V_T \times D_T \tag{1}$$

with:

$$V_T = \left(\frac{DBH}{2}\right)^2 \times H \times \pi \tag{2}$$

$B_{ab}$: Aboveground biomass per tree (kg); $V_T$: Volume per tree (m$^3$); $D_T$: Wood density (kg m$^{-3}$); *DBH*: diameter at breast height, measured at 1.3 m above ground (m); *H*: Height (m).

Aboveground biomass ($B_{ab}$) was calculated by multiplying tree volume ($V_T$) and wood density ($D_T$) (Equation (1)). The wood density is species-specific and the following values were used for poplar, cherry, and apple: 410, 608, and 610 kg m$^{-3}$, respectively. Tree volume was obtained by multiplying the diameter at breast height measured at 1.3 m above the ground (DBH) and the tree height (H), assuming that the tree resembles a cylinder in its shape (Equation (2)). This is especially true for young trees [36].

The total biomass ($B_{total}$) of a tree is composed of aboveground (=trunk, crown) and belowground (=roots) biomass. $B_{total}$ (above- and belowground) was derived from the assumption that root-biomass represents 1/3 of the total biomass of a tree (values of the root-to-shoot ratio ranging from 0.24 to 0.43 for most temperate broadleaf species; [37]). Total biomass was thus obtained by multiplying the above ground biomass by the factor 1.5.

The total carbon stock ($C_{total}$) results from the multiplication of $B_{total}$ and the carbon content ($C_c$). The latter can vary between tree species, but also between individuals of the same species, depending on growth conditions and age of the trees. The synthesis of Thomas and Martin [38] suggests values between 43.4 and 55.6 % C-content in temperate/boreal woody species. Consequently, a fixed value of 0.5 was used in this study. The amount of carbon dioxide ($CO_2$) sequestered was then computed by multiplying $C_{total}$ by 3.67, based on the molecular weight of $CO_2$. Those calculations were applied to both the measured and the modelled trees.

In each monitoring year (2014, 2017, 2020, 2023), the number of dead and newly planted trees was recorded and counted. The cumulative mortality was then calculated by summing the mortality of each observation year. A cumulative mortality of 0.2 means i.e., that 20 % of the trees died and/or were replaced since tree planting.

### 2.3. Model calibration and modelling

The potential growth of the trees was simulated using the model Yield-SAFE [24,39,40]. AF2, AF3 and AF4 were modelled using the online dashboard [25,40]. For AF1 the original Excel-spreadsheet of the model [39] was used as the online dashboard does not contain default values for apple trees. The two model versions use the same algorithms, so the results are therefore comparable. As the sour cherry (*Prunus cerasus*) is also not available in the species list of Yield-SAFE, the closely-related wild cherry (*Prunus avium*) was used to simulate the data in AF2 with the dashboard version.

The planting year was used as start for the modelling and the values of the aboveground standing biomass were extrapolated separately for each of the four monitoring years (2014, 2017, 2020, 2023), using the parameters listed in Table 2. The values of the soil type and depth were taken from the soil suitability map of Switzerland [41] and verified with

**Table 2**
Model-parameters for the four study-sites.

| Test site | AF1 | AF2 | AF3 | AF4 |
|---|---|---|---|---|
| Soil type | Medium | Medium | Medium | Medium |
| Soil depth (cm) | 85 | 80 | 60 | 60 |
| Density (trees $ha^{-1}$) | 97 | 35 | 52 | 27 |
| Modelled species | *Malus domestica* | *Prunus avium* | *Populus tremula* | *Prunus avium* |
| Model version | Excel-table | Online | Online | Online |
| Other parameters | Default | Default | Default | Default |

AF1: Apple intercropped; AF2: Sour cherry and vegetables; AF3: Poplar intercropped; AF4: Wild cherry intercropped.

the initial description of the soil profile. Since Yield-SAFE does not account for mortality, the same analysis was repeated for a dataset where dead or newly planted trees have been excluded.

The initial default input values for poplar came from the UK, nor was the sour cherry variety included. We therefore (re)calibrated the model for these two species under Swiss conditions. For this purpose, local tree measurement data on poplar from forests [42] and sour cherry from orchards [43] were used to (re)calibrate the tree parameter of the model (Table S1). Climate data were derived using the Clipick-tool [40]. The model was re-run on the original Excel-spreadsheet with the adjusted inputs.

The measured trees represent a subset of the total number of trees per hectare. Therefore, we used a bootstrapping approach to upscale the results to the size of a hectare and to the entire plot that had been converted to an agroforestry plantation [44]. The collected tree data were resampled to match the actual number of trees per hectare at each site. This procedure was repeated 10,000 times. Based on the resulting distribution of the value of sequestered $CO_{2eq}$ per hectare, the mean and 95 % confidence interval were calculated for every site and monitoring year using the functions *mean* and *quantile* (0.025, 0.975). All analyses were performed using R (version 4.2.3; RStudio IDE) [45] and all figures were created with the package ggplot2 [46].

### 2.4. Questionnaires

A questionnaire was developed to record farmers' expectations and experiences with respect to (i) eight environmental services (security of supply, soil and groundwater protection, climate adaptation and mitigation, shade for livestock, species diversity, landscape scenery), (ii) profitability (profitable business, attractive subsidies) and (iii) undesirable effects (light, water, nutrient and root competition, pest pressure, yield reduction) from their agroforestry planting. The farmers could rank the indicators from 1 (totally disagree) to 6 (totally agree). In addition, they could add additional criteria they thought relevant. The interviews were made in person in 2011, 2015 and 2024 with the owners of AF1, AF2 and AF3. The farmer managing AF4 was not included because the agroforestry system was not a farmer led project but was initiated by the cooperate landowner.

