COMMUNAUTÉ FRANÇAISE DE BELGIQUE

UNIVERSITÉ DE LIÈGE – GEMBLOUX AGRO-BIO TECH

# IMPACT OF SPATIO-TEMPORAL SHADE ON CROP GROWTH AND PRODUCTIVITY, PERSPECTIVES FOR TEMPERATE AGROFORESTRY

Sidonie ARTRU

Dissertation originale présentée en vue de l'obtention
du grade de docteur en sciences agronomiques et ingénierie biologique

Promoteurs : Ludivine LASSOIS & Sarah GARRE

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# Abstract

Currently, silvoarable agroforestry is receiving renewed interest in Europe, as a land use system that allows for combining the production of commodities with a range of non-commodity outputs, such as environmental protection. Despite the potential of this practice, it remains rarely implemented in Northwestern Europe. One of the obstacles in the adoption of silvoarable agroforestry systems is the lack of quantitative knowledge on the long term performance of different crops when they are competing for resources with trees. In the face of a wide range of possibilities, it remains difficult to obtain a clear overview of overall system functioning. In this thesis, we simplify this complexity by focusing our research questions on the resource of light, based on the assumption that in Belgian climatic conditions light is likely to be the predominant constraint for understorey crops in a silvoarable agroforestry system. With regard to this resource, we develop our research in order to gain insights into the growth mechanisms and final yield of shaded winter wheat and sugar beet crops.

We address these questions using an artificial shade system, which has been developed to reproduce the effect of the heterogeneous spatio-temporal pattern of light observed under late-flushing trees in an agroforestry system, isolated from the competition effects for water and nutrients. The shade structures recreate two shade environments: continuous and periodic. The continuous shade treatment leads to shade throughout the entire day, while the periodic shade treatment induces an intermittent shade period, which varies during the day and according to structure orientation. Winter wheat responded to the late application of both shade treatments with a significant decrease in grain yield, which was partly compensated for by an increase in grain protein content. When shaded, sugar beet compensated through morphological adaptations of the aboveground part of the plant, and by a decrease in the final root dry matter and sugar yield. Overall, for both crops, the magnitude of the final yield repercussion varied with the level and period of shade application.

Additionally, an arable plot bordered by a row of poplar trees was selected to evaluate the effect of real trees on the winter wheat. The reduction in the final grain yield follows a gradient, from underneath the trees to the centre of the field. Notwithstanding that interactions other than light competition may have occurred, the maximum yield reduction observed under the trees never reaches the level of decrease which is observed under the continuous shade treatment simulated by the artificial shade arrangement.

This experimental approach with winter wheat was complemented by a modelling study, in which we evaluate the ability of the STICS crop model to simulate crops growing under dynamic shade. The results highlight the limits of the STICS model when it is used to simulate crop growth under contrasted shade conditions.

Finally, we propose agroecology as a conceptual framework for developing sustainable and profitable agroforestry systems in Europe, and reflect on agricultural practices, food systems, and research methodologies.

# Résumé

Aujourd'hui, l'agroforesterie connait un regain d'intérêt en Europe de par sa capacité à concilier production et protection de l'environnement. Malgré le potentiel de cette pratique, elle reste peu adoptée dans le Nord-ouest de l'Europe. L'un des freins à cette adoption s'explique par le manque de connaissances et de données quantitatives permettant d'évaluer la performance des systèmes agroforestiers à long terme. Au sein de ces systèmes, la diversité d'association d'arbres et de cultures, les différentes possibilités de design et d'itinéraire techniques suivies sur la parcelle ajoutent un niveau de complexité à la compréhension des interactions pour les ressources. Au vu de cette diversité, il apparait dès lors difficile d'avoir une vision d'ensemble claire du fonctionnent de ces systèmes.

Afin de pallier cette complexité nous avons focalisé nos travaux de recherches sur la ressource lumineuse. Ce choix s'appuie sur l'hypothèse selon laquelle dans le contexte climatique Belge la lumière serait la ressource limitante principale pour les cultures au sein de systèmes agroforestier silvoarable. Ce travail s'est intéressé à comprendre les mécanismes de croissance et de productivité du froment et de la betterave sucrière dans un contexte d'ombrage agroforestier.

Dans un premier temps, un système d'ombrage artificiel a été développé afin de simuler un environnement lumineux hétérogène observé au sein de systèmes agroforestiers composés d'arbres à phénologie tardive, ainsi que pour isoler la composante lumineuse des autres compétitions possibles (eau, nutriments). La structure utilisée a permis de créer deux environnements ombragés : un ombrage continu imposé tout au long de la journée ainsi qu'un ombrage périodique qui varie spatialement au-dessus des cultures au cours de la journée en fonction de l'orientation de la structure et du mouvement du soleil. Pour le froment, l'application d'un ombrage tardif au cours de la saison induit une réduction significative du rendement en grains, partiellement compensé par une augmentation de la teneur en protéine des grains. La betterave à sucre répond aux conditions d'ombrage par des adaptations morphologiques de sa partie aérienne, ainsi que par une réduction importante de la biomasse sèche racinaire et du rendement en sucre final. Globalement, pour les deux cultures, la diminution du rendement final sous ombrage varie en fonction de la quantité ainsi que du stade phénologique de la culture au cours de laquelle l'ombrage est appliqué.

