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Winter cereal production in a Mediterranean silvoarable walnut system in the face of climate change

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ABSTRACT

One of the foreseeable consequences of climate change is a reduction in crop yields. In recent years, agroforestry systems have been identified as a strategy for climate change mitigation and adaptation. In this study we assess the potential of a silvoarable system to protect crops against extreme climate events. We studied a 9-year-old hybrid walnut silvoarable system (*Juglans x intermedia Mj209xRa*) intercropped with cultivars of two winter cereals – wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.) – for three consecutive years and compared it with monocrops and pure tree plantations. The parameters studied were grain and total biomass yield, harvest index, grain size and tree diameter increment. Plant phenology and soil and plant nutrients were also examined. Climate conditions and tree presence conditioned cereal yields, and the responses to silvoarable conditions differed among cereal species and cultivars. The silvoarable system with barley had higher production than monocrops in years with early heat events (yield increment of 55% in the first year and 15% in the second year). For wheat, no positive effect of trees in the silvoarable system was found, although grain quality improved significantly (2.56% and 2.76% N grain content in monocrops and silvoarable systems, respectively). Tree growth, measured as diameter at breast height increment, was lower in the silvoarable system (2.06 cm at the end of the study) than in the monospecific plantation (2.83 cm in the same period). The land equivalent ratio was always higher than 1 (1.34–2.08), showing that the silvoarable system was more productive than sole pure plantations and cereal monocrops.

1. Introduction

World population growth in the second half of the 20th century required an increase in crop yield that was achieved by improved agronomic techniques and seeds. However, despite the need to double food production in the 21st century to feed the increasing human population, yields have stagnated in recent years (Tilman et al., 2002) as a result of climate change and recurrent extreme weather events such as heat waves and prolonged drought (Ray et al., 2012). In the coming years, global wheat yield is likely to decrease by 6% for each degree-Celsius increment in mean temperature (Zhao et al., 2017). Any increase in arable land is expected to be insufficient to provide enough food for the rising human population this century (Alexandratos and Bruinsma, 2012), requiring the design of more productive and more sustainable systems. Many approaches have been suggested to achieve advances in ecological intensification, which aims to increase the yields of land through better use of its resources (Bommarco et al., 2013).

Agroforestry systems, defined as integrated land-use systems, are among these ecological intensification approaches (Tittonell, 2014). Agroforestry is the practice of deliberately integrating woody vegetation (trees or shrubs) with crop and/or animal production systems to benefit from the resulting ecological and economic interactions (Burgess et al., 2015). Many studies (e.g., Schoeneberger et al., 2012) have reported that trees help to regulate the climate beneath them by reducing temperature extremes, providing shelter from the wind and limiting soil surface evaporation. In Mediterranean areas, trees can stabilise grass production through the typical inter-and intra-annual rainfall variation (Gea-Izquierdo et al., 2009; Joffre and Rambal, 1993; Moreno, 2008). Woodland shade also limits water loss by crop transpiration, thus increasing the water use efficiency of the system, a key factor in adapting to climate change (Lasco et al., 2014). The role of integrated systems as a climate change adaptation mechanism has recently been recognised by the European Conference on Rural Development (EU, 2016), the European Strategy for Climate Change (EU, 2014), the European Forestry Strategy (EU, 2013) and the latest International Panel on Climate Change report (Fifth Report) (IPCC, 2015).

Silvoarable systems producing trees and crops are one of the possible combinations within agroforestry systems. The species used,

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wheat and walnut, are two of the most commonly studied species in temperate silvoarable systems (Wolz and DeLucia, 2018). Trees appear to have the ability to extend roots to deeper layers when there is competition in the shallower layer, which could help to ensure sufficient belowground resource acquisition (nutrients and water) and adequate growth rates (Andrianarisoa et al., 2015; Cardinael et al., 2015). Crop response to conditions imposed by trees under the Mediterranean climate and other water-limited regions remains uncertain (van der Werf et al., 2007). While some studies have identified plant traits that could be beneficial in certain wheat cultivars to withstand partial shade caused by pollution in some areas (Li et al., 2010), interest has recently increased in studying how shade generated by trees affects wheat yield (Dufour et al., 2013; Mu et al., 2010). However, these studies have overlooked how barley, characterised by its drought tolerance (Xia et al., 2017), could respond differently from other cereals in silvoarable systems.

This study attempts to shed light on the production of winter cereals and timber trees in a silvoarable system in a Mediterranean area in years with contrasting climate conditions. In this area, high inter-annual rainfall variations and spring heat waves are becoming common, agreeing with foreseen future climate scenarios (Gerald and Tebaldi, 2004; Giorgi and Lionello, 2008; Trnka et al., 2014). We compared the productivity of different cultivars of barley and wheat cultivated in open fields and under 9-year-old hybrid walnuts. Our specific hypotheses were:

(i) *There is competition between crops and trees that negatively affects crop yield*. This hypothesis was assessed by comparing crop yield (and soil and plant nutrients) between silvoarable vs cereal monocrops in years with no specific climatic constraint.
(ii) *During spring heat waves, winter cereals could be more productive under trees*. Crop yield was compared between silvoarable and monocrops in years with spring heat waves.
(iii) *Crop yield under silvoarable conditions depends strongly on the crop species and cultivars*. Comparisons of phenology and crop yield among silvoarable and monocrops were performed for species and cultivars differing in precocity.
(iv) *Grain quality could differ between the silvoarable combination and monocrops*. Nutrient content of barley and wheat grains produced in monocrops and silvoarable plots were compared.
(v) *Tree growth diminishes in the silvoarable system*. Stem growth was compared between trees in silvoarable and forestry plots. Leaf nutrients were also compared.