## 3. Results

### 3.1. Measured tree growth and carbon storage

The average values of the tree height, the DBH, the aboveground biomass and the total amount of $CO_{2eq}$ stored are reported in Table 3. For apples and wild cherries, the tree growth measurements could be compared to existing growth tables [47,48], showing very similar growth patterns (Fig. 2).

Fig. 3 shows a comparison of the tree growth in the four systems under investigation. It should be noted that the systems consist of different tree-species and that they were planted in different years, which is why at the onset of the monitoring, the four systems had been in place for a different number of years. Therefore, a direct comparison between tree-growth in the different systems is not possible. Continuous growth was recorded on all plots, with the poplars in AF3 growing particularly quickly and approaching an exponential growth (up to 14 m in 13 years), whereas the sour cherries in AF2 and apples in AF1 grew slowly. The wild cherries in AF4 showed a linear and constant growth over the 10 monitoring-years and reached higher values than the sour cherries in AF2 despite the younger age of the system.

Zero values of the minimum values are due to tree mortality. $CO_{2\text{-equivalents}}$ are calculated based on the total tree-biomass (aboveground and belowground). AF1: Apple intercropped; AF2: Sour cherry and vegetables; AF3: Poplar intercropped; AF4: Wild cherry intercropped.

The total $CO_{2eq}$ stock during the study period ranged from 3562 kg $CO_{2eq}$ $ha^{-1}$ (8905 kg for the whole system) in AF2 and 4189 kg $CO_{2eq}$ $ha^{-1}$ (8378 kg for the whole system) in AF4 up to 11,885 kg $CO_{2eq}$ $ha^{-1}$ (11,885 kg for the whole system) in AF3 and 13,628 kg $CO_{2eq}$ $ha^{-1}$ (76,316 kg $CO_{2eq}$ for the whole system) in AF1 (Table 3). In total the four systems stored 105 tons of $CO_{2eq}$ since their planting, this is the equivalent of around 38,000 L of gasoline burned [49].

The average increase of $CO_{2eq}$ stock per year and hectare was 0.8 tons. If we only consider the latest period between 2020 and 2023, the average value raises to 1.4 t $CO_{2eq}$ $ha^{-1}$ $yr^{-1}$ and the individual values to 2.5 t $CO_{2eq}$ $ha^{-1}$ $yr^{-1}$ (AF1), 0.6 t $CO_{2eq}$ $ha^{-1}$ $yr^{-1}$ (AF2), 2.3 t $CO_{2eq}$ $ha^{-1}$ $yr^{-1}$ (AF3), 0.4 t $CO_{2eq}$ $ha^{-1}$ $yr^{-1}$ (AF4), which thus promises significantly higher sequestration rates for the future.

**Table 3**
Summary of the parameters measured, of aboveground biomass and of carbon storage in the four monitoring years for the four agroforestry systems.

| Site | Year | Tree-age (years) | Diameter at breast height (cm) | | | Height (cm) | | | Aboveground biomass (kg $tree^{-1}$) | | | $CO_{2eq}$ (kg $tree^{-1}$) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Min | Mean | Max | Min | Mean | Max | Min | Mean | Max | Min | Mean | Max |
| AF1 | 2014 | 8 | 1.97 | 5.06 | 8.12 | 185 | 313 | 405 | 0.37 | 4.26 | 12.78 | 1.01 | 11.51 | 34.52 |
| | 2017 | 11 | 0.00 | 8.26 | 12.60 | 0 | 374 | 570 | 0.00 | 14.69 | 43.35 | 0.00 | 39.65 | 117.06 |
| | 2020 | 14 | 0.00 | 10.94 | 16.00 | 0 | 346 | 490 | 0.00 | 23.76 | 57.64 | 0.00 | 64.14 | 155.64 |
| | 2023 | 17 | 1.59 | 14.16 | 19.93 | 180 | 485 | 610 | 0.22 | 52.03 | 110.18 | 0.59 | 140.48 | 297.49 |
| AF2 | 2014 | 6 | 0.00 | 3.96 | 5.67 | 0 | 283 | 360 | 0.00 | 2.51 | 5.44 | 0.00 | 6.77 | 14.69 |
| | 2017 | 9 | 0.00 | 6.26 | 8.60 | 0 | 371 | 490 | 0.00 | 7.88 | 16.95 | 0.00 | 21.28 | 45.77 |
| | 2020 | 12 | 2.50 | 9.11 | 11.50 | 290 | 416 | 550 | 0.87 | 17.68 | 30.94 | 2.34 | 47.74 | 83.55 |
| | 2023 | 15 | 7.60 | 12.07 | 16.20 | 380 | 506 | 690 | 11.61 | 37.71 | 76.74 | 31.36 | 101.83 | 207.21 |
| AF3 | 2014 | 4 | 0.00 | 2.77 | 4.52 | 0 | 281 | 450 | 0.00 | 1.16 | 2.96 | 0.00 | 3.14 | 7.99 |
| | 2017 | 7 | 0.00 | 5.95 | 11.50 | 0 | 482 | 820 | 0.00 | 10.28 | 32.79 | 0.00 | 27.75 | 88.54 |
| | 2020 | 10 | 1.30 | 8.99 | 18.10 | 250 | 805 | 1680 | 0.14 | 34.90 | 121.32 | 0.37 | 94.22 | 327.56 |
| | 2023 | 13 | 0.00 | 11.74 | 26.00 | 0 | 786 | 1460 | 0.00 | 84.72 | 317.81 | 0.00 | 228.74 | 858.10 |
| AF4 | 2014 | 2 | 2.32 | 3.40 | 5.09 | 300 | 344 | 380 | 0.84 | 1.99 | 4.58 | 2.26 | 5.36 | 12.37 |
| | 2017 | 5 | 3.90 | 7.31 | 10.70 | 330 | 519 | 710 | 2.61 | 14.81 | 33.90 | 7.06 | 40.00 | 91.52 |
| | 2020 | 8 | 7.40 | 10.59 | 13.70 | 490 | 677 | 940 | 12.81 | 38.55 | 78.87 | 34.60 | 104.10 | 212.95 |
| | 2023 | 11 | 2.55 | 13.25 | 19.74 | 260 | 566 | 830 | 0.81 | 56.91 | 154.37 | 2.17 | 153.65 | 416.79 |

