Europ. J. Agronomy xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

European Journal of Agronomy

journal homepage: www.elsevier.com/locate/eja

Impact of spatio-temporal shade dynamics on wheat growth and yield, perspectives for temperate agroforestry

Sidonie Artru[a,*], Sarah Garré[b], Christian Dupraz[c], Marie-Pierre Hiel[a], Céline Blitz-Frayret[c], Ludivine Lassois[b]

[a] TERRA research center – AgricultureIsLife, University of Liège, Gembloux Agro-Bio Tech, Passage des Déportés 2, B-5030 Gembloux, Belgium
[b] TERRA research center, University of Liège, Gembloux Agro-Bio Tech, Passage des Déportés 2, B-5030 Gembloux, Belgium
[c] INRA, UMR SYSTEM, Equipe Amplus, Bâtiment 27, 2, Place Viala, 34060 Montpellier Cedex 1, France

ARTICLE INFO

Article history:
Received 10 March 2016
Received in revised form
30 September 2016
Accepted 9 October 2016
Available online xxx

Keywords:
Winter wheat
Spatio-temporal shade
Grain yield
Modeling
Agroforestry system

ABSTRACT

A stumbling block to the adoption of silvoarable agroforestry systems is the lack of quantitative knowledge on the performance of different crops when competing for resources with trees. In North-Western Europe, light is likely to be the principal limiting resource for understorey crops, and most agronomic studies show a systematic reduction of final yield as shade increases. However the intensity of the crop response depends on both the environmental conditions and the shade characteristics. This study addressed the issue by monitoring winter wheat (*Triticum aestivum* L.) growth, productivity and quality under artificial shade provided by military camouflage shade-netting, and using the Hi-sAFe model to relate the artificial shade conditions to those applying in agroforestry systems.

The field experiment was carried out over two consecutive years (2013–14 and 2014–15) on the experimental farm of Gembloux Agro-Bio Tech, Belgium. The shade structures recreated two shade conditions: periodic shade (PS) and continuous shade (CS), with the former using overlapping military camouflage netting to provide discontinuous light through the day, and the latter using conventional shade cloth. The experiment simulated shading from a canopy of late-flushing hybrid walnut leaves above winter wheat. Shading was imposed 16 (2013–14) and 10 (2014–15) days before flowering and retained until harvest. The crop experienced full light conditions until the maximum leaf area index stage (LAI_{max}) had been reached. In both years, LAI followed the same dynamics between the different treatments, but in 2013–2014 an attack of the take-all disease (*Gaeumannomyces graminis* var. *tritici*) reduced yields overall and prevented significant treatment effects. In season 2014–15 the decrease in global radiation reaching the crop during a period of 66 days (CS: – 61% and PS: – 43%) significantly affected final yield (CS: – 45% and PS: – 25%), mainly through a reduction of the average grain weight and the number of grain per m^2. Grain protein content increased by up to 45% under the CS treatment in 2015. Nevertheless, at the plot scale, protein yield (t/ha) did not compensate for the final grain yield decrease.

The Hi-sAFe model was used to simulate an agroforestry plot with two lines of walnut trees running either north-south or east-west. The levels of artificial shade levels applied in this experiment were compared to those predicted beneath trees growing with similar climatic conditions in Belgium. The levels used in the CS treatment are only likely to occur real agroforestry conditions on 10% of the cropped area until the trees are 30 years old and only with east-west tree row orientation.

1. Introduction

In 2014, winter-wheat (*Triticum aestivum* L.) represented around 14% of the cultivated area in Belgium with a mean yield of 9.9 t ha^{-1} (Waeyaert, 2014). Winter-wheat represents 29% of the cereal production on the world market (FAO, 2014), but at the same time, the intensive agricultural practices used to produce the crop lead to environmental problems like soil erosion, water pollution and loss of biodiversity. These facts challenge us to come up with alternative farming systems, such as mixed cropping (Malézieux et al., 2009). The combination of crops and woody components in a same field is called agroforestry and it can combine good productivity with sustainable land use (Dupraz, 2002). However, the success of such systems depends on the reinforcement of ecological processes such as facilitation and complementarity for resource capture between species (Cannell et al., 1996; Malézieux et al.,

* Corresponding author.
E-mail address: sidonie.artru@ulg.ac.be (S. Artru).

http://dx.doi.org/10.1016/j.eja.2016.10.004

2009). Complementarity is constrained if all plants use the same resources and the consequences can be severe in an environment where one resource is limiting (Ong and Huxley, 1996). In a successful agroforestry system, complementarity results from niche differentiation, either in space (e.g. different root depth) or in time (e.g. different phenology) (Tilman and Snell-Rood, 2014). In this context, research on agroforestry systems aims at quantifying and analyzing the spatiotemporal patterns of resource capture between species. However, papers covering temperate agroforestry systems reveal contrasting results (Luedeling et al., 2016; Smith et al., 2013; Tsonkova et al., 2012). This is probably due to the fact that the interactions between two different species may depend on multiple factors such as the design of the mixture (e.g. species choice, stand design . . .), the management choices (e.g. tree pruning height, tillage depth . . .) and soil and climate conditions. This makes a clear overview difficult (Batish, 2008; Jose and Gordon, 2008; Zhu et al., 1991). Nevertheless, with regard to factors hampering the performance of silvoarable agroforestry systems, light might be the principal limiting resource for the crop growing under trees subjected to Belgian soil and climate conditions (Eichhorn et al., 2006). The tree induces a heterogeneous light environment for the crop species below. A tree canopy leads to a typical sunfleck regime, varying, on one hand, within a time frame of seconds to minutes due to penetration of the sun through the canopy and wind induced movements, and on the other hand over days, months and years depending on the path of the sun, tree planting density, silvicultural practices and tree phenological stage (Leroy et al., 2009; Liu, 1991; Talbot and Dupraz, 2012). Alterations of light quantity and quality during the cropping season will induce physiological and morphological changes for the crop.

