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Net primary production and carbon budget in peach orchards under conventional and low input management systems

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A R T I C L E I N F O

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A B S T R A C T

Fruit tree orchards are an important land-use type in the Mediterranean regions despite limited information on their potential role as carbon sinks to mitigate climate change and their capacity to store soil organic carbon (SOC). The objective of this study was to evaluate the ability of peach orchards (*Prunus persica* (L.) Batsch) to fix and accumulate carbon (C) in three contrasting management systems. The first system was representative of the current management recommended to French producers with high yield objectives (REF). The second system was managed with a Low-Input strategy (LI-1) for chemical pesticide application (−70%), nitrogen fertilization and water irrigation (∼−25%). Lastly, the third system (LI-2) had the same low-input strategy but included a higher planting density (∼2-fold) and a new tree shape training system. The experiment was conducted in the South of France for 7 years from planting (2013–2019). The aboveground biomass and C repartitions in various components of systems (tree organs and grass growing in alleys) were carried out by destructive measurements each year to determine Net Primary Production (NPP), Net Ecosystem Production (NEP) and Net Ecosystem Carbon Balance (NECB).

The REF system had very high productivity during the mature tree period with 45.9 Mg ha^{-1} yr^{-1} of fresh fruit yield and 16.8 Mg ha^{-1} yr^{-1} of aboveground biomass, corresponding to 7379 kg C ha^{-1} yr^{-1} (738 g C m^{-2} yr^{-1}). Orchard NPP (tree and grass) reached 11,003 ± 353 kg C ha^{-1} yr^{-1} (1100 ± 35 g C m^{-2} yr^{-1}) and soil respiration was 3366 ± 776 kg C ha^{-1} yr^{-1} (337 ± 78 g C m^{-2} yr^{-1}) leading to an NEP of 7637 ± 853 kg C ha^{-1} yr^{-1} (764 ± 85 g C m^{-2} yr^{-1}) and an NECB of 4919 ± 858 kg C ha^{-1} yr^{-1} (492 ± 86 g C m^{-2} yr^{-1}). Carbon accumulation was distributed 53% in perennial biomass, and the soil had an annual SOC stock change of 3.8‰. In the LI-system, the reduction of inputs and chemical pesticides did not impact the average NEP and NECB, even though pest infestations reduced biomass in 2015 and 2019. The same input reductions in the LI-2 system but with increased planting density provided significant increases in NPP (+10.5%) and NEP (+20.0%), leading to an NECB of 5876 ± 890 kg C ha^{-1} yr^{-1} (588 ± 89 g C m^{-2} yr^{-1}), or 19.4% greater than the REF system during the mature tree period. This positive C accumulation was distributed 46% in the perennial biomass, which could reach 35.5 Mg C ha^{-1} (3550 g C m^{-2}) after 15 years of orchard life. The SOC stock change was 10.0‰ in the LI-2 system, greater than the 4‰ initiative of the Paris COP21. Innovative peach orchards with agroecological management can mitigate environmental impacts by combining high-quality fruit production with enhanced CO_2 sink capacity objectives.

1. Introduction

The effects of increasing CO_2 concentration and other greenhouse gases (N_2O, CH_4, among others) on the climate are now well documented (IPCC, 2013). Actions to drastically reduce CO_2 emissions and increase atmospheric CO_2 removals must be implemented to mitigate climate change and limit its impacts. Natural and anthropized ecosystems could play a major role in the biogeochemical cycles of CO_2 emissions or storage. The '4 per 1000' initiative launched at the Paris climate conference (COP21, December 2015) proposes increasing soil organic carbon (SOC) stocks by 0.4% per year in the 40 cm deep soil layer to partially offset global greenhouse gas (GHG) emissions from

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human activities. A recent study in France estimated the carbon storage potential in cultivated soils for annual crops, permanent grasslands, vineyards and forests and analyzed the cost-benefit of certain practices that could increase storage (Pellerin et al., 2020). However, this work does not document fruit crops due to a lack of data on carbon stock balances and changes in orchards.

A carbon balance must be conducted at the ecosystem scale to assess the role of ecosystems as carbon sinks or sources and accounting for lateral transfers in the agroecosystems (Chapin et al., 2006; Montanaro et al., 2021; Smith et al., 2010). In the absence of CO_2 flux measurements, biomass measurements are used to determine the Net Primary Production (NPP). The Net Ecosystem Production (NEP) of an agroecosystem is calculated by subtracting soil heterotrophic respiration (Rh), which can be estimated from litter decomposition including the belowground C derived from root turnover and changes in soil organic carbon (SOC) stock. NEP is considered a good proxy for the rate of organic carbon accumulation in ecosystems if imports and exports of organic carbon from the agroecosystem are negligible (Lovett et al., 2006). These lateral C transports can be significant in orchards and should be considered with the Net Ecosystem Carbon Balance (NECB). A positive NECB indicates an accumulation of carbon in the system, resulting in a gradual increase of SOC stocks in the medium to long term.

At the Mediterranean production area scale, some studies have been carried out to quantify carbon balances and assess soil storage for fruit species such as apple (Demestihas et al., 2018; Panzacchi et al., 2012; Zanotelli et al., 2015), citrus (Iglesias et al., 2013; Liguori et al., 2009), kiwi (Rossi et al., 2007), olive (Nardino et al., 2013; Sofo et al., 2005), and peach (Baldi et al., 2018; Montanaro et al., 2017a). However, the objectives, methodologies used, and management systems of the orchards studied appear very different, resulting in very large variability in the estimates of carbon storage capacities by orchards (for example, in peach, NPP ranging from 760 to 6550 kg C ha^{-1} yr^{-1} or 76–655 g C m^{-2}). This variability observed for primary production was undoubtedly strongly influenced by orchard designs (choice of variety and rootstock, planting density) and training systems that act on the distribution and use of light within the orchard (Corelli-Grappadelli and Marini, 2008) with a strong impact on carbon fixation, consequently influencing yield elaboration and fruit quality (Génard et al., 2008; Vercambre et al., 2014).

Carbon budgets are also strongly influenced by the cultural practices implemented to manage the orchards. The effect of organic amendments, soil management (cover crop in inter-row and/or on tree row), mechanical tillage, residue management (pruning wood left on the plot or exported) and irrigation intensity strongly influence the carbon balance (Aguilera et al., 2013; Demestihas et al., 2017, 2019; Montanaro et al., 2012, 2017b; Pardo et al., 2017). Indeed, there is a need for agroecological management systems that encourage practices that combine good productivity with ecosystem services such as carbon sequestration (Corelli-Grappadelli and Morandi, 2012; Demestihas et al., 2019). However, to our knowledge, few carbon balance studies have focused on the effect of alternative practices to reduce chemical pesticide use, but with the risk of increasing pest damages and decreasing NPP (Demestihas et al., 2019). Similarly, some alternative practices used to decrease tree susceptibility to pests and diseases, such as reducing of irrigation, nitrogen fertilization and widespread orchard ground cover to eliminate chemical weeding, could impact primary production capacities and lead to a negative carbon balance (Panzacchi et al., 2012; Testi et al., 2008; Tworkoski and Glenn, 2010).

In the present study, we conducted a system experiment [see principles in Debaeke et al. (2009) and Simon et al. (2017)] to evaluate the effect of innovative peach orchard management on reducing chemical pesticide use by more than 50% through a combination of techniques and new decision rules (Plénet et al., 2019). The objective is to realize annual balances over the period from planting to the seventh year of the orchard's life (2013–2019) by i) determining the amounts of biomass produced and the annual carbon fixation (NPP) in the different components of the aboveground parts of the trees and ii) making carbon balances by integrating an estimate of root biomass, carbon imports and exports, biomass restitutions to the soil, and the evolution of the organic carbon stock in the soil in order to evaluate NEP and NECB since planting. The comparison between the different systems tested allows us to analyze the impacts of low input strategies and planting density on the quantities of carbon stored during the juvenile period of the orchard and when the trees are mature (full fruit production). The results were compared to those observed in other situations and are discussed herein.

2. Material and methods

2.1. Experimental site and management orchard systems

The study was conducted at the INRAE experimental station in the south of France at Avignon (43° 60'N, 4° 49'E, 24 m above sea level) in a Mediterranean climate. The average annual climate data for the 1990–2019 period was 14.7 °C for annual mean temperature, 692 mm for cumulative rainfall and 1136 mm for potential evapotranspiration, with a water deficit of − 569 mm over the April to September period. The soil surface horizon (0–30 cm) was composed of 33.7 % clays, 54.0 % silts and 13.0 % sands (silty clay loam texture). The soil was rich in calcium carbonate (36.7 %) with a pH of 8.1. The organic carbon and nitrogen contents were, on average, 15.0 and 1.48 g kg^{-1} of soil, respectively, at the start of the experiment.

In February 2013, dormant budded plants of *Prunus persica* (L.) Batsch *var. nucipersica*, cultivar 'Nectarlove' grafted on rootstock *P. persica* × *P. amygdalus* 'INRA® GF677' were planted in three contiguous plots of 0.12 ha each. The 'Nectarlove' cultivar is a white-fleshed nectarine (mid-season cultivar) with a high potential for large fruit sizes.