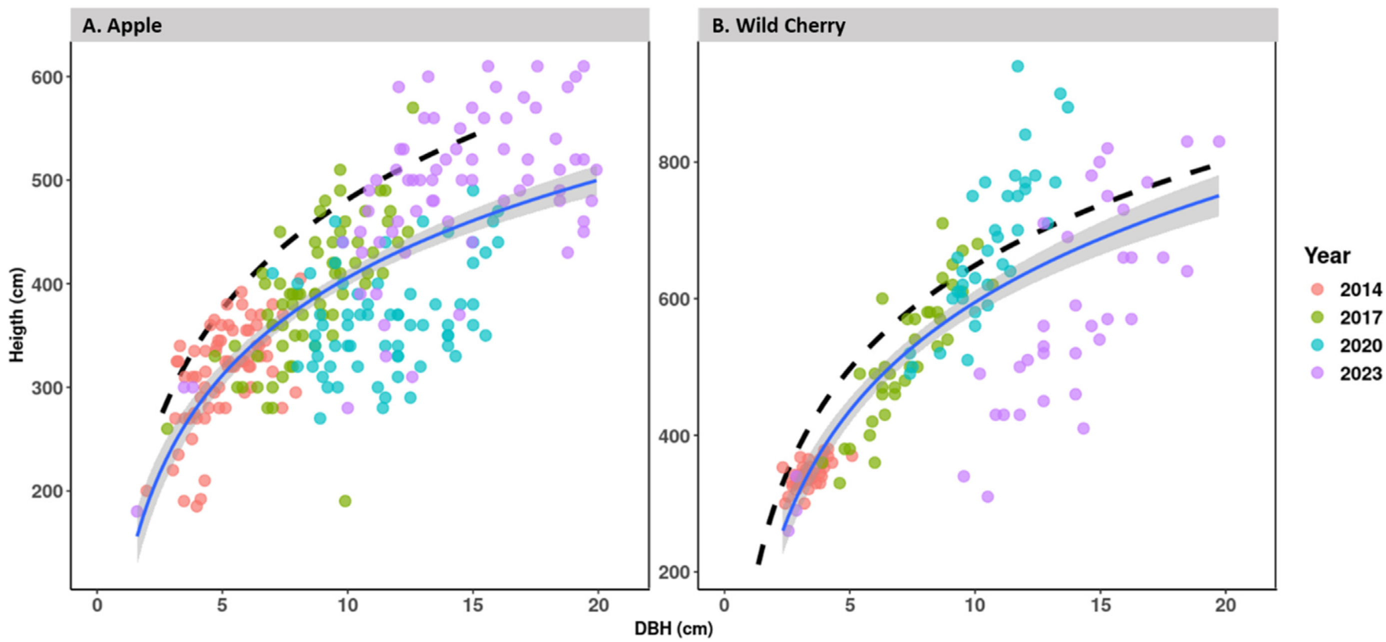


**Fig. 2.** Growing curves of apples in AF1 (A) and of wild cherries in AF4 (B). The different colours represent the four monitoring years and the blue lines the fitted relationships between DBH (diameter at breast height) and height. The dashed black lines represent the relationships between DBH and height extrapolated from Ref. [47] for apples and [48] for wild cherries.

