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RESEARCH ARTICLE

# Carbon stocks and changes in biomass of Mediterranean woody crops over a six-year period in NE Spain

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**Abstract**

Carbon sequestration and storage in biomass is one of the most important measures to mitigate climate change. Mediterranean woody crops can sequestrate carbon in the biomass of their permanent structures for decades; however, very few studies have focused on an assessment of biomass and carbon sequestration in these types of crops. This study is the first to estimate above- and belowground biomass carbon stock in Mediterranean woody crops through a bottom-up approach in the NE Iberian Peninsula in 2013. Moreover, this is the first time that an assessment of the annual changes in carbon stock in the study area over a six-year period is presented. For this purpose, eight crop- and site-specific equations relating biomass or biometric variables to crop age were calculated. Most of the data were our own measurements, but unpublished data supplied from other authors as well as data from literature were also considered. Census of Agriculture data was used to scale results from individual data up to the municipality level at the regional scale. Results show that in woody cropland in NE Spain the total biomass carbon stock in 2013 was 5.48 Tg C, with an average value of 16.44 ± 0.18 Mg C ha$^{-1}$. Between 2013 and 2019, although there was a 2.8% mean annual decrease in the area covered by woody crops, the carbon stock in the biomass of these crops increased annually by 3.8% due to the growth of the remaining woody cropland. This new estimation of carbon stocks may contribute to better understand carbon balances and serve as a baseline to global inventories. It may also serve to assess and manage carbon storage as an ecosystem service provided by Mediterranean woody cropland for mitigating climate change and, in combination with adaptive strategies, for supporting a productive and resilient agro-food system.

**Keywords** Climate change mitigation · Woody cropland · Agriculture · Allometric equations · Regional upscaling

## 1 Introduction

Climate change is clearly induced by the global increase in greenhouse gas (GHG) emissions, mainly carbon (C) compounds such as carbon dioxide or methane (IPCC 2014). Vegetation can capture carbon dioxide ($CO_2$) through photosynthesis and store it by transforming it into biomass (IPCC 2014).

In this respect, promoting carbon sequestration and storage in biomass and soils has become one of the most important mitigation measures in the fight against climate change. Therefore, reliable evaluation of C fixation in terrestrial sinks would be useful, in order to quantify their spatial and temporal variability, gain a better understanding of the carbon cycle and assist mitigation policies worldwide (Quiñones et al. 2013; Huffman et al. 2015). Moreover, although plants are able to capture atmospheric $CO_2$, their effectiveness as a C sink depends on residence times (Quiñones et al. 2013).

Forests have been widely recognized as the main C sink of terrestrial vegetation through sequestration of huge quantities of $CO_2$. However, in ecosystems that are water-limited and degraded due to climate change, such as those in the Mediterranean, water availability and disturbances could curb the increasing trend of forest as a carbon sink (Vayreda et al. 2012b). On the other hand, woody crops, particularly rainfed crops, could be considered a sustainable ecosystem based on their moderate C sink potential (when compared with forest) in the context of the Mediterranean area and future climate

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change scenarios, besides their great importance as a food source (MedECC 2020). Compared to herbaceous crops, woody crops have a significantly larger sequestration potential and can sequester C in their biomass for longer periods (Fig. 1). Many annual crops can fix large quantities of C, but their biomass usually decomposes rapidly and the rate and return of uptake are very fast (Liguori et al. 2009). Since biomass accumulated by these cover types in a single year is assumed to be equal to biomass losses from harvest and mortality for the same year, there is no net accumulation of carbon stock (Huffman et al. 2015). This knowledge is important, as managing woody crop systems could be a more feasible mitigation solution than pure afforestation or reforestation in many parts of the Mediterranean basin, given that woody crops also provide food, work, economic profit, and population maintenance, and they are closely linked with the landscape, history, and culture of the Mediterranean.

Biomass equations are crucial for understanding carbon stocks in forests and other terrestrial vegetation (Alvarez et al. 2012). These equations are the most widely used methodology in biomass estimation based on data from destructive (harvest) and non-destructive (biometric measures) methods (Vashum and Jayakumar 2012). Several biomass equations for forest above- and belowground biomass have been published since the beginning of the twenty-first century (Valentini et al. 2000; Chave et al. 2005; Montero and Ruiz-Peinado 2005; Djomo et al. 2011; Ruiz-Peinado et al. 2011; Alvarez et al. 2012; Herrero and Bravo 2012; Ruiz-Peinado Gertrudix et al. 2012; Vayreda et al. 2012a; Thurner et al. 2014; Gonzalez et al. 2015; Ruiz-Peinado et al. 2017).

To date, there have been fewer studies on the ability of woody crop biomass to act as a C sink compared with corresponding research on forests, and the contribution of croplands to global and national C balances is not fully understood. At present, there are only a few studies that assess biomass and carbon sequestration in woody crops focused on Mediterranean regions, and most of these have been made during the last decade. Almagro et al. (2010) estimated both above- and belowground biomass in an olive grove of SE Spain. Two key studies on citrus have been conducted in Mediterranean regions such as Eastern Spain (Iglesias et al. 2013; Quiñones et al. 2013). With respect to vines, some studies have been published about carbon stocks in California (Keightley 2011; Williams et al. 2011; Iglesias et al. 2013) and allometries in Spain (Miranda et al. 2017). Moreover, Montanaro et al. (2017) estimated the carbon budget in a Mediterranean peach orchard under different management practices in Italy and estimated lifetime C sequestration in the standing biomass of 14-year-old peach trees. A number of studies have estimated woody biomass on agricultural land in non-Mediterranean regions (Kumar et al. 2010; Kuyah et al. 2012a, 2012b; Kongsager et al. 2013; Kuyah et al. 2016; Ortiz-Ceballos et al. 2020; Asigbaase et al. 2021) and globally (Zomer et al. 2016; Spawn et al. 2020). There are fewer studies on changes in land use (LUC) and associated carbon sequestration potential (Padilla et al. 2010; Huffman et al. 2015). In general, despite growing interest in developing agro-environmental policies associated with climate change mitigation, studies of crop species of agricultural importance are scarce (Iglesias et al. 2013).

The importance of the mitigation-adaptation link has been highlighted by several authors (Kongsager et al. 2013; MedECC 2020). Understanding how woody crops act as a C sink would enhance this link in the Mediterranean basin due to their potential high-resilience if agricultural practices such as regenerative agriculture are performed (Luján Soto et al. 2021). In this context, there is a need to complete a first level assessment of woody crop biomass as a C sink for the Mediterranean area. Moreover, specific models should be developed for sites, crops, and typical culture practices carried out in order to move up through the tier methods established by the IPCC (IPCC 2006), gain in accuracy, and reduce

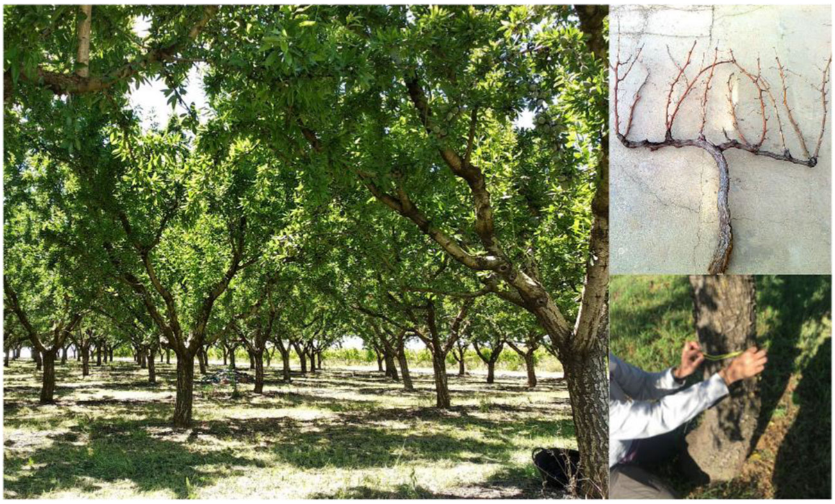

**Fig. 1** Left: A Mediterranean woody crop orchard (almond) in Gandesa (Catalonia). This image illustrates how woody crops can mitigate climate change by sequestering carbon in the biomass of their permanent structures for decades. Right: Destructive (top) and non-destructive (bottom) methods to estimate biomass in woody crops. Photographs by Eulalia Serra (left) and Inmaculada Funes (right), IRTA.

uncertainties in future assessments (Huffman et al. 2015). Research into allometric equations applicable to woody crops is important for accurate accounting of C stocks worldwide that could assist mitigation policies (Kuyah et al. 2012a), such as REDD+ (reducing emissions from deforestation, forest degradation and enhancement of forest C stocks), together with country policies and some compensatory policies and strategies developed from COP 21 and 22 (United Nations Climate Change Conference). Most traditional Mediterranean woody crops are rainfed crops or their productivity can be maximized under deficit irrigation, since they are usually resistant to high temperatures and droughts. Therefore, they may be an important element in increasing adaptive capacity to climate change and other pressures currently faced by the Mediterranean area, while potentially acting as C sinks.

This is the first study assessing above- and belowground biomass carbon stock of Mediterranean woody crops in the Iberian Peninsula and mean annual changes of stock over a six-year period. The primary aim of this study is to assess the potential of Mediterranean woody crops as a C sink with reference to literature data and destructive (Fig. 1 top right) and non-destructive methods (Fig. 1, bottom right) conducted for each woody crop as a function of crop age. The second aim is to estimate the total woody crop carbon stock in NE Spain by scaling up at the municipality level. The third and final aim is to assess carbon stock changes due to land use change in the study area over the period 2013–2019.

## 2 Material and methods

### 2.1 Study area and target woody crops

The study area consists of woody cropland in Catalonia (NE Iberian Peninsula). Catalonia presents Mediterranean climatic conditions characterized by mild winters and hot and dry summers, with mean temperature ranging from 0 to 17.3°C and annual precipitation from 1464 mm in the Pyrenees to 335 mm in the Ebro valley (Fig. 2).