The experiment aimed to compare three cropping systems that differed in planting design, tree training, strategies of protection against weeds, pests and diseases, and fertilization and irrigation practices. Table A.1 (Appendix A) presents the orchard design and the principles of the management strategies that were applied from 2013–2019. Briefly, the 'Reference' orchard management system (REF) was based on current recommendations in southern France for tree training, cultural methods and orchard protection practices, with high fruit production and economic profitability goals, without taking risks for the control of pests and diseases. The supply of irrigation water and fertilizer, especially nitrogen, was carried out according to tree requirements as recommended by Soing (1999) but aiming at minimizing the environmental impacts linked to excessive inputs. The two low-input management systems (LI-1 and LI-2) were developed to drastically reduce chemical pesticide use with a target of − 50 % compared to the REF system, thanks to alternative methods, including biocontrol products, physical barriers, intensification of the conservation biological control of pests, sanitation practices, increase in pest and disease symptom monitoring thresholds, among others, as described for apple by Simon et al. (2011).

In these two low-input systems, an organic amendment was applied locally in tree rows in 2017 with a product based on dehydrated sheep manure mixed with organic waste (Vegethumus by Frayssinet Corp. with 82% dry matter, 60% organic matter, 30% organic carbon, 2.2% total nitrogen) at a dose of 2857 kg ha^{-1} (1714 kg organic matter ha^{-1} and 857 kg C ha^{-1}). The management strategies for protection, fertilization and irrigation between the two low-input systems were identical. However, the LI-2 system was conducted with a high planting density and an oblique single Y-shape tree. In all systems, a ground cover crop in the middle of alleys between tree rows was sown at the end of November 2013 with a mixture of fescue (*Festuca arundinacea* Schreb.) and ryegrass (*Lolium perenne* L.) followed by gradual colonization by spontaneous natural vegetation.

2.2. Training systems

The double Y-shape trees (Giauque and Hilaire, 2003) were spaced

3.50 m along the row and 5.0 m between rows, resulting in a planting density of 571 trees ha^{-1}. The training trees were carried out according to the principles traditionally used in southern France for a double Y-shape as described in Bussi and Plénet (2012). The new simple oblique Y-shape tree was adapted to simple Y-shape trees (Corelli-Grappadelli and Marini, 2008; Giauque and Hilaire, 2003). The trees were spaced 2.20 m along the row and 5.0 m between the rows, giving a planting density of 909 trees ha^{-1} with two primary scaffold branches per tree (one on each side of the row). Regardless of the training system, the scaffold branches were headed at about 3.0–3.2 m in height when the trees were mature.

In both training systems, the objective of winter pruning was to form or maintain the desired tree architecture by removing excess shoots and branches and selecting the preferred unit production of 1-year-old fruiting shoots (40–80 cm long). In both training systems, the summer pruning was carried out in the first half of June to suppress excessively vigorous shoots. In all systems, fruits were manually thinned in the first 15 days of May. Fruit load was defined for each system as a function of the tree vigor, quality of the 1-year-old fruit-bearing shoot, flower bud density, fruit setting rate and the yield goal according to tree age.

2.3. Aboveground production and carbon partition

All measurements were performed annually between 2015 (i.e., trees beginning their third year) and the end of 2019 (7-year-old trees). At the end of each year, three trees per system were selected as representatives of the tree vigor variability within the system estimated by Trunk-Cross-Sectional Area (TCSA). The measurements of trunk circumference (at 30 cm above ground level) were carried out at the beginning of each year on all trees in the systems to calculate TCSA (cm^2 tree^{-1}).

The trees' aboveground biomass (AGB) was measured by differentiating compartments according to the following procedure.

2.3.1. Leaf biomass and surface

Before their natural fall, all leaves of three trees per system were manually removed and fresh weighted for each scaffold branch. A sample of 50 leaves was taken per scaffold, and the surface area was then measured (LI-3100 C, LI-COR, Inc). Next, leaves were oven-dried at 80 °C for 48 h and weighed to determine dry mass. Leaf area per tree was calculated by multiplying the total leaf mass per tree by the specific leaf area (cm^2 g^{-1}). Leaf Area Index (LAI, m^2 leaves m^{-2} soil) was then calculated by dividing the leaf area per tree by the ground area of each tree.

2.3.2. Wood biomass

Before winter pruning, the same trees used for defoliation were sawed at ground level, and the aboveground biomass was partitioned into four compartments: 1-year-old fruiting shoot, 2-year-old wood, primary and secondary branches (scaffolds), and trunk. The fresh weight of each compartment was measured at the orchard, and a sample of each compartment was used to determine dry mass content after oven drying at 80 °C for 72 h.

2.3.3. Belowground biomass

Belowground biomass (BGB) of trees was estimated according to a root/shoot functional equilibrium ratio (BGB / AGB). This ratio was set to 0.22 in accordance with the one used in the QualiTree model (Lescourret et al., 2011; Miras-Avalos et al., 2011) following the results of Grossman and DeJong (1994).

2.3.4. Winter and summer pruning

During winter pruning (January-February) and summer (around 10–15 June) pruning operations, the fresh weight of the pruned wood from six trees per system (two trees in three rows). One sample was taken per tree to determine dry matter content after oven drying at 80 °C for 72 h.

2.3.5. Early fruit fall and thinning

About 30 days after full bloom, when unfertilized fruits have been aborted, the number of young fruits at the fruit set stage was counted on 24 tagged fruiting shoots per system. The number of fruits removed at hand thinning (around 60 days after full bloom) was calculated as the difference between the number of fruits at harvest and the number of fruits at the fruit set stage. Next, the biomass of the manually thinned fruits (around mid-May) was determined based on the average weight of a fruit and its carbon concentration, measured on the three cropping systems.

2.3.6. Fruit harvest

The fresh and dry biomass of the fruits was determined during the harvest carried out at maturity (three to four pickings). The fresh weight of fruit per tree was measured each year (2015–2019) on 12 trees per system. The fruits were graded to obtain the fresh weight according to European marketing standards for fruit's visual imperfections and sizes. Samples were taken (four or five replicates of five fruits per grade) to determine the fresh and dry weight of (pulp + skin) and stone after oven drying at 80 °C for 72 h. Fruits that fell to the ground before harvests were counted, and the mass of fallen fruits was calculated considering the mean weight of one fruit. Thus, three yields were calculated: gross yield, which includes fruits harvested from trees and fallen fruits, harvested fruit yield and marketable fruit yield.

2.3.7. Cover crop in alleys

During several mowing operations of the grass in the alleys (in 2015, 2017 and 2018), when the grass growth was the largest, three sampled areas (6 m^2) in the inter-row per system were randomly chosen to measure biomass and carbon concentrations in aboveground grass. Based on visual observations, we estimate that two cuts per year in the REF system and one cut per year in LI-1 and LI-2 systems have a similar production of the measured mowing. The other cuts (two to four depending on the year) had grass production equal to 50%. Irrigation was applied using microjets for the REF system, therefore watering the alleys. In contrast, drip irrigation was used for LI-1 and LI-2 systems and only irrigated the tree rows. For the years without grass biomass measurements, the average biomass measured from all the measurement dates was used as an estimate.

2.3.8. Carbon content

One sample per tree from the different tree compartments (fruit with a distinction between the flesh and the stone, leaf, trunk, scaffold, 1 and 2-year-old fruiting shoot), and mowed grass were used to measure the carbon concentration by dry combustion (Flash EA 1112, Thermo Firmingam Milan, Italy). after being grounded in a mixer ball mill to a fine powder.

2.4. Soil organic carbon

Soil samples were taken just after planting and before sowing grass (March 2013) and in March 2019. On the tree row and in the inter-row, three samples per system were taken by sampling along three (2013) and four (2019) different rows/inter-rows. Four soil cores were taken from 0 to 30 cm and 30–60 cm depth for each sample. The soil samples were air-dried and then passed through a 2-mm sieve. Analytical determinations of soil organic carbon (SOC) were performed by the national soil analysis laboratory of INRAE (LAS, Arras, France) following ISO standards (ISO10694 for C and NF ISO13878 for N). The total carbon (Ctotal) concentration was measured by dry combustion with an elemental analyzer (LECO Autoanalyser, Milan, Italy). At the same time, soil mineral carbon measurements were performed to calculate organic carbon as SOC=Ctotal - Cmineral in the soil.

The soil bulk density was determined in March 2015 using the cylinder method. Cylinder samples from two trenches per system, the trench being perpendicular to the tree row, and three layers per profile

(0–30 cm, 30–60 cm and 60–90 cm) were used. After determining the soil dry weight per cylinder (oven drying for 48 h. at 105 °C), the density was calculated as soil dry weight per cylinder volume. These soil bulk density measurements were used to convert organic C concentration (g C kg^{-1} dry soil) measured in the 0–30 cm layer between March 2013 and March 2019 into SOC stock per hectare (Mg C ha^{-1}).

2.5. Carbon balance

The carbon balances (Smith et al., 2010) of the three orchard systems were evaluated from the annual carbon fixed in aboveground biomass (AGB), taking into account the fate of the different components (perennial biomass and biomass returned to the soil as C_{Litter}). Total NPP_{tree} was estimated as the sum of above and belowground biomass of the trees ($ANPP_{tree}+BNPP_{tree}$). C_{Litter} and C fixed in the perennial biomass were then calculated, assuming that around 50 % of the root biomass, i.e., fine roots recycled each year, according to Montanaro et al. (2017a). Similar calculations were made to determine biomass in grass growing in alleys with AGB_{grass}, BGB_{grass} considering a root shoot ratio of 0.70 and assuming that 90% of root biomass was recycled each year (Verburg et al., 2004; Watson et al., 2000). The total NPP of the orchard ($NPP_{orchard}$) was the sum of NPP_{tree} and NPP_{grass}.