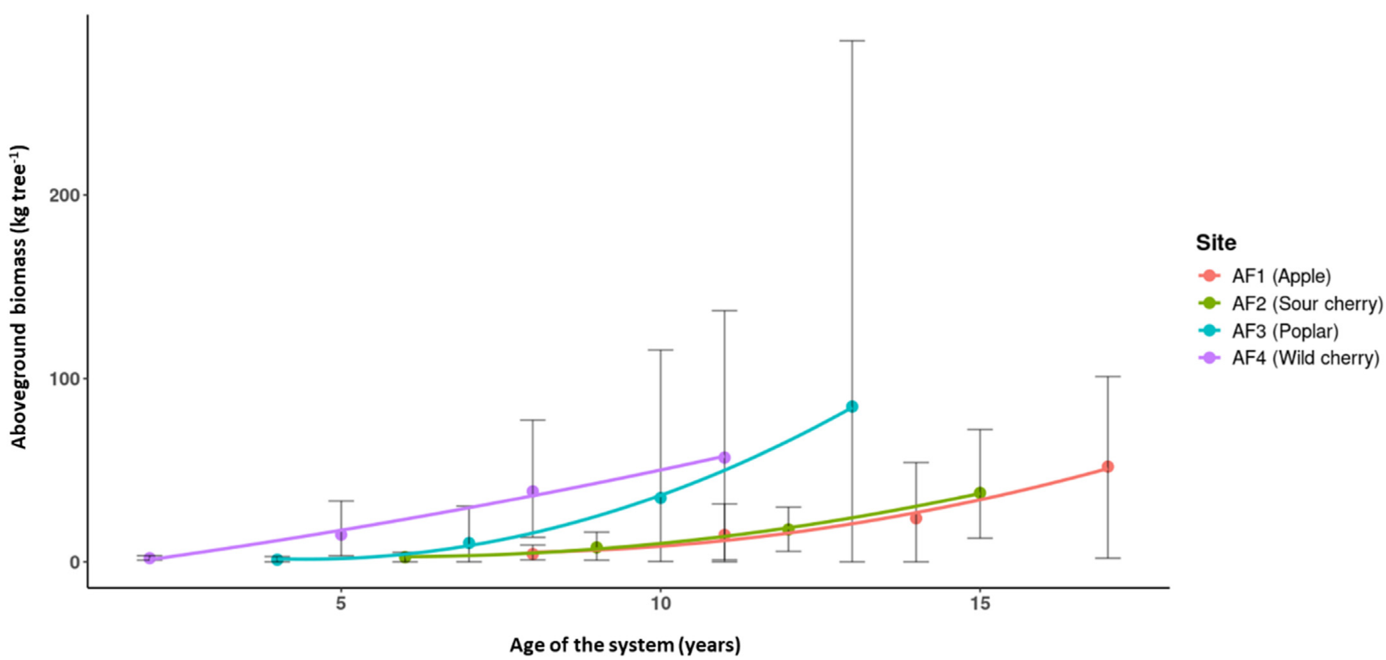


**Fig. 3.** Tree growth (aboveground biomass) in four agroforestry systems. As they were planted in different years, the lines do not overlap. The curves start at the first measuring year, between two and eight years after planting (Table 3). The error bars represent the 95 % confidence interval of the data. AF1: Apple intercropped; AF2: Sour cherry and vegetables; AF3: Poplar intercropped; AF4: Wild cherry intercropped.

### 3.2. Mortality

Table 4 represents the mortality data for each site and monitoring year. The values ranged from 0 to 25 % for the annual mortality and from 8 to 69 % for the cumulative mortality. In AF3 (poplars) the highest mortality was found: almost 50 % of the measured trees died and were replanted during the ten years of observation. However, cumulative mortality was up to 70 % as some trees died again after replanting. On the other hand, in AF4 (wild cherries) and in AF2 (sour cherries) only 8 % of the trees died during the period of observation.

### 3.3. Measured versus modelled values

The measured values of aboveground biomass were compared to the default modelled values of Yield-SAFE (Fig. 4). The matches between the default model and reality were different depending on the site and on the tree species. There was a good agreement between the two datasets in AF1 (apples) and in AF4 (wild cherries), the simulated values in AF4 and in AF1 lying within the 95 % confidence interval of the measured ones. For AF2 (sour cherries) and AF3 (poplars), the default Yield-SAFE model predicted values were too high. Even the tallest and largest trees of both

**Table 4**
Values of mortality and cumulative mortality for the four study sites and the four monitoring years.

| Site | Year | Mortality (%) | Cumulated mortality (%) |
|---|---|---|---|
| AF1 | 2014 | 0 | 16 |
| | 2017 | 6 | |
| | 2020 | 6 | |
| | 2023 | 4 | |
| AF2 | 2014 | 6 | 8 |
| | 2017 | 3 | |
| | 2020 | 0 | |
| | 2023 | 0 | |
| AF3 | 2014 | 19 | 69 |
| | 2017 | 19 | |
| | 2020 | 6 | |
| | 2023 | 25 | |
| AF4 | 2014 | 0 | 8 |
| | 2017 | 0 | |
| | 2020 | 0 | |
| | 2023 | 8 | |

AF1: Apple intercropped; AF2: Sour cherry and vegetables; AF3: Poplar intercropped; AF4: Wild cherry intercropped.

sites deviated greatly from the simulated ones (350 kg for AF3, 194 kg for AF2).

In a second step, we reran the model with the locally adjusted model parameters for AF2 and AF3. These new predicted values were much closer to those measured. For example, for AF3 the model's predictions were very similar to the median of the measurements. However, for AF2 (sour cherries), the model still predicted values that were above the measurements, although the gap was much smaller than with the uncalibrated model.

A comparison between the simulation with Yield-SAFE and the measured data, but excluding dead or replaced trees, was performed (Fig. S1). The difference between the values was smaller, but still present and in the same range as with all trees.