According to SIGPAC (2013), 26% of the land in Catalonia (847,977 ha) is used for agricultural purposes and, more specifically, woody cropland accounts for 10.4% of the total land area (335,029 ha). Woody crops represent 40% of total agricultural land use, with most of these to be found in the south-western half of the region (Fig. 1). The principal woody crops are vines, olives, non-citrus fruit trees, and citrus. Vines represent 17% of the total area devoted to woody crops, olives 37%, fruit trees 26%, nuts 17%, and citrus fruits 3%. The most important rainfed woody crops are vines, olives, and nut trees, and their geographical distribution corresponds to areas with low annual precipitation and extreme temperatures. However, fruit tree orchards, considered as high-water consuming crops, are mainly located in the central valley, where annual precipitation is lowest (Funes et al. 2021). Woody crops in general and particularly rainfed woody crops such as vines, olives, and nut trees have strong territorial, historical, and cultural links with Mediterranean areas. In this respect, NE Spain is highly representative of the Mediterranean crop pattern. This study conducted a cropland classification of major Mediterranean woody crops in NE Spain, focusing on 5 classes: vines, olives, citrus, fruit orchards, and nuts.

### 2.2 Biomass and carbon stocks estimation in woody crops

#### 2.2.1 Estimation of above- and belowground biomass

Biomass growth functions (or other biometric variables, depending on the case) were fitted as a function of crop age for citrus, seed and stone fruits, nut trees, olive, and vine cropland classes from two data sources: literature and own or unpublished data from other authors, based on destructive or non-destructive methods.

In order to perform biomass estimations, we built growth curves for each type of woody crop. For this purpose, we determined aboveground biomass (measured or estimated dry matter biomass) or other biomass-related biometric variables as a function of crop age by using data collected and paired with age. Data were collected from different conditions (type of soil, agronomic practices, training system, cultivars, planting density, irrigated/rainfed, etc.) and different sources (literature, own field measurements, and unpublished field data from other authors). Biomass estimations for olives and nut trees had to be determined indirectly. First, data from the biometric parameters trunk diameter and trunk basal area were measured at 30 cm from the ground and collected from literature or personal communication. Next, growth curves were fitted to these datasets. Finally, conversion equations from literature were used to derive estimations of biomass.

Belowground biomass was mainly calculated for each type of woody crop by using root:shoot ratios from literature, or in other cases, it was estimated as a function of age by fitting specific growth curves for belowground biomass. Data obtained from literature were only selected from studies performed under field conditions, excluding laboratory and experimental greenhouse studies. Agronomic practices considered very different from typical practices in Spain and which have a direct impact on tree or vine architecture or on total biomass per hectare were also excluded. Higher or lower plant densities could have an impact on total biomass per hectare and the training system could be determinant in tree or vine architecture. For example, training system in vineyards could impact directly on trunk height, number of cordons, etc. which consequently impact on the biomass of permanent structures. The

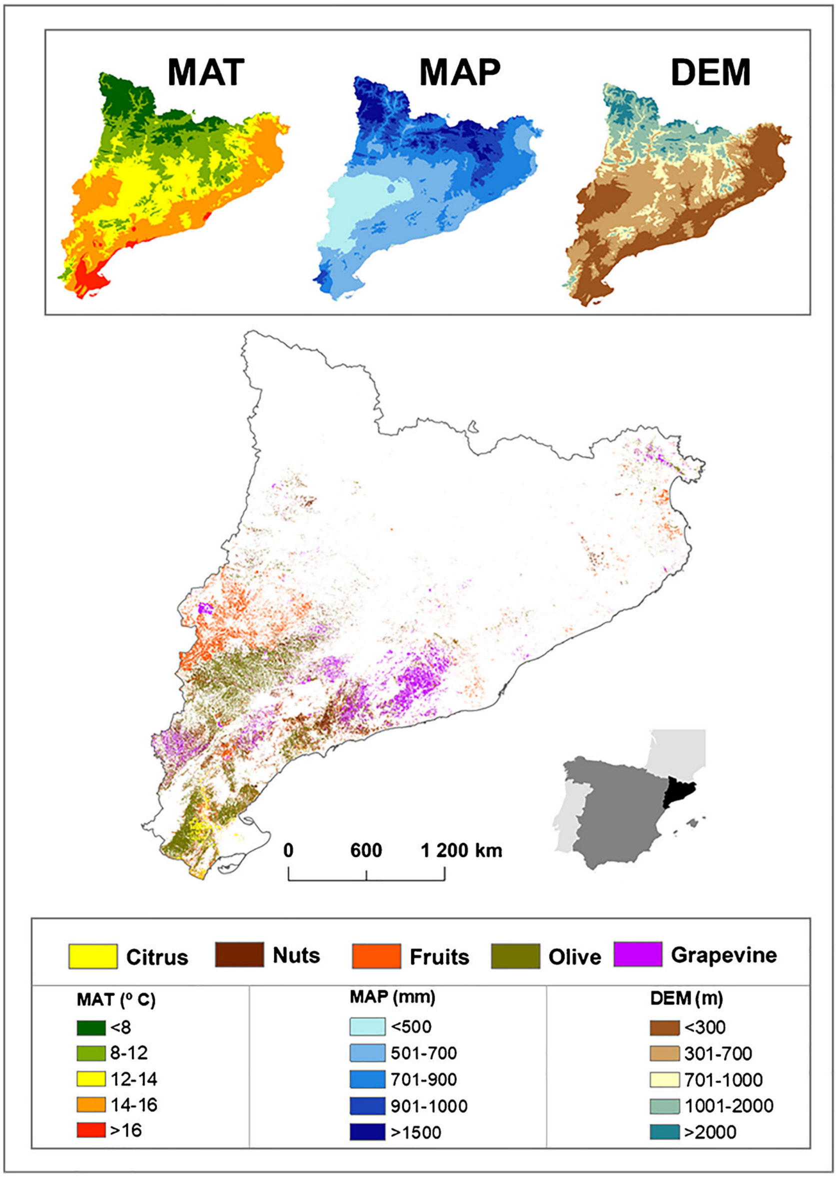

**Fig. 2** Study area (Catalonia, NE Spain): location, climatological information (MAP, mean annual precipitation, and MAT, mean annual temperature), topographical information (DEM, digital elevation model), and woody crop distribution.

bibliographic search was restricted to areas with Mediterranean conditions (Fig. A.1 and A.2. in Appendix 1).

**Grapevine** The grapevine dataset comprises biomass data from literature (Saayman and Huysteen 1980; Williams and Biscay 1991; Clingeleffer and Krake 1992; Mullins et al. 1992; Araujo et al. 1995; Williams 1996; Santesteban and Royo 2006; Keightley 2011; Santesteban et al. 2011a, 2011b; Williams et al. 2011; Escalona et al. 2012; Goward 2012; Santesteban et al. 2013), and biomass data from destructive and non-destructive methods. Some of these (from Barcelona, Spain) included destructive methods to measure belowground biomass. Detailed information relating to the vine dataset including sources, references, location, dataset size, and some agronomic culture traits can be found in supplementary information (Table B.1. in Appendix 2). Details about the non-destructive and destructive measurement procedure can be found in Appendix 3.

**Olive** Olive biomass data from destructive measures is difficult to find in literature because these measures are labor-intensive, expensive, and time-consuming. Due to the difficulties encountered when researching olive biomass data in a reasonable (appropriate) age range, the calculations were made by establishing a relationship between trunk basal area and crop age. Trunk basal area is a standard biometric variable and could be directly related with tree biomass, as is widely known in forest allometric relationships. Trunk basal area data (cm$^2$; at 30 cm from the ground) or other directly related biometric variables such as trunk basal diameter (cm; at 30 cm from the ground) were collected from literature (Aragues et al. 2005;

Almagro et al. 2010; Aragues et al. 2010; Bustan et al. 2011; Fernández et al. 2011a; Fernández et al. 2011b; Segal et al. 2011; Arnan et al. 2012; Gucci et al. 2012; Larbi et al. 2012; Mezghani et al. 2012; Nardino et al. 2013), measured or personally communicated by other authors. More details about data, measurements and data homogenization can be found in Appendix 3 and in Table B.2 of Appendix 2. To estimate aboveground biomass from trunk basal area, the equation drawn from the experiment performed in 18 young olive orchards published in Villalobos et al. (2006) was used. According to the literature reviewed (Appendix 3) and following Nardino et al. (2013), it was assumed that olive root biomass of both young and old trees was 30% of the total accumulated by their aerial part.

**Fruit trees: seed and stone fruit** The fruit trees dataset comprises data from literature (Grossman and DeJong 1994; Caruso et al. 1999a; Caruso et al. 1999b; Caruso et al. 2001; Inglese et al. 2002; Sofo et al. 2005; Solari et al. 2006; Bravo et al. 2012; El-Jendoubi et al. 2013) and from destructive and non-destructive methods. The data only consider permanent structures excluding pruning material, leaves, and fruits. Two different equations were built from the dataset: seed fruit trees and stone fruit trees. The seed fruit trees equation was fitted with data from apple and pear trees, whereas the stone fruit trees equation was built with data from peach and nectarine trees. Detailed information relating to dataset sources, references, location, dataset size, and some agronomic culture traits for seed and stone fruit trees can be found in Table B.3 in Appendix 2. Information about non-destructive and destructive methods appears in Appendix 3. The root:shoot ratio for fruit trees was considered to be 0.30. This value is based on dry weight data published for apple trees (Panzacchi et al. 2012) and peach trees (Xiloyannis et al. 2007).

**Nut trees** As with olive biomass, in the case of nuts, the calculations were performed on the basis of a relationship between trunk diameter at 30–40 cm from the ground and crop age. Trunk diameter came from measurements of almond trees that were taken in different trials at IRTA facilities located in Lleida and Tarragona. Due to the difficulty in obtaining a specific allometry of trunk diameter-aboveground biomass for nuts, a general equation for forest tree species was used, namely the group “other Broadleaves” from Montero and Ruiz-Peinado (2005), based on the similar tree morphology between nut trees and forest species such as the chestnut, carob or European nettle tree. Detailed information relating to dataset sources, references, location, dataset size, and some agronomic culture traits for nut trees can be found in Table B.4 in Appendix 2.

**Citrus** The citrus biomass dataset only comprises data from literature, from two references in particular. Quiñones et al. (2013) showed aboveground and belowground biomass data from 2- to 14-year-old Navelina orange trees (*Citrus sinensis* L.) in Valencia (Eastern Spain), while Iglesias et al. (2013) showed aboveground and belowground biomass data from 2- to 14-year-old Clemenules trees (Citrus clementina Hort. ex Tan.) in Valencia (Eastern Spain). In contrast to the other woody crops studied, citrus fruit trees are evergreen, so leaves are taken into consideration in the aboveground biomass, excluding annual pruning.