As heterotrophic soil respiration (Rh) was not measured, we assessed its importance by the carbon balance method confronting variations in SOC stocks (ΔSOC) between March 2013 and March 2019 with the amounts of organic C returned to the soil during the same period (1–6-year-old tree period), according to Baldi et al. (2018):

$$Rh_{orchard} \sim \text{NPP returned to soil} - \Delta SOC$$

where NPP returned to soil was C_{Litter} + C recycled each year from roots (50% of $BNPP_{tree}$ and 90% of $BNPP_{grass}$; Montanaro et al., 2017a; Watson et al., 2000).

With this information, we computed NEP and NECB at the orchard scale as:

$$NEP_{orchard} = NPP_{orchard} - Rh_{orchard}$$

$$NECB_{orchard} = NEP_{orchard} + LTC_{orchard}$$

This estimation accounts for tree biomass, grass biomass in the alleys, and the C importation/exportation (lateral transports, $LTC_{orchard}$) associated with the organic amendment and harvested fruits. We assumed that other fluxes were negligible compared to main fluxes, e.g., C losses by soil erosion, C emitted in volatile organic compounds, dissolved organic or inorganic C leaching.

As no sampling or destructive measurements were conducted before 2015, the NPP and C returned to the soil in 2013 and 2014 were estimated as a fraction of the NPP estimated in 2015, according to the TCSA ratio between these specific years and the 2015 TCSA. Therefore, NPP in 2013 and 2014, respectively were 10 ± 0.7% and 52 ± 1.7% in the REF system, 13 ± 0.6% and 65 ± 1.3% in the LI-1 system, and 17 ± 0.3% and 65 ± 1.0% in the LI-2 system compared to the NPP observed in 2015.

2.6. Data analyses

One-way analyses of variance (ANOVA) were performed with 12 trees as randomized replications per system to test differences in agronomic performance between management systems.

The measurements of the various biomass and carbon compartments were not carried out on the same number of trees (12 trees per system for fruits, six trees for pruning operations and three trees for destructive measurements to quantify the leaves and perennial tree components), pooling samples made data groupings from trees located on the same row to obtain three replicates per system. These trees were then classified into three vigor groups according to TCSA. Two-way ANOVA was used to test the difference between three management systems with three vigor classes as a controlled factor. Three-way ANOVA was used to assess the effects of orchard life periods, system and vigor factors on biomass production. Finally, the means of management systems were compared with the Tukey t-test at a 5% probability level.

Linear regressions were calculated to determine relationships among TCSA and different compartments of biomass and carbon, and an analysis of covariance was used to test the effects of management systems. If the differences between cropping systems were not significant, data were pooled to fit a single linear relationship.

In the carbon budgets where data came from different sources of information (biomass measurements, SOC changes, allometric relationships, among others), the uncertainties around the means were estimated with the error propagation method:

$$SEz = \sqrt{(SEx)^2 + (SEy)^2}$$

where SEz is the standard error of the variable Z, which is obtained by adding or subtracting two variables, X and Y, with their corresponding standard errors SEx and SEy. Then, the comparison of mean values between management systems was performed using the bilateral Student's t-test. All means are presented with their standard error (mean ± SE). All computations were made with XLSTAT 2020 software (Addinsoft company) or R statistical software (R core Team, 2020).

3. Results

3.1. Performance indicators observed according to system management

The decision-making and system management rules have significantly reduced chemical pesticide use (approximately −70% in LI-1 and LI-2 compared to REF, Table 1). Notably, the fertilizer use was reduced by − 20% for nitrogen, − 59% for phosphorus, and − 32% for potassium compared to the region's recommended quantities (Soing, 1999). Additionally, irrigation was reduced by 26% compared to the tree crop water requirements.

Since planting, tree growth measured by Trunk Cross-Sectional Area (TCSA) indicator was similar in the REF and LI-1 systems and lower in LI-2 since 2016 (Fig. 1). In contrast, cumulated TCSA for LI-2, expressed in m^2 ha^{-1} and measured at the beginning of 2020, was significantly higher ($F = 15.07$; $P < 0.0001$) that the REF and LI-1 systems due to a higher tree density (TCSA: 5.77 ± 0.15, 5.92 ± 0.20 and 7.29 ± 0.28 m^2 ha^{-1} in REF, LI-1 and LI-2 respectively).

The first fruit harvests were made in 2015 (three years after planting), and the fruit production reached its maximum in 2017, five years after planting (Fig. 2). Thus, the average productions of the three systems represented 24.6% in 2015 and 75.2% in 2016 of the average gross yields calculated over the period 2017–2019 when trees were fully

Table 1
Average quantities per year calculated over the fruit production period (2015–2019) in the number of chemical pesticides (number of commercial products ha^{-1} yr^{-1}), N, P_2O_5 and K_2O fertilizers (kg ha^{-1} yr^{-1}) and irrigation water (mm yr^{-1}) according to three system management strategies in INRAE Avignon site. REF: current reference management; LI-1 and LI-2: Low-Input system management 1 (571 trees ha^{-1}) and 2 (909 trees ha^{-1}). Means ± standard errors calculated over 5 years.

Inputs		Management systems		
		REF	LI-1	LI-2
Chemical pesticides (n° yr^{-1})		21.2 ± 2.5	7.0 ± 1.8	6.4 ± 1.6
Fertilizers (kg ha^{-1} yr^{-1})	N	132.2 ± 9.6	106.4 ± 8.5	106.4 ± 8.5
	P_2O_5	38.8 ± 13.1	16.0 ± 6.7	16.0 ± 6.7
	K_2O	107.8 ± 19.6	73.4 ± 11.8	61.2 ± 15.6
Water irrigation (mm yr^{-1})		649 ± 50	476 ± 45	484 ± 46

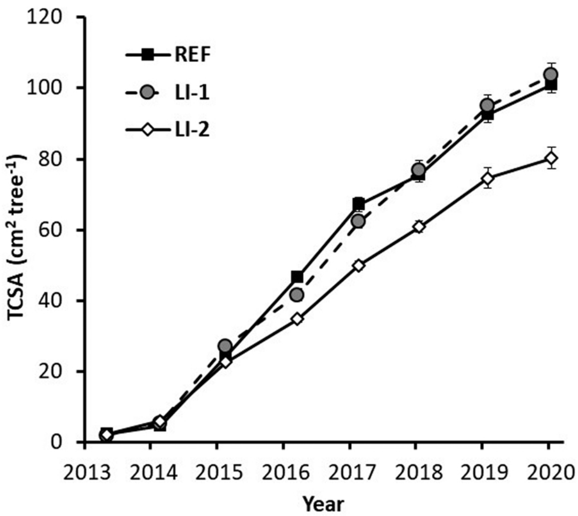

Fig. 1. Evolution of Trunk Cross-Sectional Area (TCSA in cm^2 tree^{-1}) in three management systems since planting in February 2013 of peach trees. Measurements were carried out on the same trees in January-February of each year except 2013 (June 2013). Mean ± SE ($n = 12$).

mature (45.9 Mg ha^{-1} for REF, 46.6 Mg ha^{-1} for LI-1 and 56.3 Mg ha^{-1} for LI-2). Fresh fruit production per tree followed a fairly similar pattern in REF and LI-1 systems, with average performance over 2015–2019 not being significantly different (Table 2). The input reductions in systems with the same planting density and training system did not negatively impact average performance during the first seven years of the orchard's life. It even slightly improved soluble solids contents due to water restriction (+0.8% Brix, $P < 0.001$). The number and fruit production per tree were lower in the LI-2 system than in the REF and LI-1 systems. On the other hand, the increase in planting density caused a significant increase in most performance criteria expressed per hectare compared to the REF system, with a notable + 17% for gross yield and + 27% in marketable fruit yield and a similar fruit weight and quality compared to the REF system.

Leaf area index (LAI, m^2 leaf m^{-2} soil) was significantly different over the 2015–2019 period, with LI-2 superior (29.5%) to the REF and LI-1 systems (Table 2). The LAI was also significantly higher in the mature tree period ($F = 10.03$, $P = 0.001$) in the LI-2 system (4.76 ± 0.56) compared to the REF (3.64 ± 0.31) and LI-1 (3.73 ± 0.36) systems, but no differences were observed during the juvenile period (average LAI for 2015–2016: 2.01 ± 0.16 in REF, 1.83 ± 0.20 in LI-1 and 2.34 ± 0.39 in LI-2, $F = 2.83$, $P = 0.93$).

3.2. Biomass production and C fixation in peach trees

The annual production of biomass and carbon fixed in the different components of the tree during the first five years of fruit production (period 2015–2019) are presented in Tables A.2 and A.3 (Appendix A). In mature trees, annual dry matter distribution was identical for the three cropping systems with about 47 % in fruits, 21 % in leaves, 8 % in 1-year old shoots, 11.5 % in 2-year old wood, 9 % in scaffolds, 2.9–1.3 % in trunk and summer pruning operation accounted for about 1 % of the aboveground biomass. Carbon distribution was similar except for the proportion of carbon in fruits, representing 41.3 % of the total carbon fixed by the tree's aerial parts. Indeed, fruits were characterized by a significantly lower dry matter percentage and carbon content than other components (Table A.4, Appendix A). After grouping the different organs into three components (fruits, new vegetative organs and perennial structures), Fig. 3 shows similar evolution patterns for the components in all systems despite some fluctuations. Annual dry biomass and carbon production increased between 2015 and 2016 and peaked between 2017 and 2019, i.e., when trees were mature. Therefore, data were grouped into two periods, with the juvenile tree period (2015–2016) corresponding to the first two years of fruit production and the mature tree period pooling the years 2017–2019, presenting potential production during the mature orchard lifespan.