Previous studies tested the effect of shade on crop growth and yield by applying shade at a specific moment in the development cycle and during the whole day rather than at a specific time during the day, as is observed under trees (Demotes-Mainard and Jeuffroy, 2004; Fischer and Stockman, 1980). Only a few research projects have looked at the agronomical impact of the light regime experienced by crop species under temperate agroforestry systems (Chirko et al., 1996; Dufour et al., 2013; Friday and Fownes, 2002; Gillespie et al., 2000; Liu, 1991; Mu et al., 2010; Zhang et al., 2008). These studies show a systematic reduction of final crop yield but the intensity of this decrease varies between species, as does the shade level and possible below-ground interactions. In order to differentiate the effect of light from the other possible abiotic and biotic interactions occurring between trees and crops in agroforestry system, several authors designed and used an artificial shade system (Dufour et al., 2013; Peri et al., 2002; Varella et al., 2010). Earlier articles evaluated the ability of artificial shade materials to mimic the fluctuating agroforestry light environment over the day or through the cropping season. Varella et al. (2010) demonstrated that wooden slatted structures reproduced well the daily periodic light fluctuation and the spectral composition observed under trees. In comparison, conventional plastic shade-cloth only produced a predetermined level of light reduction. Dufour et al. (2013) presented the potential of adding overlapping shade cloths during the cropping season in order to mimic the increasing leaf area of trees. These artificial structures were used to analyze crop and forage development, yield and physiological responses to shade (Dufour et al., 2013; Peri et al., 2002; Varella et al., 2010).

The general aim of the current study is to quantify the efficiency of winter wheat growth, productivity and quality in temperate conditions, under the shade of late-budding trees, replicated by an artificial shade system. In order to take into account the diversity of possible shade environment observed under agroforestry, crops have been subjected to two distinct shade conditions thus addressing two objectives. The first is a worst-case scenario of crop response to an extreme condition of continuous shade under the temperate climate conditions. The second is to monitor the response of crops to variable shade by changing the shade hourly. Finally, we aimed to compare the artificial shade conditions with real agroforestry systems through a modelling approach.

2. Materials and methods

2.1. Field experiment

The experiment was conducted during two growing seasons, 2013–14 and 2014–15, at the experimental farm of Gembloux Agro-Bio Tech (50°33′ N, 4°42′E), in the Hesbaye region, Belgium. The climate is temperate maritime, with an average annual temperature of 10.1 °C and mean annual rainfall of 799 mm over a 20 year period (1994–2014). The soil is classified as Luvisol (FAO, 2014). The plots were both part of the experimental farm in both years, but they were not exactly at the same spot in the field. Soil physicochemical homogeneity within and between both experimental plots was previously verified using the digital soil map of Wallonia and a measurement of soil electrical conductivity (EC) realized using the electromagnetic induction method (EMI) (Bah et al., 2005; Grisso et al., 2005) conducted prior to the installation of the artificial shade structures.

Winter wheat (*T. aestivum* L., cultivar Edgard) was planted on October 24th, 2013 (300 grains m^{-2}) and October 21th, 2014 (250 grains m^{-2}), the drill lines following an East-West orientation in both cases. The preceding crops were winter wheat in 2013–2014 and rapeseed in 2014–2015. Fertilization followed the conventional practice applied in Belgium, which means that three doses of nitrogen fertilizers were applied throughout the growing season. A total amount of 225 (75, 75, 75) and 175 (50, 50, 75) units of nitrogen per hectare and per year were applied, respectively for the season 2013–2014 and 2014–2015. For both cropping seasons, one herbicide (pyroxulamn (7.1%), florasulam (1.5%), cloquintocet-mextyl (7.1%) and colza oil), one plant growth regulator (chlormequat chloride (59.7%) and cholin chloride (3.2%)) and two fungicides (one composed of epoxiconazool (37.5 g/l) and metconazool (27.5 g/l); the other composed of bixafen (75 g/l) and prothioconazole (150 g/l)) were applied in spring. Winter wheat was harvested on August 5th, 2014 and August 10th, 2015 with a combine harvester.

2.2. Experimental design

The experiment included three shade levels, corresponding to three modes of daily shade dynamics. The continuous shade (CS) treatment underwent shade throughout the entire day; the periodic shade treatment (PS) corresponded to an intermittent shade on the plot varying during the day; while the crop in the no shade treatment (NS) received 100% of the available light. Within the PS plot, the variability of shade dynamics was assessed by measuring the light availability for the winter wheat at three locations along the north-south transect, defined as PS1, PS2, PS3. The shade levels were obtained by adjusting shade layers on the south face of a greenhouse tunnel structure (5 m wide, 68 m long and 2.50 m in height) set up in East-West orientation (Fig. 1). We used camouflage nets as shade material to reproduce a rapidly fluctuating sun/shade pattern. The proportion of holes to cloth in the mesh of the camouflage nets produces a combination of direct and diffuse light patches. The artificial shade was designed to mimic the shade dynamics of a hybrid walnut and was adapted to follow the development of tree-foliage in a monitoring plot in Belgium. In 2014–15, the camouflage net covered 40 cm more of the tunnel curvature than in 2014–15, in order to induce a higher overall shade level in the PS treatment. The surface of cloth was extended by around 9%