### 2.2.2 From biomass to carbon stock

The C content of biomass dry matter used in the estimations was different for each woody crop class. Based on the literature reviewed (Appendix 3) and averaging values of C content in biomass for each woody crop class, we assumed an average C content in total biomass (boveground + belowground) of 48.4% for olives, 44% for vines, 46.9% for fruit trees and nut trees, and 44.8% for citrus. Propagation of uncertainty in C content values was also determined with bootstrap techniques (see section 2.2.4 below).

Based on growth curves, C stock values per crop type at individual level were computed, either directly (i.e., age→biomass→C stock) or indirectly (i.e., age→trunk basal area→biomass→C stock for olives, or age→trunk diameter→biomass→C stock for nut trees).

### 2.2.3 Upscaling carbon stocks: from the tree to the regional level

The total carbon stock from woody crops was integrated, scaling up from the tree to the regional scale (Catalonia, NE Spain) by using the official information available about the spatial distribution of crop culture traits (age, plant density, etc.). The upscaling was based on official or statistical information about plant density at the municipality level or age distribution around the territory in each type of woody crop (Table B.5 of Appendix 2). The availability of this official information at this level was a limiting factor for some of the woody crop classes studied (see Appendix 3 for more details about the data from official registries used in the upscaling procedure). The most updated official information available corresponded to the year 2013, which explains why the upscaling of carbon stocks was specifically built for the year 2013.

In the case of crop areas older than the oldest established in allometries, the same carbon stock was assigned. In other words, if it was necessary to estimate carbon stocks in a 20-year-old citrus orchard in Catalonia, carbon stocks corresponding to a 16-year-old orchard were assumed, the oldest age in the biomass-age function for citrus used in this study.

C stock per individual (kg C per individual) depending on age was multiplied by the plant density to estimate the carbon density (Mg C ha$^{-1}$). The total C stored was calculated at the municipality level multiplying by the area (ha) of each woody crop at a particular age and the plant density obtained from official registries. The distribution area for the different woody crop classes is based on SIGPAC (2013). The description and information about SIGPAC can be found in Appendix 3 in the details about scaling up performance.

To estimate average annual carbon sequestration values (Mg C ha$^{-1}$ year$^{-1}$) for each woody crop during its mean life, an estimation was made of the mean value of carbon stock differences between consecutive ages per individual. Finally, the mean value was multiplied by the representative plant density for each crop in the study area.

#### 2.2.4 Uncertainties in carbon stock estimations

Propagation of uncertainties in C stock estimation was computed with bootstrap methods (see e.g., Davison and Hinkley 1997). Samples were drawn randomly with replacement to calculate a bootstrap estimation of (a) the expected biomass, for citrus trees, seed fruit trees, stone fruit trees and vine; (b) trunk diameter, for nut trees; or (c) trunk basal area for olive trees. Then, for (a), the biomass-C stock conversion was carried out by multiplying those biomass values with samples of C content drawn randomly with replacement. For (b) and (c), a further step was required. Trunk diameter-biomass conversion in (b) was achieved by directly applying the Montero and Ruiz-Peinado (2005) equations. Trunk basal area-biomass conversion in (c), on the other hand, was accomplished by bootstrapping the datasets in Villalobos et al. (2006), regressing (to obtain a bootstrapped estimation of the trunk basal area-biomass relationship) and applying the results of the regression to the bootstrapped trunk basal area estimation. Finally, confidence intervals (CI) at the 95% level were determined as

$$CI = \left(C_{\mathrm{T}} + z_{\frac{\alpha}{2}} \cdot \sigma_{\mathrm{T}}, C_{\mathrm{T}} + z_{1-\alpha/2} \cdot \sigma_{\mathrm{T}}\right) \quad (1)$$

where $C_{\mathrm{T}}$ is expected total $C$ stock for a given crop and area, $\sigma_{\mathrm{T}}$ stands for the bootstrapped standard deviation, and $z_{\alpha/2}$ and $z_{1-\alpha/2}$ are the corresponding quantiles of the normal distribution (for $\alpha = 0.05$, $z_{\alpha/2}$ and $z_{1-\alpha/2}$ are approximately −1.96 and +1.96, respectively).

### 2.3 Carbon stock changes in woody crops (2013–2019)

#### 2.3.1 Land use changes

First, land use changes in Catalonia from 2013 to 2019 were assessed using SIGPAC. All the SIGPAC features for 2013 and 2019 were converted to raster (100 m pixel size), land uses were reclassified to 10 classes, and a land use transition matrix was calculated.

#### 2.3.2 Carbon stock changes

Carbon stocks for woody crops in 2019 were calculated using the same procedure for woody crops in 2013 described above in section 2.2.3. For the year 2019, the woody crops area from SIGPAC (2019) was used, making two assumptions: (i) crops grew for 6 years in the remaining areas and (ii) the new crop areas were 3 years old (half the time between the two maps). The upscaling was performed considering the same spatial distribution for ages (but adding 6 years) and plant density from 2013, as no updated information was available.

## 3 Results and discussion

### 3.1 Building biomass or biometric growth curves for biomass and carbon density estimation

Depending on data availability, eight growth curves for direct prediction of biomass (above- and belowground biomass) or indirect prediction through biometric parameters (trunk basal area or trunk diameter) are provided. Figure 3 presents all the fitted curves as a function of crop age for woody crops performed in the study. Details of the resulting growth curves, including formulas, coefficients and performance indices are shown in Table B.6 (Appendix 2).

The estimated biomass carbon stock at the individual level (kg C per tree or per vine) varies depending on age and crop type (Fig. A.3 in Appendix 1). The lowest biomass carbon stocks were found in vineyards where, for example, mature vines between 10 and 20 years of age showed aboveground biomass carbon stocks ranging from 1.09 to 1.95 kg C vine$^{-1}$ and belowground carbon stocks from 0.58 to 1.01 kg C vine$^{-1}$. Highest individual carbon stocks were estimated for olive aboveground ranging from 27.2 to 97.3 kg C tree$^{-1}$, for example, in the case of crop ages from 10 to 50 years.

The eight crop-specific equations performed directly or indirectly here estimate biomass of woody crops. The Intergovernmental Panel on Climate Change (IPCC) has classified the methodological approaches in three tiers, according to the quantity of information required and the degree of analytical complexity (IPCC 2006). The approach of our assessment could be defined as tier 2 since region-specific estimates of biomass stocks by major cropland types, and management systems were considered. Moreover, good performance indices were obtained for most of the fits generated here (Table B.6 in Appendix 2)

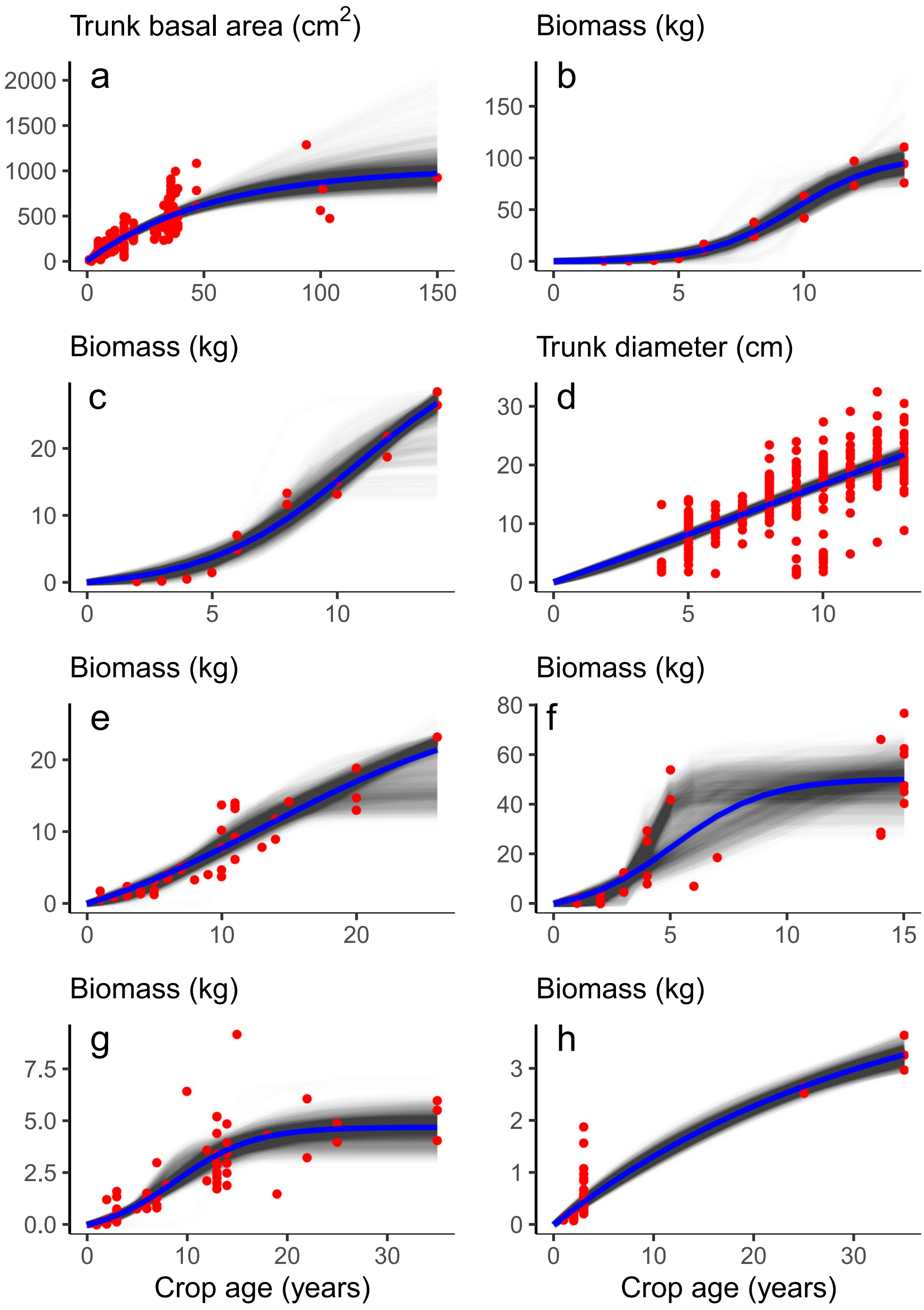

**Fig. 3** Fitted curves of biomass or biometrics variables (trunk basal area and trunk diameter) as a function of age (blue lines) to estimate above- or belowground biomass of permanent woody crop structures per individual (dry weight in kg per tree or per vine): **a** Olive trunk basal area; **b** citrus aboveground biomass; **c** citrus belowground biomass; **d** nuts trunk diameter; **e** Seed fruit trees aboveground biomass; **f** stone fruit trees aboveground biomass; **g** vine aboveground biomass; and **h** vine belowground biomass. Grey lines correspond to 1000 bootstrap simulations and black dots indicate actual observations.