The juvenile tree period was characterized by significantly lower growth and carbon fixed than the mature tree period (Fig. 4 and Table A.5 in appendix A) for all components and total aboveground tree biomass (F value between 45 and 2083 with *P-value* < 0.001; $n = 9$; ANOVA results not shown). During the juvenile tree period, total growth and carbon fixed in the LI-1 system were significantly lower than in the REF system, indicating that at the same planting density, the reduction of inputs had a negative effect by affecting mostly fruits and leaves to a lesser extent. In the LI-2 system, the increase in planting density compensated for the negative effect of input reductions because biomass and carbon were significantly increased compared to the REF and LI-1 systems. During the mature tree period, growth and carbon fixed in perennial and new vegetative components were not significantly different between the three systems, although LI-2 tended to have systematically slightly higher values. Furthermore, the LI-2 system differed significantly by biomass growth and carbon accumulated in the fruits, leading to significantly higher carbon fixed in the total aboveground tree than in the REF and LI-1 systems (+1300 kg C ha^{-1} yr^{-1}).

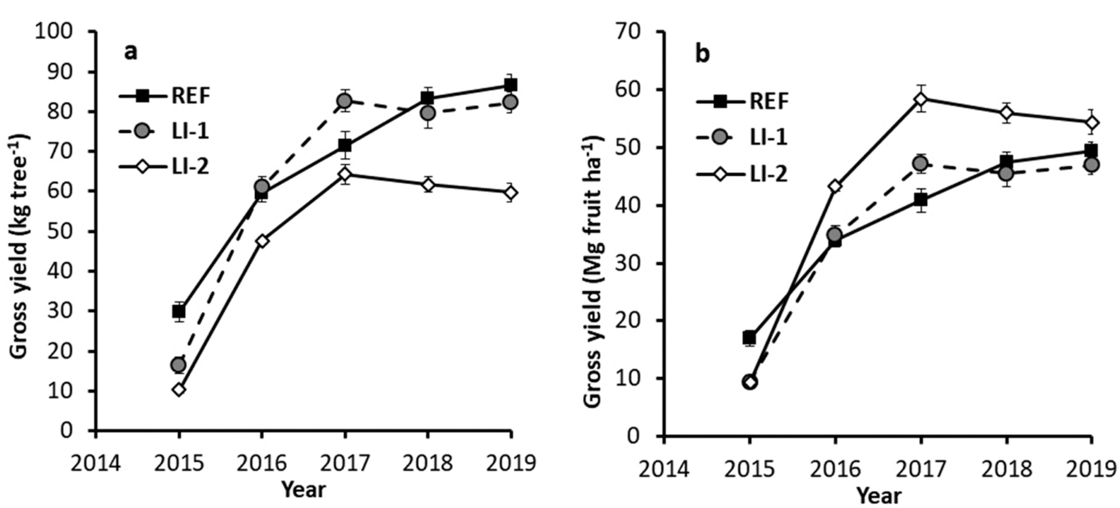

Fig. 2. Gross fresh fruit yield produced by the peach trees in three management systems from first year of fruit production: (a) yield in kg fruit tree^{-1}; (b) yield in Mg fruit ha^{-1} to integrate planting density effect (571 trees ha^{-1} for REF and LI-1; 909 trees ha^{-1} for LI-2). Planting date February 2013. Mean ± SE ($n = 12$).

Table 2
Main performance indicators (mean yr^{-1} calculated over the 2015–2019 fruit production period) according to three system management strategies. REF: current reference management (571 trees ha^{-1}); LI-1 and LI-2: Low-Input system management with 571 trees ha^{-1} and 909 trees ha^{-1}, respectively. *F* and *P*-value of ANOVA, $n = 12$ ($n = 3$ for LAI). The different letters in each line indicate significant differences ($P < 0.05$; Tuckey test) between cropping systems.

Agronomic performances per year	REF	LI-1	LI-2	*F*	*P*-value
Number of total fruits per tree yr^{-1}	389 a	375 a	285 b	54.65	< 0.0001
Gross fresh fruit weight per tree (kg $tree^{-1}$ yr^{-1})	66.17 a	64.41 a	48.73 b	50.71	< 0.0001
Number of harvested fruits per hectare (x1000)	193.6 b	197.9 b	238.6 a	24.83	< 0.0001
Gross yield (Mg fresh fruit ha^{-1} yr^{-1})	37.78 b	36.78 b	44.29 a	20.78	< 0.0001
Mass of fallen fruits per hectare (Mg ha^{-1} yr^{-1})	4.74a	2.44 c	3.21 b	48.24	< 0.0001
Harvested fruit yield (Mg fresh fruit ha^{-1} yr^{-1})	32.63 b	33.89 b	39.08 a	27.17	< 0.0001
Marketable fruit yield (Mg fresh fruit ha^{-1} yr^{-1})	27.71 b	29.18 b	35.30 a	22.76	< 0.0001
Mean fruit weight (g fresh $fruit^{-1}$)	175.9 a	177.8 a	174.6 a	0.64	0.53
Total Soluble Solids content (%)	13.2 b	14.0 a	13.4 b	20.32	< 0.0001
Leaf Area Index (LAI) m^2 leaves m^{-2} soil	3.02 b	3.00 b	3.91 a	13.63	< 0.0001

Pruned wood per hectare was significantly higher in the LI-2 system with higher density trees for juvenile and mature tree periods (Table A.5). During winter pruning operations, the amount of biomass and carbon removed from trees was more than doubled (212 % for biomass and 237 % for carbon) for mature tree period compared to juvenile tree period. The ratio between winter pruned wood and the sum of the 1-year-old shoots and 2-year-old wood was about 68 % for biomass and 70 % for carbon regardless of tree age. Winter pruned woods represented 11.5 % of total annual aboveground growth during the juvenile tree period and 13.5 % during the mature tree period.

3.3. Allometric relationship between trunk cross-sectional area and biomass of peach trees

Fig. 5 shows the linear relationships between annual biomass stored in perennial tree structures and new vegetative components with TCSA, an easily measured indicator. As the analysis of covariance did not detected a significant effect of cropping systems, data were pooled to fit a single linear relationship for all systems. The linear relationship between TCSA and biomass growth in the perennial tree structures ($R^2 = 0.95$, $P < 0.001$; Fig. 5a) and the relationship between TCSA and carbon were well fitted ($R^2 = 0.93$, $P < 0.001$; not shown). On the other hand, the relationship between TCSA - new vegetative components was less precise ($R^2 = 0.52$, $P < 0.001$; Fig. 5b), especially when TCSA was

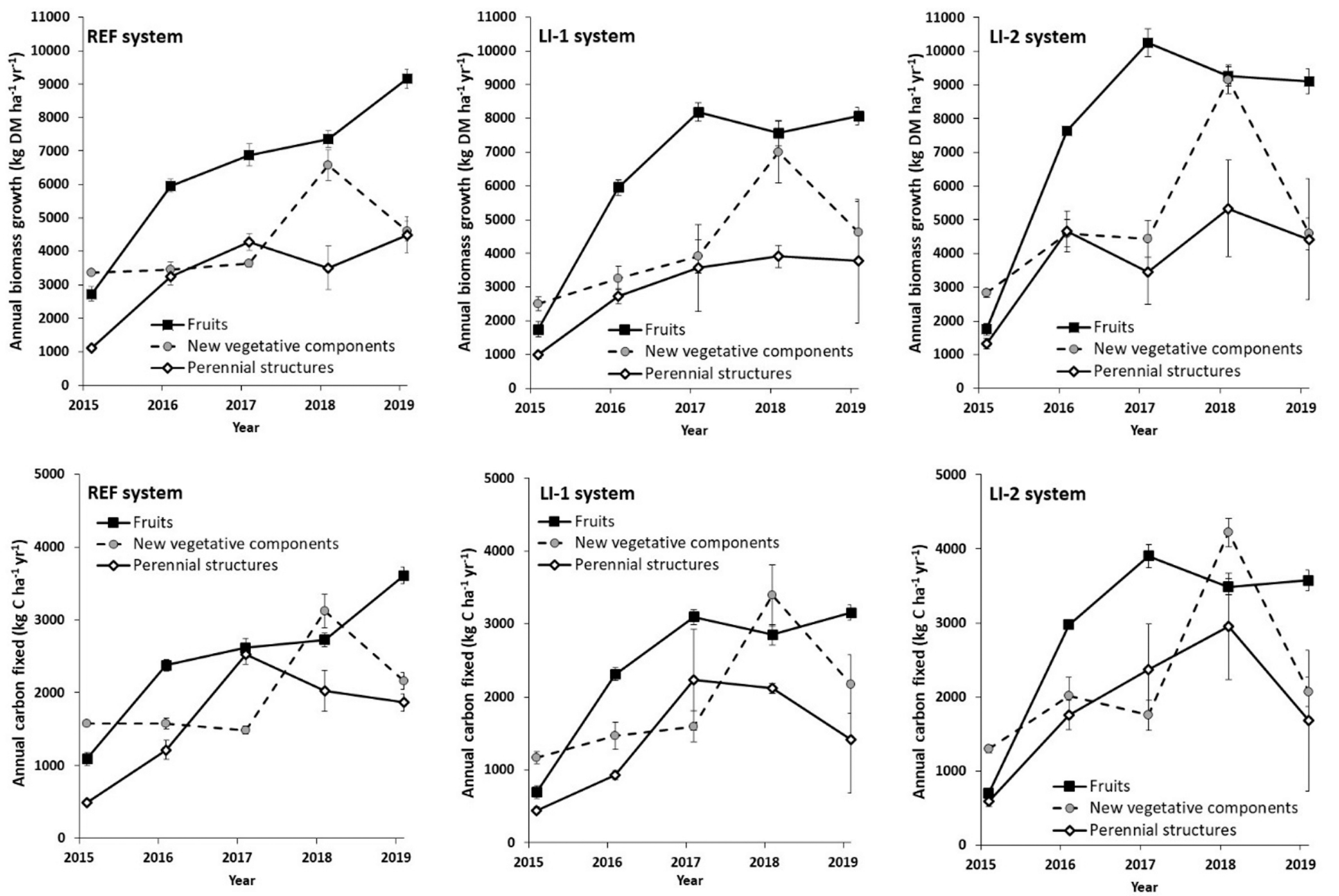

Fig. 3. Annual biomass growth (kg DW ha^{-1} yr^{-1}) and carbon fixed (kg C ha^{-1} yr^{-1}) in three aboveground components of peach trees grown under three cropping systems (REF, LI-1, and LI-2) during the first 5 years of fruit production after planting in February 2013. Mean ± SE ($n = 3$ or $n = 12$ for fruits). New vegetative components: leaves, 1-year-old shoot and summer pruning shoots; perennial structures: 2-year-old woods, scaffolds, and trunk.

