Does pollarding trees improve the crop yield in a mature alley-cropping agroforestry system?
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INTRODUCTION

In temperate areas, the sustainability of intensive monoculture systems that was advocated in the 20th century is now questioned, due to concerns over the current yield stagnation (Brisson et al., 2010), notably with respect to losses in soil organic matter (Wiesmeier, Hubner, & Kogel-Knabner, 2015), but also to a higher environmental awareness among farmers and consumers. The search for highly productive, yet sustainable and environmentally friendly agricultural systems has led to a renewed interest in agroforestry practices in temperate regions of the world (Eichhorn et al., 2006; Smith, Pearce, & Wolfe, 2013). Satellite data (LUCAS Land Use and Land Cover database) report that the total area under agroforestry in the European Union 27 is about 15.4 million hectares which is equivalent to about 3.6% of the territorial area and 8.8% of the utilized agricultural area (Herder et al., 2017). In France, agroforestry systems with grazing occupy the largest place, and hardwood systems on arable land represent only 0.4% (5,700 ha) of total agroforestry surfaces. Increased environmental, ecological and economic concerns have provided momentum for this shift in paradigm away from “chemical agriculture” (Jose, Gillespie, & Pallardy, 2004).

Several studies show that hardwood tree-based intercropping systems may offer several benefits for the environment (Montagnini, Ibrahim, & Restrepo, 2013), such as reducing soil erosion and N...
leaching (Andrianarisoa, Dufour, Bienaimé, Zeller, & Dupraz, 2015), increasing carbon sequestration (Albrecht & Kandji, 2003; Cardinael et al., 2016; Nair, Kumar, & Nair, 2009; Palma et al., 2007) and bolstering landscape biodiversity (Quinkenstein et al., 2009).

In agroforestry systems, biophysical interactions between crops and trees modify the conditions of growth for both species. If these modifications are positive, this is known as “facilitation” (Vandermeer, 1989). For instance, the trees can reduce wind speed and, consequently, evapotranspiration; they also reduce the temperature extremes (Mirck, Kanzer, Böhm, & Freese, 2016). But there are always competitive interactions for belowground resources (water and mineral elements) between the two species. Moreover, light availability for the crop is usually reduced in agroforestry systems as compared to monocropping of annual crops (Mirck et al., 2016; Miller & Pallardy, 2001; Reynolds, Simpson, Thevathasan, & Gordon, 2007; Rivest, Cogliastro, Vanasse, & Olivier, 2009) more and more because the trees canopy reduces the incident radiation on the crop and may increase crop yield (Abbate, Andrade, Culot, & Bindraban, 1997; Ram, Yadav, Dar, & Miller & Pallardy, 2001; Reynolds, Simpson, Thevathasan, & Gordon, 2007; Rivest, Cogliastro, Vanasse, & Olivier, 2009) more and more as the trees grow (Pardón et al., 2018). Practices that reduce tree canopy size or the leaf area density within the tree canopy increase the incident radiation on the crop and may increase crop yield (Abbate, Andrade, Culot, & Bindraban, 1997; Ram, Yadav, Dar, & Shanker, 2005). This can be achieved by choosing late leafing trees, like walnut trees (Juglans regia L. or Juglans regia × nigra) or some oaks (Quercus robur L., Quercus petraea Liebl. L.), by using appropriate tree plantation designs or by reducing the tree canopy by pruning, trimming or pollarding. Combining late leafing trees and early winter crops results in a reduced competition for light between the crops and trees (Talbot & Dupraz, 2012). However, a 30-day period before grain filling was proved to be a critical period with respect to light competition for the wheat yield formation (Dufour et al., 2013). This temporal gap in leafing phenology of crop and trees should be maximized, so that (a) tree–crop competition will be reduced and (b) radiation use will be optimized (Muthuri et al., 2009). The tree plantation layout also plays an important role for the crop yield. The width of the crop alley and the orientation of the tree rows modify the intensity of the shade for a given size of trees (Dufraz et al., 2018) and consequently impact the crop growth and yield (Chirko, Gold, Nguyen, & Jiang, 1996a; Dufraz & Liagre, 2008).