## 3.2 Biomass carbon stock upscaling to the regional level

Average carbon density (above- and belowground) in permanent structures of woody crops in Catalonia for the year 2013 was 16.44 ± 0.18 Mg C ha$^{-1}$ (mean ± 95% confidence interval computed from the bootstrapped standard deviation). Average carbon densities for each woody crop type in Catalonia ranged from 6.40 ± 0.02 Mg C ha$^{-1}$ in vineyards to 27.40 ± 0.34 Mg C ha$^{-1}$ for nuts (Table 1). The total carbon stock in biomass of woody crops in Catalonia for 2013 was 5.48 Tg C (Table 1), mainly from olives (39.1%), nuts (27.9%), and fruit orchards (22.0%).

Spatial distribution of carbon density at the municipality level in 2013 is shown in Fig. 4a and ranges from 0.10 to 67.13 Mg C ha$^{-1}$. Values of less than 1 Mg C ha$^{-1}$ are distributed across several municipalities in the Pyrenees and pre-Pyrenees, corresponding to fruit orchards. Values ranging

**Table 1** Woody crop area (ha), average carbon density (Mg C ha$^{-1}$), uncertainty of estimations (upper and lower limits of 95% confidence interval) and total carbon stock (Tg C) of biomass in woody cropland in Catalonia. The proportion of each crop type to the total woody crop area (ha) and to total carbon stock (Tg C) is shown in brackets (%).

| Crops | Area (ha) | Average carbon density (Mg C ha$^{-1}$) | | | Total carbon stock (Tg C) |
|---|---|---|---|---|---|
| | | Mean value | Lower limit | Upper limit | |
| Citrus | 9346 (2.8%) | 25.95 | 25.77 | 26.13 | 0.24 (4.4%) |
| Nuts | 55,893 (16.8%) | 27.40 | 27.06 | 27.75 | 1.53 (27.9%) |
| Fruits | 87,134 (26.1%) | 13.86 | 13.70 | 14.01 | 1.21 (22.0%) |
| Olive | 125,441 (37.6%) | 17.09 | 16.87 | 17.31 | 2.14 (39.1%) |
| Grapevine | 55,612 (16.7%) | 6.40 | 6.38 | 6.42 | 0.36 (6.5%) |
| Total woody crops | 333,426 | 16.44 | 16.26 | 16.62 | 5.48 |

from 1 to 10 Mg C ha$^{-1}$ are mainly concentrated in the central pre-coastal area, corresponding to vineyards. The highest carbon densities (> 30 Mg C ha$^{-1}$) are concentrated in NE Pyrenees and NE and central pre-Pyrenees, represented by fruit trees, nuts, and olive orchards, and in SE Catalonia by nuts and olive groves. The spatial distribution of uncertainties is shown in Fig. 4b. Uncertainty is represented by standard deviation (Mg C ha$^{-1}$) and shows values throughout Catalonia ranging from 0.005 to 0.24 Mg C ha$^{-1}$. Areas with the lowest uncertainty values mainly correspond to fruit orchards in the pre-Pyrenees and the central valley, and to vineyards and nut orchards in southern Catalonia. The highest uncertainty values correspond to olive groves throughout the study area and adult fruit orchards in NE Pyrenees and pre-Pyrenees. Spatial distribution of carbon density (Mg C ha$^{-1}$) and uncertainty values for each woody crop can be found in Fig. A.4. of Appendix 1.

The IPCC tier 1 global estimate from Ruesch and Gibbs (2008) for above- and belowground biomass of agricultural land was 5 Mg C ha$^{-1}$ (Zomer et al. 2016). Our results show that existing woody cropland in Catalonia makes a greater contribution to the carbon pool than the IPCC tier 1 estimation. The total carbon estimate for woody cropland is more than twice as high for fruit orchards, more than three times higher for olive, and more than five times higher for citrus and nuts in comparison with the IPCC default value. Only the carbon density estimated here for vines (6.40 Mg C ha$^{-1}$) is close to the IPCC value.

Carbon density estimates in this study are totally in line with the few studies published to date that assess the sequestration potential of woody crops. Badalamenti et al. (2019) reported carbon stocks (aboveground biomass) of 6 Mg C ha$^{-1}$ in vineyards on a Mediterranean island (Italy). However, Williams et al. (2011) estimated 3 ± 0.48 Mg C ha$^{-1}$ for aboveground biomass of vineyards and Keightley (2011) 4.15 Mg C ha$^{-1}$ (134 Mg C in 32.3 ha) for total perennial vine biomass in California. These are higher values in comparison to our estimates, considering that these values correspond to vineyards up to 14 years of age and with lower plant densities (1500–2500 vines ha$^{-1}$; data not shown). California vineyards are mostly irrigated, and both the different training system and vineyard management are different. Higher values (from 5.72 to 7.23 Mg C ha$^{-1}$) were also reported by Brunori et al. (2016) in a 10-year-old vineyard plantation with 5600 vines ha$^{-1}$ in central Italy, due to higher plant density and the different training system. Very similar values were reported for citrus, with Iglesias et al. (2013) publishing values ranging from 55 to 66 kg C tree$^{-1}$ and 27.5–33.0 Mg C ha$^{-1}$ in a 12-year-old plantation with 500 trees ha$^{-1}$ in Eastern

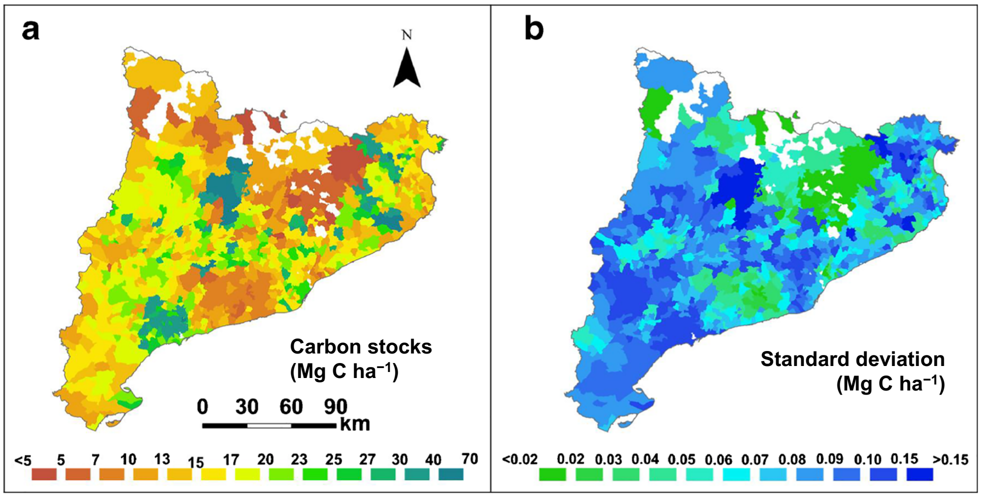

**Fig. 4** Spatial distribution of **a** average carbon density (Mg C ha$^{-1}$) in the biomass of total woody crops in Catalonia for the year 2013 and **b** uncertainty (standard deviation) of the estimations.

Spain, under similar agroclimatic conditions and agronomical management.

Higher aboveground biomass C stock potential was found for plantations in the tropics, such as palm oil, cocoa, orange, and rubber, with values of 45, 65, 76, and 214 Mg C ha$^{-1}$, respectively (Kongsager et al. 2013), due to the larger tree architecture and the climate associated with higher NPP. Furthermore, a mean value of 55.12 Mg C ha$^{-1}$ was reported for coffee agroecosystems in Mexico (Ortiz-Ceballos et al. 2020). At the global level, Zomer et al. (2016) reported 28 Mg C ha$^{-1}$ in 2000 and 29 Mg C ha$^{-1}$ in 2010, and in particular, 9.3 and 9.4 Mg C ha$^{-1}$ in Europe for agroforestry and tree cover on agricultural land, values in line with those published in this study.

It is also interesting to compare our findings to the carbon stocks reported for forests, because they are the quintessential carbon pool of terrestrial living biomass. Higher values for forest systems have often been reported in literature, but on occasions, they have been close or relatively close to those estimated here for Mediterranean woody crops. Aboveground biomass carbon stocks of high maquis, maquis forest, forest maquis, and Mediterranean old-growth forest on a Mediterranean island (Italy) were published by Badalamenti et al. (2019), showing values of 15, 35, 55, and 105 Mg C ha$^{-1}$, respectively. Aboveground biomass of Mediterranean shrubs in Spain were quantified by Pasalodos-Tato et al. (2015), showing values of 12.40 and 10.42 Mg C ha$^{-1}$ for formations of heathers and large Cistaceae, respectively, considering 49.60% as the mean value of carbon content for the shrub formations studied. Forest carbon stocks were reported for the western Mediterranean by Vayreda et al. (2012a), showing an average stand C stock (trees + understory) of 45.1 Mg C ha$^{-1}$, ranging from 41.8 to 48.5 Mg C ha$^{-1}$ for conifers and broadleaves, respectively, including above- and belowground biomass. Other carbon stock values (aboveground + belowground biomass) were reported in terms of equivalent $CO_2$ (1g C= 3.67g $CO_2$) for Mediterranean mountain range forest (Herrero and Bravo 2012). Values of 43.1 and 43.4 Mg C ha$^{-1}$ were published for *P. sylvestris* and 40.5 and 33.6 Mg C ha$^{-1}$ for *P. pinaster* in two forest regions. The average aboveground biomass carbon density for California wildland ecosystems in 2010 was 26 ± 7 Mg C ha$^{-1}$ according to Gonzalez et al. (2015).