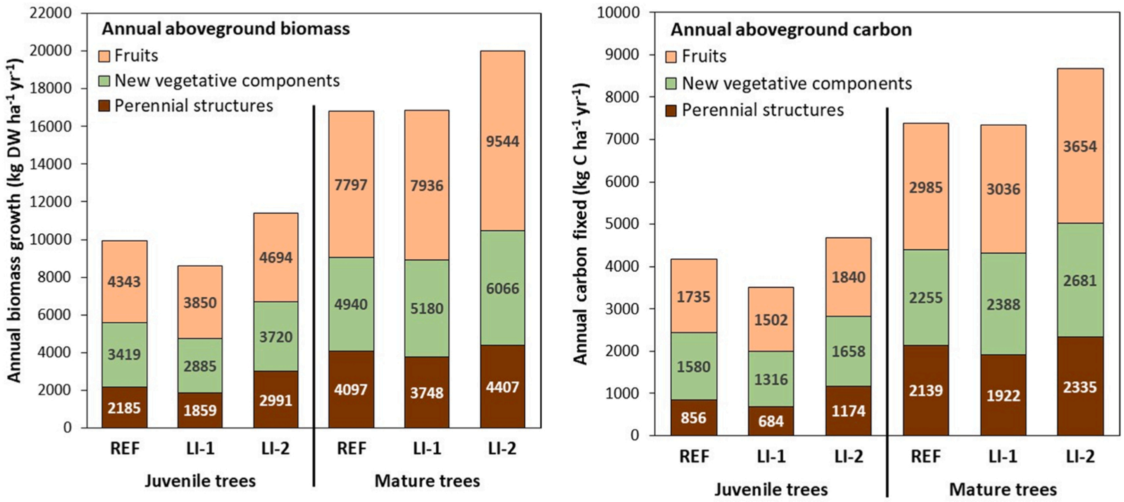

Fig. 4. Annual aboveground biomass production (kg DW ha^{-1} yr^{-1}) and carbon fixed (kg C ha^{-1} yr^{-1}) for three components and two periods of tree peach growth (juvenile trees: mean 2015–2016; mature trees: mean 2017–2019) according to three system management strategies (REF: current reference management with 571 trees ha^{-1}; LI-1 and LI-2: Low-Input system management with 571 trees ha^{-1} and 909 trees ha^{-1}, respectively).

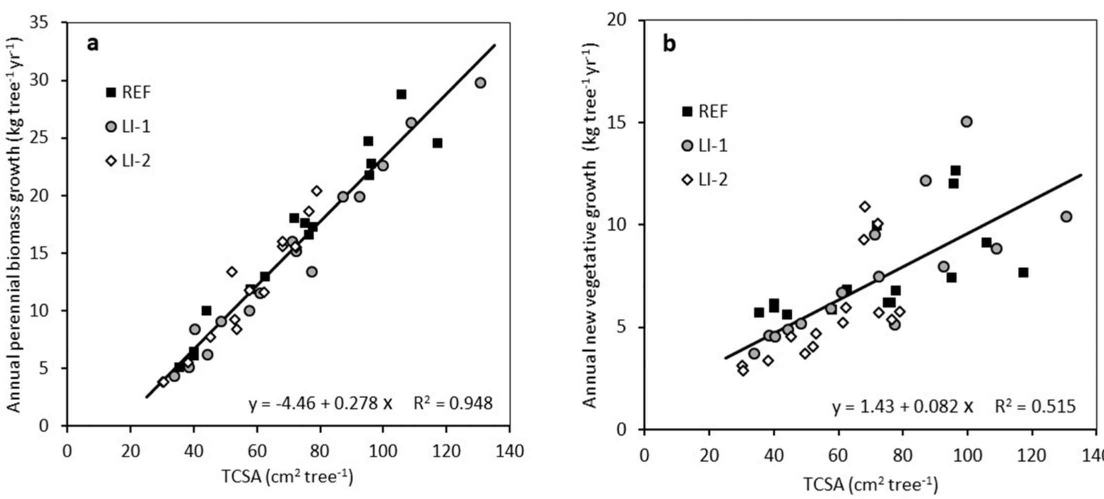

Fig. 5. Relationship between the trunk cross sectional area (TCSA, cm^2 $tree^{-1}$) over 2015–2019 and the amount of annual biomass growth (kg DW $tree^{-1}$ yr^{-1}) stored in (a) perennial tree structures and (b) new vegetative components of peach trees with pooling of three system management strategies. Linear regression (a): intercept: -4.46 ± 0.7; slope: 0.278 ± 0.010; $R^2 = 0.948$, *P-value* < 0.0001, n = 45; Linear regression (b): intercept: 1.43 ± 0.86; slope: 0.082 ± 0.012; $R^2 = 0.515$, *P-value* < 0.0001, n = 45.

greater than 60 cm^2 per tree, as well as for carbon ($R^2 = 0.47$, $P < 0.001$; not shown). Thus, the TCSA indicator predicted well the biomass growth and carbon stored in the perennial tree structures for the first seven years of the orchard's life, while the relationship is much less robust to estimate the annual vegetative growth for older trees. The relationships were not improved if annual TCSA increases were used (not shown).

3.4. Biomass production and carbon fixed par ground cover in orchard alleys

Biomass and carbon production from the aerial parts of grass located in the alleys were significantly higher in the LI-1 system than in the other systems (Table 3), mainly related to higher production in 2015. Grass carbon contents were similar between systems (on average 405.9 $\pm$ 4.9 g C kg^{-1} DW). Considering the number of cuts per year and the area occupied by grass in alleys, annual aboveground biomass productions when grass was well established (2015–2019) ranged from 2007 to 2543 kg DW ha^{-1}. The amounts of carbon fixed by grass were slightly higher in the REF system (1036 kg C ha^{-1}) but not significantly (t-test, *P-value* = 0.64) compared to the LI-1 (922 kg C ha^{-1}) and LI-2 (818 kg C ha^{-1}, *P-value* = 0.33) systems. This result might be due to a slightly larger grass area in alleys and irrigation mode (microjet) which partially irrigated the middle of alleys in the REF system.

3.5. Evolution of soil organic carbon stocks

The soil bulk densities measured in the 0–30 cm layer in March 2015 were lower in the LI-1 system (1.40 ± 0.09 g cm^{-3}) and LI-2 system (1.42 ± 0.04 g cm^{-3}) than in the REF system (1.50 ± 0.01 g cm^{-3}), undoubtedly in connection with soil organic carbon concentrations. The initial (2013) organic carbon stocks in 0–30 cm horizon and the stocks measured in 2019 were significantly different between the REF and LI-1 and LI-2 systems (Table 4). Likewise, the differences between 2013 and 2019 stocks for the soil located in the tree rows and the soil located in alleys with grass were not significantly different (F = 0.075 *P*-value = 0.79 for tree rows and F = 3.46, *P*-value = 0.08 for alleys). However, the annual evolution of SOC stocks indicated a slight decrease in the tree row zone, except in LI-2, where an increase of 1248 kg C ha^{-1} yr^{-1} was

Table 3
Annual grass biomass production (g DW m^{-2}) and carbon fixed (g C m^{-2}) for the largest cut for 3 years and mean annual biomass (kg DW ha^{-1} yr^{-1}) and carbon fixed (kg C ha^{-1} yr^{-1}) calculated in the 2015–2019 period, assuming two cuts with a maximum grass production per year in REF system and only one cut with a maximum grass production per year in LI-1 and LI-2 systems. Other cut (two to four depending on the year) had a grass production equal to 50% of the maximal production. *F* and *P*-value of ANOVA, $n = 3$ per system. For each variable (biomass or carbon), different letters in each line indicate significant differences ($P < 0.05$; Tuckey test) between cropping systems.