### 3.4. Farmers' experiences

The farmers' rating of the eight environmental services was cautiously optimistic, with the farmer of AF2 being more positive than the other two (Fig. 5). Their evaluation differed slightly between the three surveys, with no clear trend towards a decrease or an increase. "Species diversity" was the one service that was consistently rated with the maximum points 5 or 6 by all farmers. All other services were also rated 3 or higher by all farmers, with one exception (landscape scenery by the AF3 farmer in the first survey after planting). "Shade for livestock" was not applicable for the AF1 farm (no livestock); for the AF2 farm it only became relevant in 2015 for a short period of collaboration with a sheep farmer. Farmers were also generally satisfied with the profitability of their agroforestry plantations. The business profitability was rated 4 or higher by all farmers, except for one farmer in one year. Local product marketing was seen as an additional asset by the AF2 farmer. Climate adaptation and mitigation were valued moderate to high; no trend could be detected over the years.

Among the five undesirable effects listed in the questionnaire, implications by light, water, nutrient and root competition and yield reduction due to leaf fall were low to moderate. Increased pest pressure, however, was an issue in all three plantings, as well as mechanical labour and labour in general.

## 4. Discussion

The collection and publication of measurement data from temperate agroforestry systems and their consideration in modelling predictions are

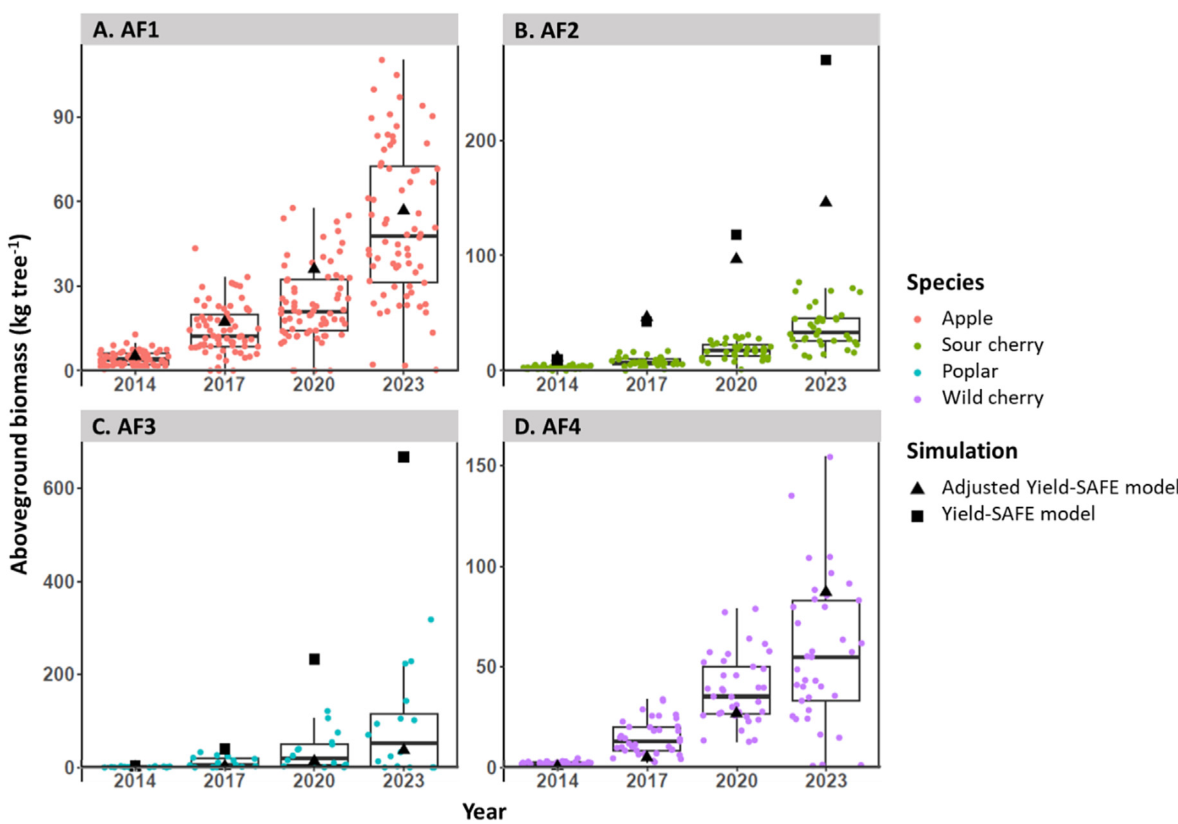


**Fig. 4.** Measured (points, boxplots) and modelled (triangles, squares) values of the aboveground tree biomass (kg tree$^{-1}$) for the four study sites and the four monitoring periods. The black squares represent the results of the simulation using Yield-SAFE model with default settings, the black triangles black squares the modelling with the locally adjusted Yield-SAFE model (only for AF2 and AF3). A) AF1: Apple intercropped; B) AF2: Sour cherry and vegetables; C) AF3: Poplar intercropped; D) AF4: Wild cherry intercropped.