Annual carbon sequestration in woody crops can be found in Appendix 2 (Table B.7) for different crop age ranges. The average sequestration rate for vineyards was around 0.35 Mg C ha$^{-1}$ year$^{-1}$ for 0 to 35 years considering a representative plant density of 3500 vines ha$^{-1}$. Olive groves displayed similar values with 0.38 Mg C ha$^{-1}$ year$^{-1}$ (average value for 0 to 50 years with 150 trees ha$^{-1}$). Fruit trees yielded an average annual sequestration rate of 1.68 and 1.84 Mg C ha$^{-1}$ year$^{-1}$ for seed fruit and stone fruit, respectively, in a plantation with stand ages ranging from 0 to 26 and 0 to 25 years and plant density of 3300 and 1500 trees ha$^{-1}$, respectively. Finally, nuts and citrus presented an average annual carbon sequestration rate of 2.25 and 3.32 Mg C ha$^{-1}$ year$^{-1}$, from 0 to 13 and 0 to 14 years, and with 200 and 800 trees ha$^{-1}$, respectively. In terms of annual carbon sequestration rates, some studies have reported similar values to those estimated here. Annual rates for citrus ranged from 2.8 to 3.3 Mg C ha$^{-1}$ year$^{-1}$ (Iglesias et al. 2013; Quiñones et al. 2013). For vineyards in Spain, Miranda et al. (2017) found a rate of 0.3 Mg C ha$^{-1}$ year$^{-1}$ (0.95 Mg $CO_2$eq ha$^{-1}$ year$^{-1}$) for permanent living vine structures.

Otherwise, the annual carbon sequestration rates reported here are values very close to those reported in terms of $CO_2$eq (1g C= 3.67 g $CO_2$eq) by Aguilera et al. (2015) as annual GHG emissions from agricultural activities in conventional fruit orchards (ranging from 964 to 6,324 kg $CO_2$eq ha$^{-1}$ year$^{-1}$, i.e., from 0.26 to 1.72 Mg C ha$^{-1}$ year$^{-1}$). Therefore, carbon sequestration from biomass of permanent structures, as well as from soils, should be considered in the carbon cycle balance and life-cycle assessments for woody crops.

According to the carbon stock and sequestration values reviewed above, Mediterranean woody crops presented similar values or at least values of the same magnitude as other woody systems or even forests. Consequently, woody crops should be considered in mitigation and land management strategies and policies due to the potential of their living biomass and, of course, their soils as a carbon sink (Lardo et al. 2018; Almagro et al. 2010; Montanaro et al. 2017). C stocks reported for agricultural soils in Catalonia for the first 30 cm were greater than those reported here for standing biomass of woody crops (Funes et al. 2019). Moreover, the mitigation potential of certain agricultural practices such as cover crops, reduced tillage, crop diversification, or agroforestry to enhance carbon sequestration in agricultural soils is widely known. The C sink capacity of soils was defined in COP 21, promoting the 4×1000 strategy (Minasny et al. 2017), and then in COP 22, also showing the importance of Mediterranean woody crops such as olive groves. In this respect, a suite of land management strategies for the Mediterranean may be necessary in order to meet goals for the near future in the study area. Conservation of high-biomass cropland and the incorporation of woody crops in new areas could help to enhance land management. Large forest wildfires in the Mediterranean are becoming more frequent. The continuity of the forest mass together with poor forest management increases the risk of extreme wildfire events. In fact, wildfires are expected to increase across the Mediterranean Basin because of climate change (Ruffault et al. 2020). Forest and landscape management is one of the strategies in the fight against wildfires. Breaking forest continuity using woody crops in a mosaic landscape could be very effective in stopping the spread of these fires. Landscape mosaics mixing different land uses are less vulnerable to burning than forests (Bertomeu et al. 2022). Therefore, the rupture of forest continuity using woody crops could be useful in wildfire management. Given that carbon losses from wildfires could potentially exceed carbon sequestration at a local scale in non-managed Mediterranean forest ecosystems (Gonzalez et al. 2015; MedECC 2020), the carbon stock losses due to land use change (from forest to woody crops) could be compensated, at the long term, by avoiding the huge carbon emissions released by wildfires.

Moreover, Mediterranean woody crops could offer an opportunity for enhancing agricultural sustainability due to their resilience and their standing biomass and soils, which could be considered C sinks. For example, woody crops can coexist with other crops or green covers in the inter-rows, and several soil management practices can be applied to enhance environmental sustainability (Tezza et al. 2019). Additionally, rainfed woody crops usually present lower emission factors compared to irrigated crops that usually receive large amounts of water and fertilizers, creating favorable conditions for increased emissions (MedECC 2020). Woody systems also make use of agroindustry byproducts as organic matter inputs (MedECC 2020).

The capacity of these crops to store C has received increasing attention of late, with different approaches. Several studies have assessed their role in the global carbon cycle focusing on the soil or the ecosystem level through net ecosystem exchange (NEE) approaches (Tezza et al. 2019; Chamizo et al. 2017; Nardino et al. 2013). All these studies reinforce the idea that standing biomass of woody crops may represent a significant C stock itself, and they highlight the role of these crops in the global GHG budget as a net sink of $CO_2$ (Tezza et al. 2019).

### 3.3 Carbon stock changes in 2013–2019

The net carbon stock change in Catalonia amounted to +0.173 Tg C year$^{-1}$ and +1.040 Tg C in 6 years, representing an annual increase of +3.8% year$^{-1}$ and 19% in 6 years.

The entire range of values of this change in Catalonia for each crop type was positive as well, excepting citrus, despite being negative in terms of area for some crop types (Table 2). This upward trend for carbon stock applies to most of the study area, with just a few areas, mainly those with olives and fruit trees, recording a decrease in carbon stocks during this period (Fig. 5).

Carbon stock increases were mainly due to tree growth and the corresponding increases in carbon density (Mg C ha$^{-1}$). This general increase occurred despite decreases in the total woody crop area (−1,681.4 ha year$^{-1}$) throughout the study area (Fig. A.5. of Appendix 1), mainly due to decreases in fruit and olive grove areas through the period 2013–2019 (Table 2). The land use change matrix can be found in Appendix 2 (Table B.8).

The increase in biomass carbon stock of woody crops analyzed for these 6 years could be reversed in the following years as a consequence of the decreasing area of woody cropland in favor of other urban and agricultural uses, principally grassland and arable land. Conversion of woody cropland to grassland and arable land is mainly aimed at agricultural intensification and feeding the meat industry in the study area, leading to high consumption of land and water resources and high GHG emissions (Vanham et al. 2016). In this context, the use of woody crops and agronomical practices associated to these become important, in order to avoid the above-mentioned problems and maintain agricultural productivity, economic stability, mitigation strategies and, consequently, the population and the landscape. Woody crops agronomical practices that favor soil conservation and carbon sequestration can be, as a few examples, the use of cover crops mowed or grazed, the application of organic amendments coming from circular economy practices, or the recovery of terracing that reduce soil erosion and water runoff.

In the Mediterranean Basin, there is a tendency towards a decrease in woody crops, substituted for natural ecological succession, with the normal variability in the transition

**Table 2** Carbon stocks and changes in woody crops in Catalonia in 2013–2019. Carbon stock changes are expressed as an annual rate and the number in brackets is the percentage of change per year.

| Crops | 2013 | | | 2019 | | | Change 2013–2019 | | |
|---|---|---|---|---|---|---|---|---|---|
| | Tg C | Mg C ha$^{-1}$ | ha | Tg C | Mg C ha$^{-1}$ | ha | Tg C year$^{-1}$ (%) | Mg C ha$^{-1}$ year$^{-1}$ (%) | ha year$^{-1}$ (%) |
| Citrus | 0.24 | 25.95 | 9346 | 0.23 | 27.25 | 8,517 | −0.002 (−0.72) | +0.22 (+0.8) | −138 (−1.5) |
| Nuts | 1.53 | 27.40 | 55,893 | 1.63 | 29.09 | 56,140 | +0.017 (+1.10) | +0.28 (+1.0) | +41 (+0.1) |
| Fruits | 1.21 | 13.86 | 87,134 | 1.42 | 17.80 | 79,726 | +0.035 (+2.92) | +0.66 (+4.7) | −1235 (−1.4) |
| Olive | 2.14 | 17.09 | 125,441 | 2.79 | 23.01 | 121,408 | +0.108 (+5.06) | +0.99 (+5.8) | −672 (−0.5) |
| Grapevine | 0.36 | 6.40 | 55,612 | 0.44 | 7.70 | 57,546 | +0.014 (+4.06) | +0.22 (+3.4) | 322 (+0.6) |
| Total Woody Crops | 5. 48 | 16.44 | 333,426 | 6.52 | 20.17 | 323,337 | +0.173 (+3.16) | +0.62 (+3.8) | −1681 (−2.8) |

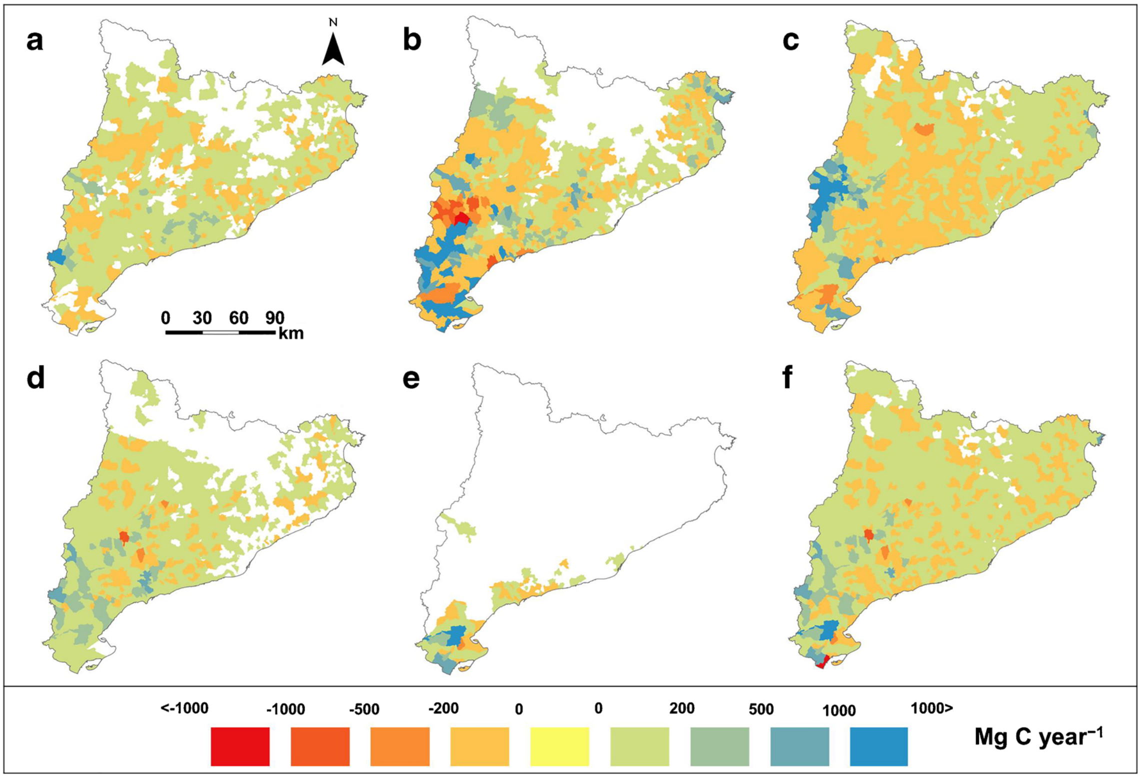

**Fig. 5** Spatial distribution of total carbon stock change for woody crops in Catalonia from 2013 to 2019 (Mg C year$^{-1}$): a grapevine, b olive, c fruits, d nuts, e citrus, and f total woody crops.