Year	REF	LI-1	LI-2	*F*	*P*-value
	Biomass (g DW m^{-2})				
2015	159 ± 12 b	295 ± 16 a	210 ± 15 b	22.7	0.002
2017	164 ± 19 a	150 ± 15 a	161 ± 11 a	0.37	0.796
2018	103 ± 26 a	103 ± 14 a	118 ± 17 a	0.19	0.832
Mean	142 ± 24 b	182 ± 52 a	163 ± 26 ab	4.47	0.027
	Carbon (g C m^{-2})				
2015	65.9 ± 5.7 b	124.3 ± 6.7 a	87.3 ± 5.0 b	27.7	0.001
2017	67.8 ± 8.7 a	61.7 ± 6.3 a	65.6 ± 6.4 a	0.18	0.837
2018	39.9 ± 10.1 a	40.1 ± 5.8 a	46.3 ± 7.0 a	0.21	0.814
Mean	57.9 ± 10.5 b	75.4 ± 22.5 a	66.4 ± 11.6 ab	4.75	0.022
	Annual aboveground biomass and carbon (2015–2019)				
Biomass (kg DW ha^{-1} yr^{-1})	2543 ± 380	2236 ± 398	2007 ± 248		
Carbon (kg C ha^{-1} yr^{-1})	1036 ± 163	922 ± 171	818 ± 108		

Table 4
Stock of soil organic carbon (mean ± SE of SOC, Mg C ha^{-1}) was measured in March 2013 and March 2019 within the 0–30 cm layer from the ground surface according to three system management strategies. Samples in March 2019 were carried out in the row of trees and the alleys with grass cover. ΔSOC (kg C ha^{-1} yr^{-1}) corresponds to a mean annual variation between 2013 and 2019 in the tree rows and alleys, and orchard corresponds to the average variation of C stock by weighted by row and alley in their respective areas. *F* and *P*-value of ANOVA, $n = 3$ in 2013 and $n = 4$ in 2019 per system. Different letters indicate significant differences ($P < 0.05$; Tukey test) between cropping systems for soil organic carbon columns. For ΔSOC, all comparisons of means with t student-test were non-significantly different (*P*-value > 0.05).

	Stock of SOC (Mg C ha^{-1})			ΔSOC (kg C ha^{-1} yr^{-1})		
Systems	2013	2019 Row	2019 Alley	Row	Alley	Orchard
REF	57± 4.3 b	53 ± 1.1 b	61 ± 1.8 b	-594 ± 744	756 ± 782	216 ± 739
LI-1	71 ± 2.5 a	69 ± 4.4 a	76 ± 1.1 a	-286 ± 843	817 ± 457	287 ± 594
LI-2	72 ± 2.7 a	80± 4.2 a	74 ± 2.0 a	1248 ± 836	237 ± 563	722 ± 580
F	7.12	14.29	22.48			
P-value	0.026	0.002	0.000			

observed. A slight increase in carbon stock was observed in alleys for all systems. The SOC stock at the orchard scale was calculated by weighting carbon stocks in the rows and alleys of their respective areas. We observed a slight annual increase in the carbon stock of the soil (216–722 kg C ha^{-1} yr^{-1}). However, there was no significant difference between the systems, even when the differences were the largest (LI-2 vs REF, *P-value* = 0.62). It must be emphasized that there are large uncertainties in these estimates due to spatial variability of the SOC and the small magnitude of C stock changes on a time scale of less than 10 years compared to the total SOC stock. These SOC changes at the orchard-scale corresponded to average annual increases of 3.8‰, 4.0‰ and 10.0‰ of SOC per year in 0–30 cm layer in the REF, LI-1 and LI-2 systems, respectively.

3.6. Carbon balances for orchards

Based on biomass production and carbon fixed in trees and grass, annual carbon fluxes were calculated to quantify different components associated with trees and periods (1–6-year-old trees and mature periods) and grass (Table A.6, appendix A). Overall (average of all systems), $NPP_{orchard}$ and C returned to soil were 1.7 and 1.6 times higher during the mature tree period than the 1–6-year-old tree period. In particular, C exportation by harvested fruits increased by 210% in relation to the increase in fruit production with orchard age. NPP_{grass} represented 18% and 14% of the total $NPP_{orchard}$ in the 1–6-year-old and mature tree periods, respectively. The proportion of C returned to soil (leaves, fruit fall, root turn-over, pruning wood) was about 50–53% of the $NPP_{orchard}$, while C fixed in perennial tree structures ($NPP_{perennial}$) was 23–25% of the total $NPP_{orchard}$. Carbon exportation by harvested fruits accounted for 26% and 31% of the NPP_{tree} and 22–27% of the $NPP_{orchard}$ in 1–6-year-old and mature tree periods, respectively.

Despite large soil respiration ($Rh_{orchard}$) of 3366 ± 776 kg C ha^{-1} yr^{-1} representing 52% of $NPP_{orchard}$ in the REF system during the 1–6-year-old tree period, the $NEP_{orchard}$ was largely positive (3089 ± 813 kg C ha^{-1} yr^{-1}, Table 5). After subtracting C exportation related to harvested fruits, $NECB_{orchard}$ remained positive (1863 ± 819 kg C ha^{-1} yr^{-1}), indicating that the REF agroecosystem acted as a carbon sink, with 88% carbon stored in the perennial tree structures. Even considering the orchard without cover crop in the alleys, the $NECB_{tree}$ demonstrates a positive carbon fixation in the REF system (999 ± 798 kg C ha^{-1} yr^{-1}) since respiration would lower carbon losses (Rh_{tree} = 2911 ± 768 kg C ha^{-1} yr^{-1}, calculated from SOC changes measured in the tree rows with a bare soil). Over the mature tree period, despite the significant increase in C harvested fruit exports, the $NECB_{mature}$ showed a net accumulation of 4919 ± 858 kg C ha^{-1} yr^{-1} with 53% fixed in perennial tree components.

Carbon balances observed in the low input LI-1 system had the same magnitude and were never significantly different from those in the REF system, indicating a weak effect of these levels of input reductions. The low inputs of organic amendments accounted for a small proportion of carbon budgets in the low-input systems.

In the low-input LI-2 system, due to a large increase in $NPP_{orchard}$ (+12.6% compared to REF, $P = 0.081$; +17.8% compared to LI-1, $P = 0.083$), and despite the increase in fruit export losses, the $NECB_{orchard}$ was higher than the REF (+46%, $P = 0.47$) and LI-1 (+41%, $P = 0.49$) systems during the 1–6-year-old-tree period. In an orchard without grass in alleys, $NECB_{tree}$ would be 221% higher than in the REF system ($P = 0.14$) showing that the positive balance was mainly explained by the increase in tree productivity in this agroecosystem. In the mature tree period, the average fluxes of accumulated C ($NECB_{mature}$

Table 5
Comparison of annual carbon budgets (mean ± SE in kg C ha^{-1} yr^{-1}) of net primary production (NPP), heterotrophic respiration (Rh), net ecosystem production (NEP), lateral transport of carbon (LTC), net ecosystem carbon balance (NECB) and C fixed in perennial tree structures and coarse roots in three system management strategies (REF: current reference management with 571 trees ha^{-1}; LI-1 and LI-2: Low-Input system management with 571 trees ha^{-1} and 909 trees ha^{-1}, respectively). Carbon budget 1 was calculated over the 2013–2018 period, i.e., 1–6-year-old trees at the orchard scale (index letter 'orchard'). Carbon budget 2 corresponded to orchards without grass in the alleys for the 1–6-year-old tree period (index letter 'tree'). Carbon budget 3 corresponded to the orchard with mature trees (2017–2019), i.e., 5–7-year-old trees in full fruit production and stabilized grass biomass production in alleys (index letter 'mature'), but with soil respiration extrapolated from 1 to 6-year-old tree period. *P*-value of student's t-test for comparison of means between REF, LI-1 and LI-2 systems with n = 3 for each system.

	Carbon (kg C ha^{-1} yr^{-1})			*P*-value of Student t-test		
Components	REF	LI-1	LI-2	REF/LI-1	REF/LI-2	LI-1/LI-2
Carbon budget 1: orchard - 1–6-year-old tree period						
$NPP_{orchard}$	6455 ± 242	6170 ± 405	7268 ± 252	0.58	0.081	0.083
$Rh_{orchard}$	3366 ± 776	3006 ± 646	2996 ± 644	0.74	0.73	0.99
$NEP_{orchard}$	3089 ± 813	3164 ± 762	4272 ± 692	0.95	0.33	0.34
$LTC_{orchard}$	-1226 ± 100	-1231 ± 72	-1548 ± 83	0.97	0.068	0.045
$NECB_{orchard}$	1863 ± 819	1933 ± 766	2724 ± 697	0.95	0.47	0.49
C $fixed_{orchard}$ in trees+grass	1647 ± 194	1503 ± 225	1859 ± 265	0.65	0.55	0.36
Carbon budget 2: trees without grass in alleys - 1–6-year-old tree period						
NPP_{tree}	5136 ± 192	4975 ± 376	6207 ± 233	0.72	0.024	0.050
Rh_{tree}	2911 ± 768	2434 ± 869	1453 ± 876	0.70	0.28	0.47
NEP_{tree}	2225 ± 792	2541 ± 947	4754 ± 906	0.81	0.103	0.17
LTC_{tree}	-1226 ± 100	-1231 ± 72	-1548 ± 83	0.97	0.068	0.045
$NECB_{tree}$	999 ± 798	1310 ± 950	3206 ± 910	0.81	0.14	0.22
C $fixed_{tree}$ in trees	1593 ± 318	1454 ± 490	1816 ± 469	0.82	0.62	0.76
Carbon budget 3: mature orchard - 5–7-year-old tree period						
NPP_{mature}	11,003 ± 353	10,729 ± 876	12,160 ± 608	0.79	0.18	0.25
$Rh_{orchard}$	3366 ± 776	3006 ± 646	2996 ± 644	0.74	0.73	0.99
NEP_{mature}	7637 ± 853	7723 ± 1088	9164 ± 886	0.95	0.28	0.36
$LTC_{mtature}$	-2718 ± 100	-2717 ± 72	-3288 ± 83	0.99	0.012	0.007
$NECB_{mature}$	4919 ± 858	5006 ± 1090	5876 ± 890	0.95	0.48	0.57
C $fixed_{mature}$ in trees+grass	2601 ± 338	2501 ± 330	2702 ± 423	0.84	0.88	0.73

= 5876 ± 890 kg C ha^{-1} yr^{-1}) were only 19.4% higher than in the REF system ($P = 0.48$). The substantial elevation of the carbon sink effect in the LI-2 system was mainly attributed to improve of carbon capture during the orchard installation period and higher planting density. Indeed, in mature trees, 46% of the $NECB_{mature}$ was sequestered by the perennial tree structures.