Finally, the shape of the tree crown has an influence on the shade produced by the tree and, consequently, on the crop yield (Jones, Sinclair, & Grime, 1998). Pollarding is a traditional practice consisting in the repeated pruning of all branches at, or near, the same point of a tree trunk (Chesney, 2012). The pollarded tree consists of a clear stem section and a compact and bushy crown. The principle of pollarding is to encourage the tree to produce new growth on a regular basis to maintain a supply of new branches for various purposes, particularly for fuel or fodder (Al Afas, Marron, Dongen, Laureysens, & Ceulemans, 2008; Burner, Pote, & Ares, 2006; Nerlich, Graeff-Hönninger, & Claupein, 2013). Reducing the canopy and, consequently, the leaf area of the trees in agroforestry systems will decrease the shadow of tree crowns and thus raise the level of incident radiation on the crop under the canopy. It will also reduce the transpiration of the trees and relax the belowground competition for water and nutrients.

The objective of this study was to evaluate the consequence on crop development and yield of pollarding the trees in a mature agroforestry field. In 2013, we pollarded fifty 18-year-old agroforestry walnuts. We compared crop growth and development in two agroforestry systems (with pollarded trees or with trees pruned at 4 m height) and in sole crop control plots. The crops were winter durum wheat (2013–2014), winter barley (2014–2015) and winter field pea (2015–2016).

## MATERIALS AND METHODS

### 2.1 Study site

The experiment was conducted in the South of France, at the Farm Estate of Restinclières (43.42°N—3.51°E, Hérault County, 15 km North of Montpellier). The climate is subhumid Mediterranean with an annual mean temperature of 15.0°C and a mean annual rainfall of 762 mm (1991–2014). The soil is a silty deep alluvial fluvisol (20% clay and 45% silt). The soil water-holding capacity, in the topsoil layer of 1 m thickness, calculated as the difference between field capacity (pF = 2.5) and wilting point (pF = 4.2) is 152 mm. The soil organic matter content is 2.1% for the 0–0.2 m soil layer, 1.5% for 0.2–0.4 cm, 1.2% for 0.4–0.6 cm, 1.0% for 0.6–1 m and 0.9% for 1-2 m.

### 2.2 Experimental design

Agroforestry crops are associated with hybrid walnuts (Juglans nigra × Juglans regia NG23). Adjacent to the agroforestry plot, a large (1 ha) pure stand crop control is available, without trees.

The walnut trees were planted in 1995 at an initial density of 200 trees/ha. They were thinned in 2004 to 100 trees/ha. At the end of 2014, the average height of the trees was 10.7 ± 0.2 m and diameter at breast height (DBH) was 23.1 ± 0.4 cm. The trees were yearly pruned until a 4 m high bole was obtained. The tree rows are 13 m apart and aligned east–west, the average distance between trees on the row is 8 m.

The usual crop rotation includes 1 year of field pea (Pisum sativum L.), followed by 3 years of winter durum wheat (Triticum turidum L. subsp. durum [Desf.] Husn.). For the first time in 2014–15, a barley (Hordeum vulgare L.) crop was settled. Wheat (“Claudio” variety, thousand kernel weight around 50 g) was sown on 23 October 2013 at 170 kg of seeds/ha, barley (“Augusta” variety, thousand kernel weight around 48 g) was sown on 6 November 2014 at 150 kg of seeds/ha, and pea (“Igloo” variety, thousand kernel weight around 200 g) was sown on 3 December 2015 at 200 kg of seeds/ha. Crop management was typical and included one herbicide application for each crop (02/12/2014, 01/03/2015 and 12/08/2015), 100 kg of nitrogen/ha (ammonium nitrate, 33.5% of N) split into two

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applications (02/15/2014 and 04/30/2014) for wheat; 70 kg of N/ha on 11 February 2015 (ammonium sulphate, 21% of N) and 70 kg of N/ha on 31 March 2015 (ammonium nitrate, 33.5% of N) for barley; no fertilizer for pea.

2.3 | Pollarding trees

The alley-cropping experimental plot includes 340 walnut trees. Fifty of these trees were pollarded for the first time at two dates: (a) 5 trees on the 31 March 2013 and (b) 45 trees on the 4 December 2013. They were topped at 4 m height: the trunk above 4 m and all branches were removed. The pollarded trees were located on two adjacent tree rows.

2.4 | Crop monitoring

The crop measurements were performed on 1 m² subplots: in the full sun control (FSC), five random subplots each year; in regular agroforestry (NPOL), the subplots were located on five transects, composed of three locations each: close to the northern side of a tree (centre of the subplot at 2 m from the tree row, NPOL-N), in the middle of the alley (centre of the subplot at 6.5 m from the tree rows, NPOL-C) and close to the southern side of a tree (2 m, NPOL-S); in pollards agroforestry (POL). The number of subplots varied between the years. In 2014, five transects with two locations: at 2 m north (POL-N) and south (POL-S) from the trees, because there was no shade in the middle of the POL alley; in 2015, seven transects with three locations (the same locations as in NPOL, POL-N, POL-C and POL-S); in 2016, five transects with the same three locations.