Pour aller plus loin, une expérimentation a été mené sur une parcelle bordée de peupliers afin d'évaluer la croissance et la productivité du froment dans un contexte ou la lumière ne serait plus l'unique ressource potentiellement limitante. La présence des arbres induit une diminution du rendement final en grains suivant un gradient allant de l'arbre au centre de la parcelle.

L'expérimentation d'ombrage artificiel menée sur le froment a été complétée par une approche de modélisation afin d'évaluer la capacité du modèle de culture STICS à simuler la croissance et la

productivité de froment sous ombrage. D’une manière générale, le modèle arrive à reproduire la dynamique de croissance en biomasse aérienne du froment sous ombrage continu mais se révèle incapable de simuler la biomasse aérienne en conditions d’ombrage périodique. Les résultats de cette étude mettent en évidence les limites de STICS à simuler le rendement final en grains en conditions d’ombrage.

Pour finir, nous présentons le concept de l’agroécologie et le proposons comme modèle pour le développement de systèmes agroforestiers rentables et durables en Europe.

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# Introduction

## 1. Agroforestry: definition, current status, and challenges in Europe

Agroforestry has been defined by Mosquera-Losada et al. (2012) as the "practice of deliberately integrating woody vegetation (trees or shrubs) with crops and/or livestock production to benefit from the resulting ecological and economic interactions". Behind this fairly simple definition, the generic term "agroforestry" encompasses a multitude of possible tree–crop–animal associations and scales of integration (field, farm, or landscape), resulting in a range of terminologies (Table 1). From a historical viewpoint, agroforestry is a new term for old practices; the presence of trees in farmland was common in European landscapes (den Herder et al., 2017). However, over the last decade the extent of many traditional agroforestry systems has declined dramatically with agricultural land consolidation, and within the current European agricultural landscape the systems that remain are still vulnerable (Mosquera-Losada et al., 2012; Wezel et al., 2014).

Currently, agroforestry is receiving renewed interest from scientists and politicians in Europe, as a land use system that supports multiple ecosystem services. In fact, in addition to provisioning services (eg. food, feed, and fiber), agroforestry systems are expected to improve regulatory ecosystem services (eg. nutrient retention, soil erosion control, carbon sequestration, pollination, and pest control), as well as cultural services (eg. landscape aesthetic, heritage values, and recreational services) (Smith et al., 2013). A recent meta-analysis conducted at the European scale reported an overall enhancement of ecosystem services—mainly erosion control, biodiversity, and soil fertility—within agroforestry systems, as compared to conventional agriculture and forestry land use practices (Torralba et al., 2016). There has therefore been an effort by policy makers to promote the adoption of agroforestry system practices through the creation of specific subsidies. In the Common Agricultural Policy (CAP), holdings of more than 15 hectares are required to implement "ecological focus areas" on at least 5 % of their arable land and farms. Since 2013, agroforestry practices have been included in the CAP's "ecological focus areas" list, and farmers can receive "greening payments" for the implementation of such systems under Pillar I (Reg.(EU)1307/2013). Farmers can also receive subsidies by national governments through the rural development programs under Pillar II (Reg.(EU)1305/2013) (see Boutsen et al., (2016) for the Walloon context). Furthermore, agroforestry has been mentioned in the European Forestry Strategy, and is supported as a sustainable land management strategy by the United Nations Intergovernmental Panel on Climate Change (IPCC).

From a research perspective, another recent meta-analysis has revealed that the number of publications concerned with agroforestry—silvoarable, silvopastoral, buffer strips, and multipurpose trees systems—and ecosystems services has risen continuously between 1993 and 2010, with more than 80 % of these publications published after 2007 (Fagerholm et al., 2016). In addition, farmers are becoming interested in gaining a better understanding, since these systems can offer a diversified production pattern and mitigate environmental issues. Nevertheless, this depends a lot on the socio-economic context and the type of agroforestry system. In Northwestern Europe, silvoarable agroforestry systems are still only implemented rarely, despite the potential of this practice, and there is little prospect of wide scale implementation (Wezel et al., 2014). Among the various challenges to implementation, uncertainty regarding crop growth and productivity remain important issues (Borremans et al., 2016; Graves et al., 2009; Wezel et al., 2014).