Considering carbon fixed in perennial tree structures during the first six years of the orchard's life and extrapolating the annual fluxes measured on mature trees over the commercial lifespan of peach orchards (about 15 years), the amount of carbon stored in standing biomass would be between 33.3 ± 1.1 Mg C ha^{-1} in the REF system (~ 27.3 Mg C ha^{-1} in aboveground trees) and 35.5 ± 1.4 Mg C ha^{-1} in the LI-2 system (~ 29.1 Mg C ha^{-1} in aboveground trees). No significant differences were observed between systems due to uncertainties associated with this extrapolation. However, the $NECB_{orchard}$ would be much higher (25%) in the LI-2 (69.2 ± 3.2 Mg C ha^{-1}) than in the REF system (55.4 ± 3.3 Mg C ha^{-1}), reflecting higher organic restitution in the soil with high tree planting density, resulting in higher SOC storage than in the conventional system, even if soil respiration could simultaneously increase.

4. Discussion

4.1. NPP and carbon budget in conventional peach orchards

The data acquired during the seven years since planting the peach trees are representative of this fruit's production in France, with a Mediterranean climate and management methods currently used in commercial orchards. Indeed, the REF system corresponds to the dominant management system with a double Y-shape tree training system and 500–600 trees ha^{-1}. Protection against pests and diseases mobilized many chemical treatments. However, this aspect was in line with results obtained in surveys on pesticide use in peach orchards since 2015 (Cretin and Triquenot, 2018). The yields measured in the REF system when the trees were mature (45.9 Mg of fresh fruit weight ha^{-1}) were higher than the averages observed for white nectarine cultivars (31.7 Mg ha^{-1}) in the commercial orchards (EFI peach database, Plénet et al., 2009) but similar to the best performing plots (around 40–50 Mg ha^{-1} for the 80-percentile observed in the peach EFI database for mid-season cultivars with high yield potential; Giauque and Hilaire, 2003; Plénet et al., 2003). The increase in production was rapid with 37% and then 75% of the yield of mature orchards from the third and fourth years after planting. These results are typical of what is currently sought in modern peach orchards to reach maximum productivity as soon as the fifth year after planting (Caruso et al., 2015; Reig et al., 2020).

The results of the NPP observed in the REF system for the period with mature trees are among the highest values reported for peach orchards grown in the Mediterranean area (Sofo et al., 2005; Montanaro et al., 2017a; Baldi et al., 2018). At the same planting density, the high LAI (3.64 ± 0.31) or leaf biomass (1590 kg C ha^{-1} yr^{-1}) observed in our study compared to the leaf biomass reported by Montanaro et al., 2107a; 1139 kg C ha^{-1} yr^{-1}) probably explains this high capacity to fix carbon and the high fruit production. However, the amounts of carbon fixed by grass cover in the REF system were lower than those reported by Montanaro et al. (2017a) (1350 kg C ha^{-1} yr^{-1} vs. 1036 kg C ha^{-1} yr^{-1} in the REF system).

Compared to results observed on other fruit tree species, the NPP_{mature} in the peach REF system was higher than in 10-year-old apple trees (Zanotelli et al., 2015). The LAI observed on apple trees had the same magnitude (3 m^2 m^{-2}) leading to similar NPP_{tree} values. However, the differences in the $NPP_{orchard}$ can be explained by low grass production in apple orchards (520 kg C ha^{-1} yr^{-1}) compared to that measured in the present study, probably due to narrow alley widths (3 m) and greater tree heights in apple orchards. In addition, tree root biomass (BNPP) was much higher (1667 kg C ha^{-1} yr^{-1} in peach vs. 1050 kg C ha^{-1} yr^{-1} in apple) due to a root-shoot ratio of 0.22 (Grossman and DeJong, 1994; Lescourret et al., 2011) compared to that of 0.14 measured on apple (Zanotelli et al., 2015) related to the use of a dwarfing rootstock (M9) on apple which reduces root biomass (Stutte et al., 1994) compared to the rootstock 'GF677' on peach which confers high vigor (Reig et al., 2020). Liguori et al. (2009) reported lower NPP values (6900–7100 kg C ha^{-1}

yr^{-1}) in 12–14-year-old orange (*Citrus sinensis*) orchards. In contrast, for 14-year-old clementine orchards [*Citrus clementina*, ~10,000 kg C ha^{-1} yr^{-1}, Iglesias et al. (2013)] and olive orchards in Spain [*Olea europea*, 11, 850 kg C ha^{-1} yr^{-1}, Nardino et al. (2013)], NPP values were quite similar to our REF system. The high values observed in evergreen species were probably explained by the longer period of carbon fixation during the year than deciduous species.

A lower biomass production (57 %) was observed during the peach orchard establishment period (total AGB = 4172 ± 205 kg C ha^{-1} yr^{-1}) compared to the mature orchard period (7379 ± 281 kg C ha^{-1} yr^{-1}), as also shown by Iglesias et al. (2013) in citrus. This increase in biomass production correlated with the differences (55 %) in leaf development between the two periods (LAI = 2.01 ± 0.16 in juvenile trees; 3.64 ± 0.31 in mature trees in the REF system). The increase in LAI between the two periods corresponded to the increase in tree volume and thus space occupation over time, which was accompanied by an increase in the rate of interception of light radiation, which is a key element of orchard productivity (Corelli-Grappadelli and Marini, 2008; Palmer et al., 2002). Even though productivity was quite strongly correlated with LAI, other factors have to be considered to explain the large variability in the NPPs observed in different studies, such as climatic conditions, orchard management, and soil maintenance.

The high NPP in the REF system led to very positive NEP regardless of the period, ranging from 3089 ± 813 kg C ha^{-1} yr^{-1} (309 ± 81 g C m^{-2} yr^{-1}) during the orchard juvenile phase to 7637 ± 853 kg C ha^{-1} yr^{-1} (764 ± 85 g C m^{-2} yr^{-1}) for a mature orchard. Carbon exports with harvested fruit were significant (1226 and 2718 kg C ha^{-1} yr^{-1}) and represented 40% and then 36% during these periods of orchard life. In the mature tree period, the REF system accumulated significant amounts of carbon ($NECB_{mature}$ = 4919 ± 858 kg C ha^{-1} yr^{-1}; 492 ± 86 g C m^{-2} yr^{-1}) even without applying an organic amendment. Carbon organic imports strongly impacted NECB since in a conventional peach system without organic compost, NECB was 889 kg C ha^{-1} yr^{-1} while massive compost inputs (about 3900 kg C ha^{-1} yr^{-1}) in a sustainable system allowed to reach NECB of 7341 kg C ha^{-1} yr^{-1} (Montanaro et al., 2017a). For apple tree, Zanotelli et al. (2015) reported values of 4030 kg C ha^{-1} yr^{-1} and 690 ± 520 kg C ha^{-1} yr^{-1} for NEP and NECB respectively. Higher carbon exports partly explained the significant difference in NECB by fruits (4180 kg C ha^{-1} yr^{-1}) in connection with the high yields of apples. Our estimates of soil respiration ($Rh_{orchard}$ = 3366 ± 776 kg C ha^{-1} yr^{-1}, 337 ± 78 g C m^{-2} yr^{-1}) were similar to those reported in peach systems [around 3200 kg C ha^{-1} yr^{-1}, Montanaro et al. (2017a)]. They were within the ranges encountered for different fruit crop species [apple: 1490 ± 80 kg C ha^{-1} yr^{-1} in Panzacchi et al. (2012) and 4550 ± 910 kg C ha^{-1} yr^{-1} in Zanotelli et al. (2015); *Citrus*: 2700 kg C ha^{-1} yr^{-1} in Iglesias et al. (2013); 4200 kg C ha^{-1} yr^{-1} to 5900 kg C ha^{-1} yr^{-1} in Liguori et al. (2009)], with these estimates based on soil CO_2 emission measurements. Our estimates of respiration in peach orchards with bare soil (Rh_{tree} = 2911 kg C ha^{-1} yr^{-1} calculated from ΔSOC over the tree row) were lower (−14%) than the respiration calculated at the orchard scale with grass ground cover in alleys ($Rh_{orchard}$). The increase in soil respiration under grass ground cover was related to the strong correlation between microbial activity and amounts of fresh organic matter restituted (Sheng et al., 2010). However, this could be counterbalanced by more severe water stress in alleys during the summer blocking microbial activity (Testi et al., 2008). Although our estimates of soil respiration were surrounded by imprecision related to the high variability of soil carbon contents, separate monitoring of SOC stock variations in tree rows (fertilizer and water supply) and alleys (grass growth with repeated mowing, pruning wood grouped in the alleys to be shredded) highlighted the spatial structuring of the soil carbon changes under differentiated management (Montanaro et al., 2012). At the end of the orchard's lifespan, as shown by the first trends of our results, the carbon concentrations in the 0–30 cm deep soil layer could be quite different, with decreases of SOC stock in tree rows in the absence of localized organic amendments and strong accumulation in the alleys. However, on average, at the orchard scale and over the first six years of the orchard's life, SOC concentration increased by 3.8‰ in the REF system, close to the '4 per 1000 initiative' proposed at the Paris climate conference (COP21) to partially offset GHG emissions from human activities. Our study demonstrates the possibility of very largely positive NEP and NECB balances in current conventional peach orchards, even without massive external organic carbon inputs, which is important for the carbon autonomy of sustainable orchards, leading to increased soil carbon storage.