2.5 | Collected data

2.5.1 | Climate and radiation recording

In the FSC plot, a weather station (data logger: CR-1000© Campbell Scientific, Inc.) recorded hourly air temperature and humidity, rainfall and global radiation.

Hemispherical photographs were taken in the middle of each agroforestry subplots at 90 cm height at the following dates: at the beginning of trees budburst, while the crops were close to the end of their vegetative stages (04/23/2014, 04/14/2015 and 04/28/2016), at the end of wheat flowering (05/06/2014), at the milky grain stage of wheat and barley (06/04/2014 and 05/22/2015) and after the harvest of pea (06/21/2016). The photographs were analysed with WinScanopy software (Regent Instruments Inc.), and the percentage of the total radiation transmitted to the crop was computed. To obtain the percentage of incident radiation during the whole crop cycle, we assumed the first photograph (leafless trees) to account for the period from the sowing of the crop to the budburst of the trees and the second one to represent the period from the budburst of the trees to the harvest of the crop. We multiplied each value of radiation percentage by the number of days for the corresponding period.

2.5.2 | Trees and crops phenology

The crop phenological stages were observed from sowing to harvesting. After budburst, the walnut trees annual growth begins with the elongation of preformed shoots with short internodes and a limited number of nodes, called short shoots. We recorded the proportion of fully expanded short shoots. The phenology of hybrid walnut trees is different from an individual to another. So, the phenology of all the pollarded and control trees, near the crop subplots, was weekly monitored from budburst to the end of the short shoots growth. After the short shoots expansion, long shoots keep growing but this occurs after the crop harvest.

2.5.3 | Crop growth

On 24 April 2014, 22 April 2015 and 18 April 2016, we collected all crop plants on 50 cm length of crop rows near the marked subplots. For wheat and barley, we measured the height of the main tiller, the number of tillers and the number of ears, and we separated green leaves, yellow leaves, stems and ears of each plant and dried them separately during two days in an oven at 60°C. For the pea, all the aerial parts of the plants were dried together. On a subsample of five plants of the three crops, the green leaf area was measured with a scanner and WinFolia software (Regent Instruments Inc.). After drying, each part of each plant was weighted, for calculating the specific leaf area.

2.5.4 | Crop yield and yield components

On 16/06/2014, 10/06/2015 and 16/06/2016, the subplots were manually harvested. The whole sample was weighted on the field. The ears were separated from the straw and counted. The ears and a subsample of straw were weighted on the field then dried in an oven at 60°C during two days and finally weighted. We then calculated the total straw dry weight. Grains were separated from the ears and weighted in order to calculate the yield. Finally, 1,000 grains were mechanically counted for each subplot and weighted. The harvest index, which is the weight of produced grains as a percentage of the total plant aerial biomass, was calculated.

We calculated the field relative yield and radiation of NPOL and POL systems compared to FSC. Surfaces used in computations of yield within NPOL and POL systems included the 2 m wide uncropped area under the tree lines. To account for the effect of the distance to the trees, we calculated the yield at the field scale as a weighted average of the subplot measures: 2.5 m for the measures close to the trees and 6 m for the measure in the middle of the alley, divided by 13 m of total alley width.
TABLE 1 Main climatic parameters during the crops cycles (from sowing to harvest)/Averages per day

| Crop     | Sowing date | Harvest date | Degree days sum (°C) | Rainfall sum (mm) | Global radiation sum (MJ/m²) |
|----------|-------------|--------------|----------------------|------------------|-----------------------------|
| Wheat    | 13/10/23    | 14/06/16     | 2695/11.4            | 285/1.2          | 2858/12.1                   |
| Barley   | 14/11/06    | 15/06/18     | 2542/11.3            | 512/2.3          | 2952/12.2                   |
| Pea      | 15/12/03    | 16/06/13     | 2211/12.3            | 357/1.9          | 2368/12.3                   |

2.6 Statistical analysis

The effect of FSC, NPOL and POL treatments on incident radiation, crop yield and yield components was assessed by a one-way analysis of variance (ANOVA) testing the effect of subplot type (FSC, NPOL-N, NPOL-C, NPOL-S; POL-N, POL-C, POL-S) for each year. We used ANOVA because the edaphic conditions, checked by soil analyses, are very homogenous, and the position of the subplot relative to the tree row combined with the tree type can be considered as the only source of variation. Before making the ANOVA, the normality of the residuals was tested with a Shapiro test and the homogeneity of variances with a Bartlett test. When the residuals were not normal or variances not homogenous, we used a Kruskal–Wallis test ($p < .05$) and a post hoc Nemenyi test to compare the means. When the ANOVA revealed significant differences, we compared the means by a Tukey HSD test. Statistical analyses were performed with the R software (R software, Free software developed at Bell Laboratories—3.3.1. version).