Totally disagree
Totally agree

| | AF1 2011 | AF1 2015 | AF1 2024 | AF2 2011 | AF2 2014 | AF2 2024 | AF3 2011 | AF3 2015 | AF3 2024 |
|---|---|---|---|---|---|---|---|---|---|
| **Environmental services** | **3.7** | **5.0** | **4.0** | **6.0** | **5.5** | **5.3** | **4.4** | **5.1** | **4.6** |
| Security of supply | 4 | 5 | 3 | 6 | 6 | 6 | 5 | 1 | 2 |
| Soil protection | 3 | 4 | 4 | 6 | 6 | 6 | 5 | 6 | 5 |
| Groundwater protection | 3 | 6 | 4 | 6 | 5 | 6 | 5 | 6 | 5 |
| Climate adaptation | 3 | 5 | 4 | 6 | 5 | 5 | 4 | 6 | 4 |
| Climate mitigation | 3 | 4 | 3 | 6 | 6 | 6 | 5 | 6 | 5 |
| Shade for livestock | n.a. | n.a. | n.a. | n.a. | 4 | 1 | 4 | 6 | 6 |
| Species diversity | 5 | | 5 | 6 | 6 | 6 | 5 | 6 | 6 |
| Landscape scenery | 5 | 6 | 5 | 6 | 6 | 6 | 2 | 4 | 4 |
| ***Additional positive points*** | | | | | | | | | |
| Attractive for recreation | | 6 | 6 | | | | | | |
| Maintains cultural landscape | | | 5 | | | | | | |
| Promotion of natural enemies | | | | 6 | 6 | | | | |
| It's fun work | | | | | 6 | 6 | | | |
| Ecological improvement | | | | | | | 6 | 6 | |
| N & P loss reduction | | | | | | | | 6 | |
| **Profitability** | **5.0** | **4.0** | **4.5** | **5.0** | **4.5** | **5.5** | **5.5** | **4.0** | **4.5** |
| Profitable business | 4 | 2 | 4 | 5 | 4 | 5 | 6 | 4 | 4 |
| Attractive subsidies | 6 | 6 | 5 | 5 | 5 | 6 | 5 | 4 | 5 |
| ***Additional positive points*** | | | | | | | | | |
| Local product marketing | | | | 6 | 6 | | | | |
| **Undesirable effects** | **3.2** | **2.2** | **2.8** | **1.8** | **2.2** | **2** | **2** | **1.4** | **3.2** |
| Light competition | 3 | 2 | 3 | 1 | 1 | 1 | 1 | 1 | 3 |
| Water and nutrient competition | 3 | 1 | 2 | 1 | 1 | 1 | 2 | 1 | 3 |
| Root competition | 3 | 1 | 2 | 1 | 1 | 1 | 2 | 1 | 4 |
| Increased pest pressure | 5 | 6 | 5 | 5 | 5 | 5 | 4 | 3 | 4 |
| Yield reduction due to leaf fall | 2 | 1 | 2 | 1 | 3 | 2 | 1 | 1 | 2 |
| ***Additional negative points*** | | | | | | | | | |
| Mechanical labour impeded | 4 | 4 | 2 | 5 | 4 | 2 | | 2 | 5 |
| More labour | | | 5 | | | | 6 | | |
| Biodiversity subsidy requirements | | | 5 | | | | | | |
| Complex organization | | | | | | 6 | | | |
| Yield loss in tree strip | | | | | | | 5 | 3 | |

**Fig. 5.** Farmers' rating of ecosystem services, profitability and undesirable effects provided by their agroforestry systems between 2011 and 2024. The rating ranged from “1 – Totally disagree” (red) to “6 – Totally agree” (blue). AF1: Apple intercropped; AF2: Sour cherry and vegetables; AF3: Poplar intercropped. n.a: not applicable.

in high demand and important for practice, science, and policy. Also, while numerous pioneer farmers have several years of experience by now with their individual agroforestry systems, this knowledge is hardly ever shared. Our study can contribute to an improvement of the (precarious) database of empirical agroforestry data, but it also comes with limitations. In the following sections, we discuss both the limitations and the implications of our results.

### 4.1. Limitation of the study

We are aware that the study with only four different agroforestry systems has a limited sample size, which reduces the (general) significance. Also, only a sub-sample of the trees were actually measured. Although the systems are almost the same age, they were not planted in the same year. As for young systems, this can be relevant, the actual year of planting was accounted for in the modelling exercise to make the analysis consistent (Fig. 3). Different numbers of trees per hectare or different tree species would produce different results, as Crous-Duran et al. [50] and Sereke et al. [51] present in their modelling exercises. Different locations and management also have a big impact on the performance of the individual agroforestry system [52]. In addition, the monitoring only covers the "juvenile" phase of the agroforestry systems and the conclusions drawn are thus only preliminary.

### 4.2. Impact

For this monitoring study, we had deliberately chosen four sites with different tree species and tree densities to cover the variety of systems implemented by pioneer farmers. Consequently, the carbon storage varied by a factor three between the four sites, being lowest in AF2 (sour cherry, 35 trees per hectare) and highest in AF1 (apple, 97 trees per hectare). AF3 and AF4 were planted with faster growing tree species (poplar, wild cherry), but tree densities were lower (52 and 27 trees per hectare, respectively) than in AF1 and AF3 was affected by increased tree mortality in the first years after planting.

When comparing our measurements to existing datasets for the same species, apples in AF1 (Fig. 2, A) showed very similar growing patterns, in the shape of the growing curve and in the ratio between DBH and height, as the results presented by Gerhold [47], Johnson and Gerhold [53] and Troxel [54].

The growth of wild cherries in AF4 (ratio DBH-height) was very similar to the findings of Schindler et al. [48] for a similar context (species, temperate region, fruit production). It is worth highlighting (Fig. 2, B) that the height of many trees has decreased between 2020 and 2023. This is probably due to the pruning regime, which reduced the overall height of the crown.