Lastly, we evaluated the overall yields of the study systems by calculating the land equivalent ratio (Mead and Willey, 1980) over three years to determine whether the silvoarable system is more productive than forestry and monocrops in the face of climate change.

The experiment is part of the European project AGFORWARD, which aims to promote agroforestry systems in Europe through proposals for innovation and social recognition of their environmental services. This study helps to identify crops adapted to silvoarable systems under a Mediterranean climate.

2. Material and methods

2.1. Study site

The experiment was conducted from 2013 to 2016 in a hybrid walnut plantation in central-western Spain (Toledo, Spain; coordinates ETRS89 39° 50′ 54″N 4° 28′ 2″W, 411m a.s.l). The climate of the region is Mediterranean, with hot dry summers and cool rainy winters. Average annual temperature and rainfall are 15.2 °C and 439 mm, respectively. Drought usually occurs from June to September. The soil is Fluvisol, with a depth of more than 1.4 m. Initial soil analysis indicated a sandy loam texture with an acidic pH in the upper 20 cm (pH 6 in water) (Table A1 in Supplementary material), making the area suitable for cultivating the species used in the study.

The study was carried out in a 9-year-old (in 2013) hybrid walnut plantation, planted in former cereal fields at 6 m between-row and 5 m within-row spacing (333 trees ha^{-1}). Before 2013, the whole plantation had been treated with herbicides in tree rows and ploughed in alleys to keep it weed free. In the study period, canopy closure was almost complete and trees were pruned each year before and during the study. At the beginning of the experiment, mean tree height and diameter at breast height (DBH) were 10.5 m and 15.3 cm, respectively. Every summer (July–September), trees were irrigated at the same rate in the silvoarable and forestry systems using a drip irrigation system, with a total amount of 2000 m^3 ha^{-1} and water quality adequate for walnut irrigation (Table A2 in Supplementary material). The nutrient content applied to trees through irrigation in summer was 40 kg N ha^{-1}, 17.5 kg P ha^{-1} and 41.5 kg K ha^{-1}. The plantation was certified by the Forest Stewardship Council (FSC). The woodland was a clone of Nat7 of hybrid walnut *Juglans x intermedia Mj209xR*a, resulting from pollination of *Juglans major* Torr. *var. 209 (Mj209)* with *Juglans regia* L. *(Ra)*. This hybrid is known for its fast growth (hybrid vigour) and low fruit yield, and has considerable capacity to adapt to different soils and warm areas of the Iberian Peninsula. Walnut buds usually break after mid-April. A large adjoining area without trees that had previously been cultivated with winter cereals (wheat and barley) was used for the monocrop system.

2.2. Experimental layout

Three vegetation systems were compared: intercropping of cereals in walnut plantation alleys ("silvoarable"), cereals grown in open fields ("monocrops") and pure tree plantation without intercropping ("forestry"). Silvoarable and forestry plots were adjacent to each other, in the same walnut plantation area (Fig. A1 in Supplementary material). Trees in the silvoarable and forestry plots had received similar management before the study and were similar in size. The systems were established at a distance from each other (Fig. A1 in Supplementary material) because it was a private plantation that did not allow a randomised block design. However, to ensure that soil conditions were similar between treatments, soil properties were evaluated and no apparent differences were detected for the more common parameters (Table A1 in Supplementary material).

For the silvoarable treatment, six plots measuring 120 m^2 (20 m long × 6 m wide, including 5 trees in each line and cropped alleys 4 m wide) were cultivated and located randomly per cultivar of cereal. Six 2 × 2 m plots were established per cereal variety without trees as a control for cereal production (monocrops), spaced 0.5 m apart (Fig. A2 in Supplementary material). The forestry control comprised three plots of trees without cereals (45 trees per plot). The location of the plots varied across the three years. Cereal species were carefully sown by hand spreading in early November each year in the silvoarable and monocrop systems. Soil was prepared by harrowing in June and again a few days before sowing. All cereal plots were fertilised in November (just before sowing) with 48 kg ha^{-1} N, 31 kg ha^{-1} P and 60 kg ha^{-1} K and in February (cereal tillering) with 55 kg ha^{-1} N.

The winter cereal species were barley (*Hordeum vulgare* L.) and wheat (*Triticum aestivum* L.). The sowing rate was 180 kg ha^{-1} for barley and 220 kg ha^{-1} for wheat. The selected cultivars varied over the years depending on seed availability but were the same each year in the monocrop and silvoarable systems. Barley cultivars were Doña Pepa and Azara in 2013, Basic, Lukhas, Hispanic and Dulcinea in 2014 and Meseta and Hispanic in 2015. Wheat cultivars were Kilopondio and Bologna in 2013, Ingenio, Sublim and Nogal in 2014 and Ingenio, Nogal, Botticelli and Idalgo in 2015. All of these cultivars are commonly sown in Spain in Mediterranean areas because of their proven adaptation to drought and high temperatures.