3 RESULTS

3.1 Meteorological conditions and incident radiation

Regarding the growing conditions of the three crops, pea had the smallest sum of degree days, total rainfall and global radiation, while barley had the highest values (Table 1). These differences are partially explained by the length of the crop cycles: 192 days for pea, 224 for barley and 236 for wheat. The climatic conditions were more favourable in 2014–2015 than during the others years: both radiation and rainfall were the highest. A heavy rainfall event happened in November 2014 (234 mm) right after barley sowing; then, there were regular rains, excepted in May (only 3.5 mm).

Figure 1 shows the impact of the trees on the available radiation for the crops at the onset of the trees budburst, which occurred approximately 10 days before cereal flowering and 20 days after the beginning of pea flowering. Until budburst, the radiation decrease was only due to the trunk and branches and this happened during the whole crop vegetative growth. In 2014 and 2015, the cropped alley in POL received significantly ($p_{value} = .25 \times 10^{-5}$ and $1.31 \times 10^{-5}$ in 2014 and 2015, respectively) more light than in NPOL. But in 2016, during the third year of canopy recovery, this effect was no longer significant ($p_{value} = .22$, NS).

Within the cropped alley, the patterns depended on the location: in the south of the POL cropped alley, relative radiation was more than 95% in 2014: significantly higher than at the same position in NPOL ($p_{value} = .029$). This value decreased steadily during the two following years, and in 2016, there was no significant difference between POL and NPOL at this position ($p_{value} = .99$, NS). In the centre and the north of the cropped alley, the effect of tree pollarding was consistent over the 3 years. The radiation level was higher with pollarded trees than with NPOL trees over the 3 years. Table 2 summarizes the relative radiation reaching the crop during the crop cycles for the 3 years. The available light under the pollarded trees drastically decreased during the 3 years, mainly in the south of the alley (reduced by 35% for the whole crop cycle), while the light under the non-pollarded trees decreased slower (reduced by 13% in the south of the alley). It reflects the rapid evolution of the crowns of pollarded trees and the slower increase of the crowns of non-pollarded adult trees.

3.2 Trees and crops phenology

The tree phenology was affected by pollarding. In 2014, the budburst of the pollarded trees was delayed by 1 week on average, as compared to the non-pollarded trees and the pollarded trees produced no short shoots, growing directly in the form of long shoots that lead to a fast extension of their canopies. In 2015, almost 75% of the pollarded trees produced short shoots. In 2016, all the pollarded trees made both short and long shoots. In 2015 and 2016, the beginning of the budburst was still delayed by almost 1 week, but there was no difference for the end of the budburst between pollarded
and control trees; the short shoots growth lasts longer for pollards, so the end of this stage was still delayed.

Barley flowering was earlier than durum wheat's one, even if it was sown later in the season. So, the beginning of walnut tree budburst matched with the beginning of barley flowering but the beginning of wheat flowering took place after tree shoots started to expand (Figure 2). Consequently, the tree shade occurs earlier and longer in the cycle for a wheat crop than for a barley one. The peas had a continuous growth and an indefinite flowering and pod production, so even if the flowering began before the trees budburst, it lasted after the short shoots of trees began to grow.

There was no noticeable phenological difference between the crops grown under different tree canopies and in FSC. So, each year, all the plots were harvested the same day.

### 3.3 | Crop growth

The crop biomass measured at the LAI\textsubscript{max} stage is reported in Figure 3. This time coincided with the beginning of the budburst of the walnut trees. The standard errors are very high, but the tree presence tended to reduce the average crop biomass under both types of agroforestry trees, mainly in the south of the alley. Pollarding the trees had a slight but not statistically significant positive effect on the biomass of the crops for wheat and barley in the middle of the cropped alley (\(p\text{wheat} = .335, p\text{barley} = .961\)). But 3 years after pollarding, the pea biomass at LAI\textsubscript{max} was higher in NPOL than in POL.

### 3.4 | Crop yield and yield components

Table 2 compares the values of the different yield components measured for the three crops.