The comparison between the poplars in AF3 and the ones in the silvoarable experiment in UK [55] showed that the growth was much slower in our study site. However, the ratios between DBH and height in a 7-year-old system were comparable, indicating that the trees in our study followed a similar growing curve, but were smaller (mean poplar tree in AF3 with 5.9 cm DBH and 4.8 m height versus mean poplar tree in England with 16 cm DBH and 10 m height). In the UK experiment, fast growing hybrid-poplars varieties ("Trichobel", "Gibecq", "Beaupré" and "Robusta") were planted [55], which grow much faster than the common *Populus tremula* used in the study-site of AF3 [56]. To our knowledge there are not any growth data of sour cherry in agroforestry systems, not allowing any comparison with AF2, but underlining the need of more measurements in this field.

A point which is often overlooked in (agroforestry) monitoring systems is the mortality of individual trees due to damage, pest or diseases. Studies in urban areas have shown the importance of reporting tree mortality to understand its extent and causes [57]. In the four monitored systems, mortality was highly variable, ranging from 8 to 69 % and taking place especially in the first years after planting. The main cause for mortality, especially for the fruit trees, were voles feeding on the tree roots (see also Fig. 5). In some instances, the trees were also damaged unintentionally by agricultural machinery. These values confirm that mortality can have an important effect and that the replacement of trees is a factor to be considered when planning the investments costs for an agroforestry system.

#### 4.2.1. Comparison between measured and modelled values

In comparison to previous modelling exercises (e.g., Ref. [51]), our study has the advantage that the model outcomes can be validated with real data. This exercise shows that, at two of four locations (AF1, AF4), the (default) values of the model already matched the measured data well. The expected growth as modelled by the default Yield-SAFE (for hybrid-poplars varieties) was not reliable for our AF3 system with *Populus tremula*. However, the model could easily be adapted to the local conditions and varieties based on measured poplar trees in Switzerland, which resulted in a very good fit to the tree growing curve as observed in the agroforestry system. This means that for three out of four sites (AF1, AF3 and AF4) the modelled and measured data match well, indicating that for these cases the model can be used as a reliable planning tool for similar contexts (silvoarable agroforestry with wild cherries, poplars or apples).

On the other hand, the simulated data mismatched against the measurements for the remaining site (AF2). In this case, not even the largest trees were in the same range as the modelled data, indicating that the default model did either not fit this purpose or was substantially overestimated (Fig. 4). Furthermore, we did not find any datasets about the long-term growth of *Prunus cerasus* (AF2). To close this gap, we used field data from traditional Swiss cherry orchards consisting of mixed cherry varieties. Unfortunately, even after (re)calibrating the model (based on the mixed dataset), the sampled AF2 trees did not reach the model outcomes.

The main reason for the discrepancy could be that wild cherries (*Prunus avium,* default Yield-SAFE) or a mix of cherry varieties (adjusted Yield-SAFE) were used to simulate sour cherries (*Prunus cerasus*). Despite the fact that the two species are closely related, the simulation did not work correctly, since it is known that *Prunus cerasus* grows less (up to 10 m tree height) than *Prunus avium* (up to 25 m) [58]. We observed that the growing pattern of the sour cherry trees was very similar to that of *Malus domestica* in AF1 (Fig. 3). Since *Malus domestica* and *Prunus cerasus* belong to the same family (*Rosaceae*), grow in a similar context (silvoarable agroforestry) and pursue the same agronomic goal of fruit production, the data for *Prunus cerasus* could be considered plausible, indicating that the function of the trees (fruit production instead of wood production) is more important than the phylogenetic distance. However, we again see the need to measure more field trees in order to gradually close these knowledge gaps.

While the Yield-SAFE model is able to account for tree species, management, location, etc., tree mortality is one of the factors that has not been accounted for as yet. The model assumes that all trees will survive and can be harvested. To test its effect on our results, we ran the model twice, once with all trees (Fig. 4) and a second time after excluding all dead or replaced trees from the analysis (Fig. S1). The discrepancy between the model and the measurements decreased in the second run. However, the differences were relatively small with overall mean standing biomass in 2023 of all four sites of 53.2 kg/tree with all trees and of 58.4 kg/tree without dead trees. It becomes clear that although tree mortality strongly affects agroforestry systems in the first few years, as long as the trees are replaced, this will hardly affect the final outcome.

Moreover, differences in management (e.g. pruning regime, fertilizers, irrigation) or (extreme) climate events (such as drought in 2022 or extreme precipitation in 2021) can also strongly impact tree growth and mortality [59]. These points are not (yet) included in the model, which uses average values for climate and management.

Finally, the Yield-SAFE model does not account for differences in individual tree performance. Agroforestry models often assume that all trees are identical, grow equally fast and equally well; and damage, pest infestation or death do not occur. This is in stark contrast to our observations in the field, where the maximum difference between the smallest and the tallest tree in each site in the last monitoring year was between 44 % and 97 % of biomass growth. We suggest that model(s) should account for the variability in tree growth. Measured field data as well as our results presented here can help to evaluate the uncertainty of model results.

#### 4.2.2. Potential for carbon storage

We have used $CO_{2eq}$, based on the measurement of tree biomass, to calculate carbon storage performance. It is expressed either as the total amount of carbon stored at the time the trees were measured (11–17 years after planting) or as an annual sequestration rate. Both values mirror the fact that we monitored just the first years of the life cycle of the agroforestry systems. Sereke et al. [51] modelled Swiss silvoarable agroforestry systems and predicted exponential tree growth to start only after 10–25 years after planting (for walnut and cherry, respectively). Carbon storage should therefore preferably be monitored over the total lifespan of an agroforestry system (e.g. Refs. [19,60]), which would also allow meaningful comparisons between systems.