4.2. Effects of low-input system management

The reduction of inputs compared to the REF system (−67% chemical pesticides, −19.5% nitrogen fertilizers and −26.6% irrigation water) in the low input system (LI-1) grown with the same tree density and training system as the REF system did not cause a significant yield reduction. A slight significant increase in fruit sugar content was even observed in association with water reduction (Casagrande et al., 2021; Mercier et al., 2009). The NPP values were statistically similar in the LI-1 and REF systems. However, the significantly lower aboveground growth compared to the REF system during the juvenile period (2015–2016, Table A5) may be counterbalanced by higher root system growth associated with moderate stresses (Panzacchi et al., 2012). This result confirmed that trees were more sensitive to risks associated with reduced inputs during the orchard establishment period than at the mature stage (Chalmers et al., 1981; Tworkoski and Glenn, 2010).

The large reduction in chemical pesticides on LI-1 led to a moderate increase in tree and fruit pest symptoms (results not shown), except for two years. In 2015, there was a severe infestation of *Taphrina deformans*, the causal agent of peach leaf curl, reduced leaf area and fruit load, inducing lower aboveground NPP in LI-1 (Tables A3 and A5). In 2019, the removal of chemical aphicide insecticides induced a high infestation of aphids (*Myzus persicae*, *Hyalopterus amygdali*, *Myzus varians*, 91 % of long shoots of the year infested). This infestation reduced aboveground NPP compared to the REF system (Table A.3) but in a more moderate way than expected. Our observations confirmed the results of Grechi et al. (2010), who showed small impacts of aphids on fruit growth through compensatory processes, particularly growth recovery after aphid-induced defoliation. However, repeated heavy infestations can gradually reduce tree vigor and the number of 1-year-old fruiting shoots available for year n + 1 (Bevacqua et al., 2016). In other years of experimentation, low aphid infestations can be linked to reducing nitrogen fertilization which reduces the sensitivity of trees to aphids (Sauge et al., 2010). Moreover, in the LI-1 system, minimizing chemical fungicides to control brown rot (*Monilia* spp.) did not significantly increase pre-harvest fruit rots and thus yield losses. This observation was probably due to the concomitant reduction in irrigation used in LI-1, which could increase sugar content and reduce the formation of microcracks on the fruit, the gateway to brown rot (Gibert et al., 2010; Mercier et al., 2008).

The reduction in inputs did not impact net accumulation in the LI-1 system (+3.7% for $NECB_{orchard}$ and +1.8% for $NECB_{mature}$ compared to the REF system, Table 5). Indeed, the small reduction observed in net production (−4.4% for $NPP_{orchard}$, −2.5% for NPP_{mature}, not significant) was compensated by a decrease in Rh soil respiration (−10.7%). This reduction was likely due to the decrease in carbon returning to the soil (Table A.6) and the large reduction in soil moisture associated with the localized in-row drip-irrigation used in LI-1 system (Gao et al., 2020; Zornoza et al., 2018).

The LI-2 system had the same input reduction as LI-1 but differed from REF and LI-1 systems in planting density and tree shape (909 trees ha^{-1} and simple Y oblique shape tree). Additionally, the LI-2 system had significantly higher harvested fruit yield (+19.8%) and tree biomass production than the REF system, increasing in $NPP_{orchard}$ (+813 kg C ha^{-1} yr^{-1}, +12.6%). The $NEP_{orchard}$ and $NECB_{orchard}$ were 38% and 46% higher than in the REF system, although the differences were not significant due to uncertainties in the estimation of soil respiration. Similarly, average fluxes in orchards with mature trees increased by + 1527 kg C ha^{-1} yr^{-1} (+20%) for NEP_{mature} and + 957 kg C ha^{-1} yr^{-1} (+19%) for $NECB_{mature}$ compared to the REF system.

Many studies have shown the increase in fruit yields and productivity associated with increasing planting density or tree training systems to optimize solar radiation interception (Anthony and Minas, 2021; Corelli-Grappadelli and Marini, 2008; DeJong et al., 1999; Grossman and DeJong, 1998). Increases of planting densities are especially interesting during the juvenile period since productivity gaps often decrease with orchard age, as shown for fruit yields (Fig. 2). In 2015, the low biomass production (Fig. 3) on LI-2 compared to the REF system was due to severe infestations of *Taphrina deformans* reducing LAI as described on LI-1. An increase in planting density may not be sufficient to compensate for the decrease in NPP under very strong pest and disease infestations, especially those developing at the beginning of the growing season. On the other hand, on average, over the first six years of the orchard's life as well as in the mature tree period (5–7-year-old trees), the combination of planting density and training system allowed for a very strong increase in the annual accumulation of carbon (NEP and NECB) compared to the current orchard management strategy.

This increase was accompanied by higher restitution of carbon to the soil (6027 ± 370 kg C ha^{-1} yr^{-1} in LI-2 vs. 5684 ± 313 kg C ha^{-1} yr^{-1} in the REF system) which allowed an increase in SOC stock (722 ± 580 kg C ha^{-1} yr^{-1} in LI-2 vs. 216 ± 739 kg C ha^{-1} yr^{-1} in the REF system), corresponding to an average annual increase of 10‰ well above the 4‰ recommended by COP 21. An elevation of the decomposing organic matter fractions could explain some of this increase in SOC. Peach leaves have a fairly rapid decomposition time [half-time of carbon decomposition of 46 weeks (Ventura et al., 2010)], but the decomposition of pruning wood can take several years (Germer et al., 2017). The fraction that will actually be sequestered over the long term due to interactions with the soil matrix that provide physical and chemical protection to microbial degradation of organic carbon is difficult to estimate because it depends on many parameters (Dignac et al., 2017). At the same time, respiration losses may also increase over time due to the microbial activity stimulation with fresh matter inputs (Fontaine et al., 2007). However, over the orchard life, massive litter restitutions should make it possible to reach a new equilibrium with a higher SOC stock than the initial one as reported after 14 years of peach orchard life (Baldi et al., 2018; Montanaro et al., 2017a).

The increase in NECB in the LI-2 system was also accompanied by an annual increase in carbon fixed in perennial tree structures (+12.9%) compared to the REF system and could represent 35.5 ± 1.4 Mg C ha^{-1} (3550 ± 140 g C m^{-2}) at the end of the orchard's lifespan (15 years), higher than the standing biomass measured in 14-year-old peach orchards (Baldi et al., 2018; Montanaro et al., 2017a). This large carbon storage will play a GHG mitigation role during the orchard life. Its impact on global change on a longer time scale will depend on the tree wood use at the end of the orchard's life. Burning in the field would constitute an immediate return of CO_2 to the atmosphere without any real service, except for the carbon stored in the soil during the orchard's life. On the other hand, using wood for domestic heating instead of other fossil fuel energy sources would increase the GHG mitigation service. Other modes of valorization come in the form of compost and wood chips that could improve the provision of orchard ecosystem services (carbon recycling and soil fertility) (Demestihas et al., 2017), although it would be accompanied by a release of CO_2 into the atmosphere. Our results show that orchards under agroecological management but with a higher planting density than current peach orchards would be a good compromise between fruit production services, reducing environmental impacts linked to using inputs such as pesticides and improving carbon sink and sequestration capacities in peach agroecosystems.

5. Conclusions

Our study was conducted in peach orchards located in the Mediterranean area and evaluated NPP, NEP and NECB for seven years since planting. The results were within the highest values reported for fruit tree species. Low-input management strategies for pesticides, irrigation and fertilization, did not significantly impact NEP and NECB. A low-input system associated with a higher planting density and a new tree training system significantly increased fruit yield and NPP during the first seven years of the orchard's life. This system produces a strong increase in carbon accumulation (NEP and NECB) in the perennial tree structures and the soil. These results highlight the importance of matching carbon balances with a precise description of cropping systems because these practices strongly influence the intensity of carbon fluxes. The results indicated that without massive input of external organic matter, peach orchards managed with high fruit production objectives but with agroecological strategies allowed an increase of 4‰ or more of SOC stock as recommended by the COP21 initiative in Paris.

However, these results must be confirmed over the orchard's life (15 years) to consolidate the carbon fluxes (NPP, NEP and NECB) under climatic hazards and pest and disease risks. The reduction of inputs could modify the longevity of trees and thus impact carbon balances over the orchard's life. Evaluating SOC changes on a time scale greater than a decade would also be more appropriate. It is also very important to consolidate the interest of increasing planting densities on productivity while integrating the effect on economic balances for producers (amortization of planting costs and labor time) as these are essential parameters for their adoption in commercial orchards. Similarly, it would be interesting to complete these carbon balances with a life cycle analysis (LCA) to integrate the carbon footprint of the practices, as some alternative practices may have a higher impact than conventional ones. However, our results indicate that the combination of planting density × tree training system coupled with low-input management would be a good compromise to increase the capacity of peach orchards to accumulate and sequester carbon for the climate change mitigation service while enhancing the provision of other ecosystem services.

CRediT authorship contribution statement

Daniel Plénet: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Visualization, Project administration, Funding acquisition. **Julie Borg:** Investigation, Writing – review & editing. **Quentin Barra**: Investigation. **Claude Bussi**: Writing – review & editing. **Laurent Gomez**: Investigation, Writing – review & editing. **Mohamed-Mahmoud Memah**: Writing – review & editing**. Françoise Lescourret**: Writing – review & editing. **Gilles Vercambre**: Investigation, Formal analysis, Writing – review & editing.

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. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2022.126578.

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