#### 3.4.1 | Within alley crop yield variability

Even if there are not many significant differences, it appeared that the wheat and pea yields were lower in the south of the alley as compared to the north or middle (Table 3). For the wheat, this was mainly due to a decrease of the number of grains per spike and the number of spikes per m\(^2\) (Table 4). For the pea, the 1,000 grains weight

| TABLE 2 | Relative radiation available in the cropped alleys during the whole crop growth cycle |
|---------|---------------------------------------------------------------|
|         | Near the trees—North of the alley | Middle of the alley | Near the trees—South of the alley |
| POL     | 2014 98.0 ± 0.3 | NA                  | 94.5 ± 1.5 |
|         | 2015 97.0 ± 0.3 | 95.4 ± 0.4          | 81.2 ± 2.1 |
|         | 2016 86.9 ± 3.1 | 88.7 ± 1.0          | 61.4 ± 1.3 |
| NPOL    | 2014 89.4 ± 2.3 | 84.6 ± 3.3          | 73.6 ± 1.1 |
|         | 2015 89.5 ± 1.1 | 84.1 ± 1.6          | 76.1 ± 2.9 |
|         | 2016 82.6 ± 1.7 | 80.0 ± 3.3          | 64.7 ± 4.3 |

Note: The intervals are the standard errors (five replications).
the most impacted yield component, then the number of pods per m² (Table 4). For barley, we did not record any significant yield change in agroforestry as compared to FSC conditions.

### 3.4.2 | Alley with pollards versus agroforestry yield variability

Wheat yield was higher under pollarded trees (in average, \( \text{POL}_{\text{yield}} = 4.0 \text{ t/ha} \); \( \text{NPOL}_{\text{yield}} = 3.0 \text{ t/ha} \), \( p_{\text{value}} = .0094 \)) than under regular trees, the first year after pollarding. The difference was high and significant in the southern part of the alley (\( p_{\text{value}} = .0146 \)). Conversely, during the third year after pollarding, the average yield of peas was lower under pollarded trees (in average, \( \text{POL}_{\text{yield}} = 2.6 \text{ t/ha} \); \( \text{NPOL}_{\text{yield}} = 2.7 \text{ t/ha} \), \( p_{\text{value}} = .9136, \text{NS} \)). But the balanced yield was slightly higher for POL: 2.42 ± 0.43 t/ha than for NPOL: 2.28 ± 0.24 t/ha. The difference was important, but not significant (\( p_{\text{value}} = .984 \)) in the southern part of the alley, where the shade was higher under pollarded than under non-pollarded trees before bud-burst (Figure 1), and the most affected yield component was the number of pods per m² (Table 3).

### 3.4.3 | Whole alley crop yield comparison

In 2014, the relative yield of wheat and the relative radiation, computed at the field level (i.e. taking into account the "lost" area under the tree row), were, respectively, 59% (yield) and 70% (radiation) of FSC for NPOL, while they were 85% and 94% of FSC for POL. For barley in 2015, yield and radiation were, respectively, 82% and 71% in NPOL, while they were 82% and 78% in POL. For pea in 2016, yield and radiation were, respectively, of 64% and 65% for the NPOL system, while they were of 63% and 69% for the POL system.

### 4 | DISCUSSION

The importance of tree competition for light on crops is emphasized in several articles about agroforestry, for wheat, (Chirko, Gold, Nguyen, & Jiang, 1996b; Dufour et al., 2013; Li, Meng, Fu, & Wang, 2016).

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**TABLE 3** Yield and yield components of wheat (2014), barley (2015) and peas (2016) in full sun control (FSC), in pollarded trees alley cropping (POL) and in regular agroforestry (NPOL) plots