The four study systems sequestered an average of 0.8 t $CO_{2eq}$ $ha^{-1}$ $yr^{-1}$ since their planting in the woody biomass. Even at this early stage, the agroforestry systems demonstrate their potential for carbon storage and as carbon farming measure, as highlighted by Kay et al. [13] and Kim et al. [61], who indicate a potential between 0.03 and 26 t $CO_{2eq}$ per hectare and year. In addition to storing carbon in the woody biomass, agroforestry systems can also increase the carbon content in the soil. Actually, in AF1, Seitz et al. [62] found an increase of 0.86 t $ha^{-1}$ $yr^{-1}$ already only seven years after planting. In addition, the tree lines of silvoarable agroforestry systems also reduce soil erosion [63] and thus conserve soil and organic matter on site.

An increase in the agricultural area dedicated to agroforestry can therefore contribute substantially to reach the climate goals defined in climate strategies, such as the Swiss Climate Strategy for Agriculture and Nutrition [64] or the European Climate Law [3,12]. Both strategies aim to achieve climate neutrality by 2050, but overlook the enormous potential of agroforestry to achieve these goals [65].

#### 4.2.3. Farmers' perception

Here, we report on interviews with only three farmers, which makes the findings anecdotal rather than representative. Still, we covered thirteen years, which allows to trace the evolution of their perception over the establishment phase of the agroforestry system.

The farmers' responses reflect their individual expectations of their respective agroforestry system. The first survey in 2011 captured the anticipation of positive effects to come, reflecting the potential benefits that motivated them to engage in an agroforestry planting. While AF4 was initiated by the company owning the land and wanting to improve its environmental accounting, AF1, AF2 and AF3 were initiated by three pioneer farmers whose common motivation was the desire to explore a new approach towards farming, which should be both, profitable and generating environmental benefits. It is noteworthy that they seem not to have been disappointed. There were some ups and downs regarding most criteria, but no clear trend – neither positive nor negative.

The positive evaluation of ecosystem services echoes the evaluation of other Swiss agroforestry farmers interviewed [30]. But also the stakeholders interviewed by Garcia de Jalón et al. [66] saw improved biodiversity, wildlife habitats and landscape aesthetics as the outstanding benefits of European agroforestry systems. The AF1 farmer remarked that as he turned older, he increasingly disliked "clean" landscapes and that even voles had their role in the food-web for birds of prey. The farmer who planted AF3 appreciated it that he could shape the landscape by planting trees. He gave the example of the colours of the trees' autumn leaves and he wanted to pass on "big, striking trees" to his children.

Farmers were positive also about the contribution of their agroforestry systems to climate mitigation and adaptation. Their evaluations were optimistic right from the start and remained so during the two following interviews.

The additional positive aspects brought up by the farmers reflect their personal situation: the organic farmer (AF2) is attentive to biological control and a pleasant working environment for the helpers and for himself; the municipality with ground water pollution (AF3) has expectations regarding water quality. One farmer particularly emphasized the local product marketing as an asset, an aspect that is frequently brought up by farmers, particularly in a peri-urban environment [67,68].

Farmers also perceived disadvantages of agroforestry, namely "Increased pest pressure" and "Additional labour". The first is mainly caused by voles, slugs, or birds. Regarding labour demand, it can be expected that the planting of trees generally increases the workload. We were surprised, however, that the tree lines are seen to impede mechanical labour. This is against the general expectation, that alley cropping with straight lines of trees does not interfere with mechanical labour [69].

## 5. Conclusions

Our study provides one of the first long-term socio-ecological datasets for modern temperate agroforestry and therefore contributes to a better understanding of these systems and their performance and perception by the farmers under different conditions. The study underlines the importance of providing empirical datasets on tree growth and farmers' experience in agroforestry systems to create a better data basis for research and practice. This will improve the performance of the models and thus ameliorate their predictions. Understanding farmer perceptions and expectations helps to make realistic recommendations and to avoid deceptions.

Our data can support further development of the Yield-SAFE model, which in our analysis has been shown to work well when calibrated to local conditions and tree species or varieties. However, our results and (re)calibration demonstrates the importance of local empirical datasets on tree-growth in order to make robust predictions to provide reliable planning tools. In addition, we would also recommend that the models show a range of possible outcomes (individual tree growing curves) rather than focusing on one single outcome (average tree growing curves). Too simplistic or overly optimistic models are not ideal for practitioners, landowners, or policy makers as they can raise expectations of outcomes that cannot be achieved in reality.

In conclusion, our dataset will facilitate practical application and policy strategies to reach the ambitious climate targets, and promote the overall implementation of agroforestry in the long run.

## CRediT authorship contribution statement

**Giotto Roberti:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Data curation. **Felix Herzog:** Writing – review & editing, Methodology, Conceptualization. **Mareike Jäger:** Writing – review & editing, Conceptualization. **Sonja Kay:** Writing – review & editing, Writing – original draft, Conceptualization.

## Data availability statement

The datasets generated during and/or analysed during the current study are available in the Zenodo repository, https://doi.org/10.5281/zenodo.14968106.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.csag.2025.100055.

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