process due to edaphic, environmental and previous agricultural use (MedECC 2020). Moreover, the conversion of woody crops to other land uses such as herbaceous crops or large-scale photovoltaic infrastructures, mainly occurs due to market fluctuations. In particular, rainfed woody crops are the most susceptible to suffering the consequences of speculation and market trends. In fact, the LUC observed in the study area would appear to be a direct response to changing market needs, rather than a country strategy focused on food security and climate change mitigation and adaptation. Some examples are (i) the increase in the area occupied by vineyards due to the expansion of the wine sector in recent decades in view of the higher added value of wine and cava, (ii) the smaller area devoted to citrus due to soil salinization, irregular spring cold stress and the low prices offered by the global market (South and North Africa), which economically endanger production in the EU, and (iii) the increase in the area devoted to high-yielding almond trees in the irrigated area of the central valley (Urgell and Segarra-Garrigues channels), which would appear to be directly related with rising almond prices and speculation in water markets.

In Mediterranean conditions, the main problems generated by crop abandonment are fire due to forest recovering, and aridity, due to increases in superficial water runoff in arid or semiarid conditions. Therefore, if no mitigation and adaptation strategies are considered in territorial management, there will be a decrease in woody cropland (mainly rainfed crops) for the following years in the study area and consequently an inevitable decrease in the C pool, together with the loss of a significant element of Catalonia's landscape, society, culture, and agrobiodiversity.

### 3.4 Limitations

Some limitations in this study must be recognized. Firstly, although in general the equations performed were based on fairly good representative and even site-specific data for Mediterranean climates, the lack of specific allometries for olives and nuts in order to estimate biomass based on trunk diameter or basal area is a significant limitation. Thus, some general or less specific allometries and carbon factors had to be used due to the lack of information in this procedure. Allometries based on forest species (Montero and Ruiz-Peinado 2005) were used for nuts, whereas allometries for young olive trees were employed for olives (Villalobos et al. 2006). Therefore, further efforts are required to improve the estimates by collecting site- and crop-specific data and refining the modeling.

With respect to upscaling, several limitations must be recognized. Firstly, it is possible that carbon stocks are being underestimated, given that crop areas with ages outside the range in the crop-specific fits were assigned carbon stocks corresponding to the oldest age presented in the equation. Important underestimations here could affect citrus and nut carbon stock estimation due to the low representativeness of the range of ages in the equation performed for the entire spatial distribution of crop age in the study area (Table B.9 of Appendix 2). Secondly, many assumptions about crop traits such as age and plant density distribution had to be made for the study area due to the lack of a specific agricultural census for olives and nuts.

Finally, a few sources of error could not be taken into account in the uncertainty analysis. Although the error in allometric estimates of biomass for olives and nuts was considered in error propagation of the prediction, it was not possible to obtain the error associated with using these non-specific allometries. Moreover, no error was available for agricultural census and SIGPAC to consider in error propagation.

### 3.5 Implications for policy and future research

The estimation of carbon stocks produced in this new assessment may assist in assessing carbon storage as an ecosystem service in Mediterranean woody cropland for mitigating climate change. In this respect, the results could serve as a baseline for shaping policy and considering land management issues through assessment of cropland mitigation potential by spatial analysis based on empirical data. As Williams et al. (2011) noted in the case of California at the beginning of the last decade, most regulations and policies were focused on emissions. Moreover, carbon sequestration was only proposed under the categories of reforestation, improved forest management or avoided conversion. However, these results offer new land management possibilities, considering C stocks together with other ecosystem services. Future research should focus on (i) improving carbon stock estimations in woody crops, and (ii) spatial analysis by testing mitigation strategies and land use scenarios using these estimations as a baseline, together with soil carbon stocks (Funes et al. 2019).

## 4 Conclusion

This is the first study to assess Mediterranean woody crops as a carbon sink at the regional scale and to analyze their uncertainties by using data from different sources and methodologies. We went to great lengths to assess carbon stocks of above- and belowground biomass, based mainly on local unedited data relating to these types of crops. The total biomass carbon stocks for woody cropland in NE Spain were 5.48 Tg C, with an average value of 16.44 ± 0.18 Mg C $ha^{-1}$. Moreover, for the first time an appraisal has been offered of recent carbon stock changes over the period 2013–2019 for Mediterranean woody crops in NE Spain, by scaling up at the municipality level. A mean annual increase of 3.8% was estimated over the studied period, notwithstanding the decrease of the area covered by woody crops. These novel findings can be useful for quantifying the carbon consequences of land use management, updating global inventories and assessing the ecosystem services of carbon storage in woody cropland in mitigating climate change.

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**Code availability** Not available

**Authors' contributions** All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Inmaculada Funes and Roberto Molowny-Horas. The first draft of the manuscript was written by Inmaculada Funes, and all authors edited and commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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**Data availability** Not available

## Declarations

**Ethics approval** Not applicable

**Consent to participate** Not applicable

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## References

Aguilera E, Guzmán G, Alonso A (2015) Greenhouse gas emissions from conventional and organic cropping systems in Spain. II. Fruit tree orchards. Agron Sustain Dev 35(2):725–737. https://doi.org/10.1007/s13593-014-0265-y

Almagro M, Lopez J, Boix-Fayos C, Albaladejo J, Martinez-Mena M (2010) Belowground carbon allocation patterns in a dry Mediterranean ecosystem: a comparison of two models. Soil Biol Biochem 42(9):1549–1557. https://doi.org/10.1016/j.soilbio.2010.05.031

Alvarez E, Duque A, Saldarriaga J, Cabrera K, de las Salas G, del Valle I, Lema A, Moreno F, Orrego S, Rodríguez L (2012) Tree aboveground biomass allometries for carbon stocks estimation in the natural forests of Colombia. Forest Ecol Manag 267:297–308. https://doi.org/10.1016/j.foreco.2011.12.013

Aragues R, Puy J, Royo A, Espada JL (2005) Three-year field response of young olive trees (Olea europaea L., cv. Arbequina) to soil salinity: trunk growth and leaf ion accumulation. Plant Soil 271(1-2):265–273. https://doi.org/10.1007/s11104-004-2695-9

Aragues R, Guillen M, Royo A (2010) Five-year growth and yield response of two young olive cultivars (Olea europaea L., cvs. Arbequina and Empeltre) to soil salinity. Plant Soil 334(1-2):423–432. https://doi.org/10.1007/s11104-010-0393-3

Araujo F, Williams LE, Matthews MA (1995) A comparative-study of young Thompson-Seedless grapevines (Vitis-vinifera l) under drip and furrow irrigation.2. Growth, water-use efficiency and nitrogen partitioning. Sci Hortic-Amst 60(3-4):251–265. https://doi.org/10.1016/0304-4238(94)00711-n

Arnan X, Lopez BC, Martinez-Vilalta J, Estorach M, Poyatos R (2012) The age of monumental olive trees (Olea europaea) in northeastern Spain. Dendrochronologia 30(1):11–14. https://doi.org/10.1016/j.dendro.2011.02.002

Asigbaase M, Dawoe E, Lomax BH, Sjogersten S (2021) Biomass and carbon stocks of organic and conventional cocoa agroforests, Ghana. Agric Ecosyst Environ 306:107192. https://doi.org/10.1016/j.agee.2020.107192

Badalamenti E, Battipaglia G, Gristina L, Novara A, Rühl J, Sala G, Sapienza L, Valentini R, La Mantia T (2019) Carbon stock increases up to old growth forest along a secondary succession in Mediterranean island ecosystems. PLoS One 14(7):e0220194. https://doi.org/10.1371/journal.pone.0220194

Bertomeu M, Pineda J, Pulido F (2022) Managing wildfire risk in mosaic landscapes: a case study of the Upper Gata River catchment in Sierra de Gata, Spain. Land 11(4):465

Bravo K, Toselli M, Baldi E, Marcolini G, Sorrenti G, Quartieri M, Marangoni B (2012) Effect of organic fertilization on carbon assimilation and partitioning in bearing nectarine trees. Sci Hortic-Amst 137:100–106. https://doi.org/10.1016/j.scienta.2012.01.030

Brunori E, Farina R, Biasi R (2016) Sustainable viticulture: the carbon-sink function of the vineyard agro-ecosystem. Agric Ecosyst Environ 223:10–21. https://doi.org/10.1016/j.agee.2016.02.012

Bustan A, Avni A, Lavee S, Zipori I, Yeselson Y, Schaffer AA, Riov J, Dag A (2011) Role of carbohydrate reserves in yield production of intensively cultivated oil olive (Olea europaea L.) trees. Tree Physiol 31(5):519–530. https://doi.org/10.1093/treephys/tpr036

Caruso T, Giovannini D, Marra FP, Sottile F (1999a) Planting density, above-ground dry-matter partitioning and fruit quality in greenhouse-grown 'Flordaprince' peach (Prunus persica L. Batsch) trees trained to "free-standing Tatura". J Hortic Sci Biotechnol 74(5):547–552