| Yield (t/ha) | 1,000 grains weight (g) | Number of spikes or pods per m² | Number of grains per spike or pod | Harvest Index (%) |
|-------------|--------------------------|---------------------------------|----------------------------------|------------------|
| 2014        |                          |                                 |                                  |                  |
| FSC         | 4.48 ± 0.17              | 47.3 ± 1.6                     | 291 ± 16                         | 32.8 ± 0.9       | 41.0 ± 3.9       |
| POL-N       | 4.13 ± 0.24              | 46.2 ± 0.7                     | 296 ± 15                         | 30.2 ± 1.2       | 41.9 ± 0.4       |
| POL-S       | 3.40 ± 0.36              | 50.1 ± 1.1                     | 220 ± 18                         | 28.5 ± 1.4       | 43.9 ± 1.0       |
| NPOL-N      | 3.28 ± 0.30              | 45.7 ± 1.4                     | 266 ± 15                         | 26.9 ± 1.3       | 45.7 ± 5.3       |
| NPOL-C      | 3.38 ± 0.32              | 47.7 ± 0.8                     | 300 ± 24                         | 23.8 ± 1.8       | 38.2 ± 1.6       |
| NPOL-S      | 2.44 ± 0.38\(^a\)        | 46.9 ± 0.8                     | 204 ± 27\(^a\)                   | 25.3 ± 1.9\(^a\) | 40.0 ± 2.5       |
| 2015        |                          |                                 |                                  |                  |
| FSC         | 5.55 ± 0.24              | 53.9 ± 1.0                     | 501 ± 14                         | 20.6 ± 0.8       | 30.7 ± 1.0       |
| POL-N       | 5.35 ± 0.22              | 54.2 ± 1.3                     | 521 ± 27                         | 19.1 ± 0.7       | 29.6 ± 0.6       |
| POL-C       | 5.33 ± 0.27              | 53.6 ± 1.2                     | 553 ± 17                         | 18.0 ± 0.7       | 28.7 ± 0.3       |
| POL-S       | 5.47 ± 0.22              | 56.3 ± 1.0                     | 515 ± 10                         | 18.8 ± 0.5       | 27.7 ± 0.4       |
| NPOL-N      | 5.13 ± 0.15              | 53.6 ± 1.1                     | 521 ± 29                         | 18.5 ± 1.0       | 28.0 ± 0.9       |
| NPOL-C      | 5.66 ± 0.36              | 54.8 ± 0.4                     | 566 ± 24                         | 18.2 ± 0.7       | 29.8 ± 1.2       |
| NPOL-S      | 5.08 ± 0.18              | 54.3 ± 1.5                     | 537 ± 29                         | 17.5 ± 0.3       | 30.9 ± 1.2       |
| 2016        |                          |                                 |                                  |                  |
| FSC         | 3.97 ± 0.46              | 184.1 ± 14.8                   | 574 ± 85                         | 3.9 ± 0.2        | 48.0 ± 2.0       |
| POL-N       | 2.83 ± 0.61              | 135.1 ± 6.3                    | 502 ± 110                        | 3.8 ± 0.1        | 51.8 ± 1.2       |
| POL-C       | 3.60 ± 0.27              | 140.9 ± 2.3                    | 668 ± 59                         | 3.9 ± 0.1        | 53.6 ± 0.7       |
| POL-S       | 1.57 ± 0.53\(^a\)        | 108.4 ± 6.0\(^a\)              | 267 ± 41\(^a\)                   | 5.0 ± 0.5        | 48.6 ± 2.0       |
| NPOL-N      | 2.66 ± 0.39              | 154.8 ± 6.7                    | 413 ± 56                         | 4.2 ± 0.2        | 56.7 ± 2.7\(^b\) |
| NPOL-C      | 3.51 ± 0.21              | 138.6 ± 4.4                    | 569 ± 58                         | 4.7 ± 0.6        | 54.8 ± 1.9       |
| NPOL-S      | 2.04 ± 0.34\(^a\)        | 132.4 ± 9.5                    | 379 ± 44                         | 4.0 ± 0.1        | 49.0 ± 1.6       |

Note: In POL and NPOL, the plots are located in the north (N), centre (C) and south (S) of the alley. The intervals are the standard errors.

\(^a\)Indicates values significantly different of the FSC.

For barley, we did not record any significant yield change in NPOL as compared to FSC conditions.
DUFOUR et al. (2008) and other annual crops, such as corn and soybean (Reynolds et al., 2007). The radiation reduction has different impacts on the three crops involved in this study.

(i) Li et al. (2008) showed that, in a temperate climate, 9-year-old Paulownia (Paulownia × ‘Tomentosi-fortunei 33’) trees reduced drastically the incoming photosynthetically active radiation (PAR) and the leaf area index (LAI) of a spring wheat crop. The intercropped wheat LAI was reduced by at least 50% at flowering time. Both incoming PAR and LAI decreases resulted in a reduction of the light intercepted by the wheat and, consequently, the yield was also reduced by 50%. According to Mu et al. (2010), relative grain yield losses and LAI reduction in winter wheat were less than the reduction of solar radiation, applied as a constant shade from wheat stem elongation to grain maturity (22% and 33% reductions of PAR resulted in 8% and 21% yield decreases).

In our study, the shade was not constant along the crop cycle as tree leaf area increased progressively after budburst. Overall, the yield decrease was higher than the radiation decrease and driven by the number of grains per spike and the number of spikes per m² decreases in agroforestry. The final number of spikes per m² results from tiller demographics, that is generation, development and survival; likewise, the number of grains per spike involves floret initiation, survival and fecundation within each of the developing ears and grain setting (Slafer, Savin, & Sadras, 2014).

(ii) A reduction in spring barley post-anthesis incident radiation decreased yield by 20%, mostly because of 1,000 grains weight reduction (Kennedy, Lynch, Spink, & Bingham, 2018). Total aboveground dry matter and harvest index were also reduced. The slight decrease of barley yield in our agroforestry systems could reflect a higher radiation use efficiency of winter barley and/or a better adaptation due to the shorter cycle that allowed this crop escaping the shade of the tree during sensitive stages such as flowering. However, the better performance of barley in agroforestry compared to the other crops might also be due to lower tree–crop root competition due to more favourable climatic conditions in 2015 and to a radiation use efficiency increase linked to good water supply (Tabarzad, Ghaemi, & Zand-Parsa, 2016).

(iii) For pea, the yield decrease in agroforestry plots was approximately the same as the radiation one. The grains weight was the most impacted yield component: for all the alley-cropping plots (average of POL and NPOL), 73% of the FSC. So, the light reduction interfered with the grain filling. Indeed, the grain filling began at the middle of the tree budburst, when the light decrease is noticeable and went on during almost all the short shoots elongation. The number of grains per pods was slightly higher in the associated pea, probably because the pea flowering began before the tree budburst and the fecundation took place with a little shade, but in protected conditions anyway.

Harvest indexes (HI: ratio of harvested grain to total shoot dry matter) in the two agroforestry systems were equal to or greater than those in the FSC for the three crops (Table 3). For wheat and barley, the seed yield was dependent on total biomass accumulation. The reproductive efficiency of the three crops was not

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### TABLE 4 Relative values of yield and yield components of wheat (2014), barley (2015) and peas (2016) in pollarded trees agroforestry (POL) and in regular agroforestry (NPOL) plots, in % of the full sun control

| Orientation | Trees | Crop   | Yield | 1,000 grains weight | Number of spikes or pods per m² | Number of grains per spike or pod |
|-------------|-------|--------|-------|---------------------|---------------------------------|---------------------------------|
| North       | POL   | Wheat  | 92.0  | 97.8                | 101.9                           | 92.0                            |
|             |       | Barley | 100.4 | 100.4               | 104.1                           | 92.8                            |
|             |       | Pea    | 71.4  | 73.4                | 87.4                            | 105.5                           |
|             | NPOL  | Wheat  | 73.2  | 96.7                | 91.5                            | 81.8                            |
|             |       | Barley | 99.4  | 99.4                | 104.1                           | 90.0                            |
|             |       | Pea    | 67.0  | 84.1                | 72.1                            | 106.7                           |
| Middle      | POL   | Wheat  | NA    | NA                  | NA                              | NA                              |
|             |       | Barley | 99.4  | 99.4                | 110.5                           | 87.3                            |
|             |       | Pea    | 90.7  | 76.5                | 116.6                           | 98.8                            |
|             | NPOL  | Wheat  | 75.4  | 100.8               | 103.1                           | 72.5                            |
|             |       | Barley | 101.6 | 101.6               | 113.1                           | 88.4                            |
|             |       | Pea    | 88.5  | 75.3                | 99.2                            | 119.8                           |
| South       | POL   | Wheat  | 75.9  | 106.0               | 75.8                            | 86.9                            |
|             |       | Barley | 104.3 | 104.3               | 102.9                           | 91.4                            |
|             |       | Pea    | 39.6  | 58.9                | 46.5                            | 127.1                           |
|             | NPOL  | Wheat  | 54.3  | 99.3                | 70.3                            | 77.0                            |
|             |       | Barley | 100.6 | 100.6               | 107.4                           | 85.0                            |
|             |       | Pea    | 51.5  | 71.9                | 66.1                            | 102.5                           |
affected by the tree presence. For the pea, the harvest indexes were higher than for the other crops, especially in the north of the agroforestry alley where it was significantly higher than control. It reveals a stronger partitioning of dry matter towards the seed for pea than for wheat and barley, and in the north of the alley cropping.