Caruso T, Inglese P, Sottile F, Marra FP (1999b) Effect of planting system on productivity, dry-matter partitioning and carbohydrate content in aboveground components of 'Flordaprince' peach trees. J Am Soc Hortic Sci 124(1):39–45

Caruso T, Barone E, Di Vaio C (2001) Factors affecting tree crop efficiency in young peach trees: rootstock vigour and training system. In: Palmer JW, Wunsche JN (eds) Proceedings of the Seventh International Symposium on Orchard and Plantation Systems. Acta Hortic, vol 1. International Society Horticultural Science, Leuven, pp 193–197

Chamizo S, Serrano-Ortiz P, López-Ballesteros A, Sánchez-Cañete EP, Vicente-Vicente JL, Kowalski AS (2017) Net ecosystem CO2 exchange in an irrigated olive orchard of SE Spain: influence of weed cover. Agric Ecosyst Environ 239:51–64. https://doi.org/10.1016/j.agee.2017.01.016

Chave J, Andalo C, Brown S, Cairns MA, Chambers JQ, Eamus D, Fölster H, Fromard F, Higuchi N, Kira T, Lescure JP, Nelson BW, Ogawa H, Puig H, Riéra B, Yamakura T (2005) Tree allometry and improved estimation of carbon stocks and balance in tropical forests. Oecologia 145(1):87–99. https://doi.org/10.1007/s00442-005-0100-x

Clingeleffer PR, Krake LR (1992) Responses of Cabernet-Franc grapevines to minimal pruning and virus-infection. Am J Enol Vitic 43(1):31–37

Davison AC, Hinkley DV (1997) Bootstrap methods and their application. Cambridge Series in Statistical and Probabilistic Mathematics. Cambridge University Press, Cambridge. https://doi.org/10.1017/CBO9780511802843

Djomo AN, Knohl A, Gravenhorst G (2011) Estimations of total ecosystem carbon pools distribution and carbon biomass current annual increment of a moist tropical forest. Forest Ecol Manag 261(8):1448–1459. https://doi.org/10.1016/j.foreco.2011.01.031

El-Jendoubi H, Abadia J, Abadia A (2013) Assessment of nutrient removal in bearing peach trees (Prunus persica L. Batsch) based on whole tree analysis. Plant Soil 369(1-2):421–437. https://doi.org/10.1007/s11104-012-1556-1

Escalona JM, TomÀS M, Martorell S, Medrano H, Ribas-Carbo M, Flexas J (2012) Carbon balance in grapevines under different soil water supply: importance of whole plant respiration. Aust J Grape Wine Res 18(3):308–318. https://doi.org/10.1111/j.1755-0238.2012.00193.x

Fernández JE, Moreno F, Martin-Palomo MJ, Cuevas MV, Torres-Ruiz JM, Moriana A (2011a) Combining sap flow and trunk diameter measurements to assess water needs in mature olive orchards. Environ Exp Bot 72(2):330–338. https://doi.org/10.1016/j.envexpbot.2011.04.004

Fernández JE, Torres-Ruiz JM, Diaz-Espejo A, Montero A, Alvarez R, Jimenez MD, Cuerva J, Cuevas MV (2011b) Use of maximum trunk diameter measurements to detect water stress in mature Arbequina olive trees under deficit irrigation. Agr Water Manage 98(12):1813–1821. https://doi.org/10.1016/j.agwat.2011.06.011

Funes I, Save R, Rovira P, Molowny-Horas R, Alcaniz JM, Ascaso E, Herms I, Herrero C, Boixadera J, Vayreda J (2019) Agricultural soil organic carbon stocks in the north-eastern Iberian Peninsula: drivers and spatial variability. Sci Total Environ 668:283–294. https://doi.org/10.1016/j.scitotenv.2019.02.317

Funes I, Savé R, de Herralde F, Biel C, Pla E, Pascual D, Zabalza J, Cantos G, Borràs G, Vayreda J, Aranda X (2021) Modeling impacts of climate change on the water needs and growing cycle of crops in three Mediterranean basins. Agric Water Manag 249:106797. https://doi.org/10.1016/j.agwat.2021.106797

Gonzalez P, Battles JJ, Collins BM, Robards T, Saah DS (2015) Aboveground live carbon stock changes of California wildland ecosystems, 2001–2010. Forest Ecol Manag 348:68–77. https://doi.org/10.1016/j.foreco.2015.03.040

Goward J (2012) Estimating and predicting carbon sequestered in a vineyard with soil surveys, spatial data and GIS management. University of New South Wales

Grossman YL, Dejong TM (1994) Peach - a simulation-model of reproductive and vegetative growth in peach-trees. Tree Physiol 14(4): 329–345. https://doi.org/10.1093/treephys/14.4.329

Gucci R, Caruso G, Bertolla C, Urbani S, Taticchi A, Esposto S, Servili M, Sifola MI, Pellegrini S, Pagliai M, Vignozzi N (2012) Changes of soil properties and tree performance induced by soil management in a high-density olive orchard. Eur J Agron 41:18–27. https://doi.org/10.1016/j.eja.2012.03.002

Herrero C, Bravo F (2012) Can we get an operational indicator of forest carbon sequestration?: a case study from two forest regions in Spain. Ecol Indic 17:120–126. https://doi.org/10.1016/j.ecolind.2011.04.021

Huffman T, Liu J, McGovern M, McConkey B, Martin T (2015) Carbon stock and change from woody biomass on Canada's cropland between 1990 and 2000. Agric Ecosyst Environ 205:102–111. https://doi.org/10.1016/j.agee.2014.10.009

Iglesias DJ, Quinones A, Font A, Martinez-Alcantara B, Forner-Giner MA, Legaz F, Primo-Millo E (2013) Carbon balance of citrus plantations in Eastern Spain. Agric Ecosyst Environ 171:103–111. https://doi.org/10.1016/j.agee.2013.03.015

Inglese P, Caruso T, Gugliuzza G, Pace LS (2002) Crop load and rootstock influence on dry matter partitioning in trees of early and late ripening peach cultivars. J Am Soc Hortic Sci 127(5):825–830

IPCC (2006) Guidelines for national greenhouse gas inventories. In: Eggleston HS, Buendia L, Miwa K, Ngara T, Tanabe K (eds) Prepared by the National Greenhouse Gas Inventories Programme. IGES, Japan ISBN 4-88788-032-4

IPCC (2014) Climate Change 2014: synthesis report. Contribution of working groups I, II and III to the Fifth Assessment Report of the Intergovermmental Panel on Climate Change. IPCC, Geneva ISBN 978-92-9169-143-2

Keightley KE (2011) Applying new methods for estimating in vivo vineyard carbon storage. Am J Enol Vitic 62(2):214–218. https://doi.org/10.5344/ajev.2010.10081

Kongsager R, Napier J, Mertz O (2013) The carbon sequestration potential of tree crop plantations. Mitig Adapt Strateg Glob Chang 18(8): 1197–1213. https://doi.org/10.1007/s11027-012-9417-z

Kumar P, Murugan P, Murkute A, Bala Singh S (2010) A carbon sequestration strategy involving temperate fruit crops in the trans-Himalayan region. J Hortic Sci Biotechnol 85(5):405–409. https://doi.org/10.1080/14620316.2010.11512688

Kuyah S, Dietz J, Muthuri C, Jamnadass R, Mwangi P, Coe R (2012a) Allometric equations for estimating biomass in agricultural landscapes: I. Aboveground biomass. Agric Ecosyst Environ 158:216–224. https://doi.org/10.1016/j.agee.2012.05.011

Kuyah S, Dietz J, Muthuri C, Jamnadass R, Mwangi P, Coe R (2012b) Allometric equations for estimating biomass in agricultural landscapes: II. Belowground biomass. Agric Ecosyst Environ 158: 225–234. https://doi.org/10.1016/j.agee.2012.05.010

Kuyah S, Mbow C, Sileshi GW, van Noordwijk M, Tully KL, Rosenstock TS (2016) Quantifying tree biomass carbon stocks and fluxes in agricultural landscapes. Methods for Measuring Greenhouse Gas Balances and Evaluating Mitigation Options in Smallholder Agriculture. Springer, Dordrecht. https://doi.org/10.1007/978-3-319-29794-1_6

Larbi A, Ayadi M, Ben Dhiab A, Msallem M, Caballero JM (2012) Planting density affects vigour and production of 'Arbequina' olive. Span J Agric Res 10(4):1081–1089. https://doi.org/10.5424/sjar/2012104-556-11

Lardo E, Fiore A, Quinto GA, Dichio B, Xiloyannis C (2018) Climate change mitigation role of orchard agroecosystems: case studies in southern Italy. In: 6th International Symposium on Tropical and Subtropical Fruits, Kafr El Sheikh, Egypt, Sep 26 2016. Acta Hortic: 13-17. https://doi.org/10.17660/ActaHortic.2018.1216.2

Liguori G, Gugliuzza G, Inglese P (2009) Evaluating carbon fluxes in orange orchards in relation to planting density. J Agric Sci 147:637–645. https://doi.org/10.1017/s002185960900882x

Luján Soto R, Martínez-Mena M, Cuéllar Padilla M, de Vente J (2021) Restoring soil quality of woody agroecosystems in Mediterranean drylands through regenerative agriculture. Agric Ecosyst Environ 306:107191. https://doi.org/10.1016/j.agee.2020.107191

MedECC (2020) Climate and environmental change in the Mediterranean Basin – current situation and risks for the future. First Mediterranean Assessment Report [Cramer, W, Guiot, J, Marini, K (eds.)] Union for the Mediterranean, Plan Bleu, UNEP/MAP, Marseille, France, 632pp. ISBN: 978-2-9577416-0-1. https://doi.org/10.5281/zenodo.4768833

Mezghani MA, Labidi F, Khairi M, Amor AO, Sahli A (2012) Study of the behaviour of olive cultivars cultivated under different tree-trainings: vegetative and productive characteristics. Acta Hortic 949: 439–446

Minasny B, Malone BP, McBratney AB, Angers DA, Arrouays D, Chambers A, Chaplot V, Chen ZS, Cheng K, Das BS, Field DJ, Gimona A, Hedley CB, Hong SY, Mandal B, Marchant BP, Martin M, McConkey BG, Mulder VL et al (2017) Soil carbon 4 per mille. Geoderma 292:59–86. https://doi.org/10.1016/j.geoderma2017.01.002

Miranda C, Santesteban LG, Escalona JM, De Herralde F, Aranda X, Nadal M, Intrigliolo DS, Castel JR, Royo JB, Medrano H (2017) Allometric relationships for estimating vegetative and reproductive biomass in grapevine (Vitis vinifera L.). Aust J Grape Wine Res 23(3):441–451. https://doi.org/10.1111/ajgw.12285

Montanaro G, Tuzio AC, Xylogiannis E, Kolimenakis A, Dichio B (2017) Carbon budget in a Mediterranean peach orchard under different management practices. Agric Ecosyst Environ 238:104–113. https://doi.org/10.1016/j.agee.2016.05.031

Montero G, Ruiz-Peinado RMM (2005) Producción de biomasa y fijación de CO2 por parte de los bosques españoles. Monografías INIA Serie Forestal n° 13:270 p.

Mullins MG, Bouquet A, Williams LE (1992) Biology of the grapevine. Cambridge University Press, Cambridge

Nardino M, Pernice F, Rossi F, Georgiadis T, Facini O, Motisi A, Drago A (2013) Annual and monthly carbon balance in an intensively managed Mediterranean olive orchard. Photosynthetica 51(1):63–74. https://doi.org/10.1007/s11099-012-0079-6

Ortiz-Ceballos GC, Vargas-Mendoza M, Ortiz-Ceballos AI, Mendoza Briseño M, Ortiz-Hernández G (2020) Aboveground carbon storage in coffee agroecosystems: the case of the Central Region of the State of Veracruz in Mexico. Agronomy 10(3):382

Padilla FM, Vidal B, Sánchez J, Pugnaire FI (2010) Land-use changes and carbon sequestration through the twentieth century in a Mediterranean mountain ecosystem: implications for land management. J Environ Manag 91(12):2688–2695. https://doi.org/10.1016/j.jenvman.2010.07.031

Panzacchi P, Tonon G, Ceccon C, Scandellari F, Ventura M, Zibordi M, Tagliavini M (2012) Belowground carbon allocation and net primary and ecosystem productivities in apple trees (Malus domestica) as affected by soil water availability. Plant Soil 360(1-2):229–241. https://doi.org/10.1007/s11104-012-1235-2

Pasalodos-Tato M, Ruiz-Peinado R, del Río M, Montero G (2015) Shrub biomass accumulation and growth rate models to quantify carbon stocks and fluxes for the Mediterranean region. Eur J For Res 134(3):537–553. https://doi.org/10.1007/s10342-015-0870-6

Quiñones A, Martinez-Alcantara B, Font A, Forner-Giner MA, Legaz F, Primo-Millo E, Iglesias DJ (2013) Allometric models for estimating carbon fixation in citrus trees. Agron J 105(5):1355–1366. https://doi.org/10.2134/agronj2013.0015

Ruesch, A, Gibbs HK (2008) New IPCC tier-1 global biomass carbon map for the year 2000. Available online from the Carbon Dioxide Information Analysis Center [http://cdiac.ess-dive.lbl.gov], Oak Ridge National Laboratory, Oak Ridge, Tennessee

Ruffault J, Curt T, Moron V, Trigo RM, Mouillot F, Koutsias N, Pimont F, Martin-StPaul N, Barbero R, Dupuy J-L, Russo A, Belhadj-Khedher C (2020) Increased likelihood of heat-induced large wildfires in the Mediterranean Basin. Sci Rep 10(1):13790. https://doi.org/10.1038/s41598-020-70069-z

Ruiz-Peinado Gertrudix R, Montero G, del Rio M (2012) Biomass models to estimate carbon stocks for hardwood tree species. For Syst 21(1):11. https://doi.org/10.5424/fs/2112211-02193

Ruiz-Peinado R, del Rio M, Montero G (2011) New models for estimating the carbon sink capacity of Spanish softwood species. For Syst 20(1):13. https://doi.org/10.5424/fs/2011201-11643

Ruiz-Peinado R, Bravo-Oviedo A, Lopez-Senespleda E, Bravo F, del Rio M (2017) Forest management and carbon sequestration in the Mediterranean region: a review. For Syst 26(2):25. https://doi.org/10.5424/fs/2017262-11205

Saayman DE, Huysteen LV (1980) Soil preparation studiets. I. The effects of depth and method of soil and preparation and of organic material on the performance of Vitis vinifera (var Chenin blanc) on huntton/Sterkspruit soil. S Afr J Enol Vitic 1:107–121

Santesteban LG, Royo JB (2006) Water status, leaf area and fruit load influence on berry weight and sugar accumulation of cv. 'Tempranillo' under semiarid conditions. Sci Hortic-Amsterdam 109(1):60–65. https://doi.org/10.1016/j.scienta.2006.03.003

Santesteban LG, Miranda C, Royo JB (2011a) Regulated deficit irrigation effects on growth, yield, grape quality and individual anthocyanin composition in Vitis vinifera L. cv. 'Tempranillo'. Agr Water Manage 98(7):1171–1179. https://doi.org/10.1016/j.agwat.2011.02.011

Santesteban LG, Miranda C, Royo JB (2011b) Thinning intensity and water regime affect the impact cluster thinning has on grape quality. Vitis 50(4):159–165

Santesteban LG, Guillaume S, Royo JB, Tisseyre B (2013) Are precision agriculture tools and methods relevant at the whole-vineyard scale? Precis Agric 14(1):2–17. https://doi.org/10.1007/s11119-012-9268-3

Segal E, Dag A, Ben-Gal A, Zipori I, Erel R, Suryano S, Yermiyahu U (2011) Olive orchard irrigation with reclaimed wastewater: agronomic and environmental considerations. Agric Ecosyst Environ 140(3):454–461. https://doi.org/10.1016/j.agee.2011.01.009

SIGPAC (2013) Agricultural plots geographical information system. Government of Catalonia (Shapefile. Annual)

SIGPAC (2019) Agricultural plots geographical information system. Government of Catalonia (Shapefile. Annual)

Sofo A, Nuzzo V, Palese AM, Xiloyannis C, Celano G, Zukowskyj P, Dichio B (2005) Net CO2 storage in Mediterranean olive and peach orchards. Sci Hortic-Amst 107(1):17–24. https://doi.org/10.1016/j.scienta.2005.06.001

Solari LI, Johnson S, DeJong TM (2006) Hydraulic conductance characteristics of peach (Prunus persica) trees on different rootstocks are related to biomass production and distribution. Tree Physiol 26(10):1343–1350. https://doi.org/10.1093/treephys/26.10.1343

Spawn SA, Sullivan CC, Lark TJ, Gibbs HK (2020) Harmonized global maps of above and belowground biomass carbon density in the year 2010. Sci Data 7(1):112. https://doi.org/10.1038/s41597-020-0444-4

Tezza L, Vendrame N, Pitacco A (2019) Disentangling the carbon budget of a vineyard: the role of soil management. Agric Ecosyst Environ 272:52–62. https://doi.org/10.1016/j.agee.2018.11.002

Thurner M, Beer C, Santoro M, Carvalhais N, Wutzler T, Schepaschenko D, Shvidenko A, Kompter E, Ahrens B, Levick SR, Schmullius C (2014) Carbon stock and density of northern boreal and temperate forests. Glob Ecol Biogeogr 23(3):297–310. https://doi.org/10.1111/geb.12125

Valentini R, Matteucci G, Dolman AJ, Schulze ED, Rebmann C, Moors EJ, Granier A, Gross P, Jensen NO, Pilegaard K, Lindroth A, Grelle A, Bernhofer C, Grünwald T, Aubinet M, Ceulemans R, Kowalski AS, Vesala T, Rannik U et al (2000) Respiration as the main determinant of carbon balance in European forests. Nature 404(6780):861–865. https://doi.org/10.1038/35009084

Vanham D, del Pozo S, Pekcan AG, Keinan-Boker L, Trichopoulou A, Gawlik BM (2016) Water consumption related to different diets in Mediterranean cities. Sci Total Environ 573:96–105. https://doi.org/10.1016/j.scitotenv.2016.08.111

Vashum KT, Jayakumar S (2012) Methods to estimate above-ground biomass and carbon stock in natural forests - a review. J Ecosyst Ecography 2(4):1–7

Vayreda J, Gracia M, Canadell JG, Retana J (2012a) Spatial patterns and predictors of forest carbon stocks in Western Mediterranean. Ecosystems 15(8):1258–1270. https://doi.org/10.1007/s10021-012-9582-7

Vayreda J, Martinez-Vilalta J, Gracia M, Retana J (2012b) Recent climate changes interact with stand structure and management to determine changes in tree carbon stocks in Spanish forests. Glob Chang Biol 18(3):1028–1041. https://doi.org/10.1111/j.1365-2486.2011.02606.x

Villalobos FJ, Testi L, Hidalgo J, Pastor M, Orgaz F (2006) Modelling potential growth and yield of olive (Olea europaea L.) canopies. Eur J Agron 24(4):296–303. https://doi.org/10.1016/j.eja.2005.10.008

Williams LE (ed) (1996) Grape. In: Photoassimilate distribution in plants and crops: source-sink relationships. Marcel Dekker Inc.: New York

Williams LE, Biscay PJ (1991) Partitioning of dry-weight, nitrogen, and potassium in Cabernet-Sauvignon grapevines from anthesis until harvest. Am J Enol Vitic 42(2):113–117

Williams JN, Hollander AD, O'Geen AT, Thrupp LA, Hanifin R, Steenwerth K, McGourty G, Jackson LE (2011) Assessment of carbon in woody plants and soil across a vineyard-woodland landscape. Carbon Balance Manag 6(1):11–11. https://doi.org/10.1186/1750-0680-6-11

Xiloyannis C, Sofo A, Celano G, Nuzzo V (2007) Absorption of atmospheric CO2 in peach trees and partitioning in the different plant organs. In: Hrotko K (ed) Proceedings of the Eighth International Symposium on Canopy, Rootstocks and Environmental Physiology in Orchard Systems. Acta Hortic, vol 1. International Society Horticultural Science, Leuven, pp 519–524

Zomer RJ, Neufeldt H, Xu J, Ahrends A, Bossio D, Trabucco A, van Noordwijk M, Wang M (2016) Global tree cover and biomass carbon on agricultural land: the contribution of agroforestry to global and national carbon budgets. Sci Rep 6(1):29987. https://doi.org/10.1038/srep29987