Tree shape modifications through pruning (e.g. branches pruning, pollarding), tree row orientation and spacing (Muchiri, Pukkala, & Miña, 2002) and the choice of tree species according to their phenology result in different temporal and total shading effects on the underlying crop. With respect to pruning, Ram et al. (2005) found that 5 years after plantation of Albizia procera, the yield wheat (Triticum aestivum) was 415% higher in 70% pruning than trees allowed to grow normally. However, our results showed that pollarding, that is almost 100% pruning, increased by 20% the wheat yield in agroforestry. Due to the penology of hybrid walnut with a late budburst, the effect of shade on the phenology of the crops was minor, which is in line with Slafier (1995) observations in controlled conditions. Indeed, the phenology of the hybrid walnut is favourable for a winter crop as its budburst occurs when the LAI_{max} stage of the crop is over. Moreover, pollarding delayed the trees budburst, extending the time period with slight shade. Nevertheless, the shade of trunks and branches was not negligible, particularly 3 years after pollarding, and in the south part of the cropped alley (north of the trees), the light reaching the crop was less than 80% of FSC in April 2016. The fast regrowth of the trees during the years after pollarding gives their canopy a specific shape and a high leaf density, with many large branches near the pollarding point (Lang et al., 2015) and an unusual hanging pattern of branches that sometimes collapse at the insertion point. Then, the resulting shade level close to the pollarded tree trunks was very high during the third growing season.

Pollarding trees mitigated significantly the wheat yield loss during the first year after crown cutting. During the second year after pollarding, the yield (barley) near the pollarded trees remained higher (non-significant) than in agroforestry, but, as the barley was less influenced by the tree presence, the effect of pollarding was less important. This phenomenon can be linked to the earliness of barley, as compared to the wheat, but also to the more favourable meteorological conditions in 2015 than in 2014 or 2016: higher mean global radiation per day and higher rainfall just after sowing, ensuring a good water recharge of the soil and good growth initiation for the crop. Finally, in the third year after pollarding, the yield (pea) was lower near the pollarded trees than near the non-pollarded trees. This can be linked to the important decrease of incident radiation under the pollarded trees, particularly in the south part of the cropped alley, due to a high density of branches in the canopy of the pollarded tree.

We did not investigate the influence of tree pollarding on the underground interactions between trees and crop, but it may also play a part in the observed yield variations. Anyway, the tree canopy reduction decreases the rain interception and the transpiration of tree leaves (Pollock & Mead, 2008) and can have an influence on the water absorption by tree roots. Jones et al. (1998) showed that tree crown pruning reduces tree root length density of Prosopis juliflora and has a significant impact on soil water content but has no effect on Acacia nilotica roots. Pollarding 8- or 12-year-old poplars reduces their root length and root mass (McIvor, Douglas, Dijssel, Hedderley, & Brock, 2019).

Pollarding timber trees provides an additional production to the agroforestry system exploiting the cut branches biomass for energy, fodder or wooden chips (Burner et al., 2006; Mansion, 2015). In order to account for this supplementary product, the land equivalent ratio (LER) of a plot can be calculated. The LER is the sum of the relative yields of crop and trees compared to the sole crop and forestry controls. It can be defined as the relative land area required as sole crops to produce the same yields as intercropping (Graves et al., 2010; Mead & Willey, 1980). In the case of agroforestry plot with pollards, there are three productions and the LER must include the relative yield of branches and thus require data from a monocropping control for branch biomass production. Further studies are ongoing to address the issue. Experimental work should also document the correlation between timber production (as indicated mainly by the trunk DBH growth) and branch biomass production for different pollarding and non-pollarding management schemes for the trees. Particularly, the pollarding frequency is a key factor of the system sustainability and productivity. The results will allow quantifying the trade-offs between the three productions of a pollard alley-cropping system: crop, timber wood and branches biomass.

5 | CONCLUSION

In our agroforestry system, pollarding trees increased significantly the light availability for the winter crops during the two first years after pollarding, but this effect vanished during the third year, especially close and north to the tree lines. Crop yield was significantly increased only in the first year after pollarding. During the third year, the denser and lower branches of pollarded trees strongly reduced crop yield close to the trees. Even so, the transient stimulation of the crop production achieved by pollarding the trees evidenced in this paper may not be sufficient to improve the overall attractiveness of these alley-cropping systems, which would depend on economic return that can be obtained from all the harvested products. An alley-cropping system with pollards has multiple products, including biomass from the branches of pollarded trees, and these should be taken into account when choosing the optimal management of the system. Therefore, some indicators such as the LER or the net present value of the system are more appropriate to look for the optimum management scheme rather than just crop yield.
Further experimental work should document several successive pollarding cycles of the trees to assess the sustainability of this drastic management of the trees. They should allow identifying the best pollarding frequency to optimize the trade-off between timber, branch wood and crop productions over the whole cycle of the agroforestry system.

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