**Table 1.** Classification of major agroforestry practices in Europe proposed by Nerlich et al. (2012).

| Agroforestry practices | Definition |
|---|---|
| Silvoarable systems | Trees are planted in single or multiple rows, with arable or horticultural crops between the rows. |
| Silvopastoral systems | Trees are combined with forage and livestock production, including stands that are high density (forest or woodland grazing), and low density (open forest trees). |
| Orchard intercropping | Fruit tree systems on arable land or grassland, mixed with grazing animals. |
| Forest farming | Utilising forested areas for producing or harvesting natural or cultivated specialty crops, for medical, ornamental, or culinary uses. |
| Riparian buffer | Perennial vegetation (grass, shrubs, trees) are planted in strips between arable land or pastures in order to enhance aquatic resources (rivers, streams, lakes) and protect them from the negative effects of agricultural practices. |
| Windbreaks | Rows of trees are planted around farms and fields to protect crops, animals, and soil from the wind. |

## 2. When trees come to the field

As summarised in Figure 1, integrating trees into a cropped area modifies the crop abiotic growth environment in terms of light, water, and nutrient availability, as well as in terms of microclimatic conditions (temperature, relative humidity, wind speed, etc), and soil structure and water holding capacity (Batish et al., 2008). Hence, in terms of spatio-temporal dynamics, this adds a level of complexity for resource use, since different types of competition can occur and potentially hinder crop growth. According to Tilman and Snell-Rood (2014), the success of species association results from niche differentiation, either in space (eg. different root depth), or in time (eg. different phenology). This theory hinges on the reinforcement of ecological processes, such as facilitation and complementarity for resource capture between species (Cannell et al., 1996; Malezieux et al., 2009). However, tree-crop interactions may depend on multiple factors, such as design of the mix (eg. species choice, stand design), management choices (eg. tree pruning height, tillage depth), and soil and climatic conditions.

In the face of such a large range of possibilities, it remains difficult to obtain a clear overview of overall system functioning, form the right research questions, and adopt the correct scientific practices.

With regard to climatic conditions in Belgium, over the two last decades greater monthly extremes in weather conditions have been recorded during the crop growing season, as compared to the previous decade. According to Gobin (2010), under the three typical Belgium soils (clay, loam, and loamy sand), drought and heat stress events may occur during the summer, and waterlogging stress events during the spring.

Nevertheless, in this thesis we simplify the complexity by focusing on one specific resource: light. Our selection of light as a focus is based on the assumption of Eichhorn et al. (2006), that light is probably the predominant constraint for silvoarable productivity in the northern latitudes of Europe, such as in Belgium.

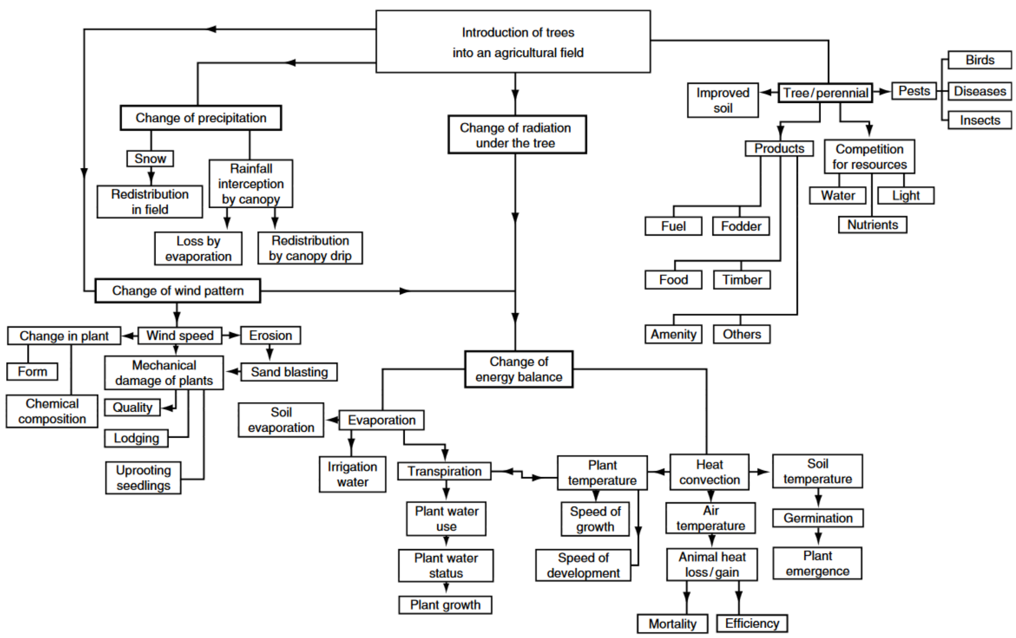



**Figure 1.** Schematic representation of abiotic change following the introduction of trees into an agricultural field (From Batish, 2008).

# 3. Characterisation of the agroforestry light environment

Within an agroforestry system, the presence of trees induces a spatio-temporal heterogeneous light environment for understory species, and the radiation available below the tree changes in quantity, periodicity, and quality. These three factors are influenced by the spatial distribution of the trees on the plot (ie. tree row orientation, and tree spatial distribution within and between rows), tree canopy features (ie. foliage density, canopy size and shade, and tree phenology), as well as the sizes of trees. Furthermore, the tree canopy leads to a typical sunfleck regime, resulting in shadow patches at ground level. The light environment varies within a time period—which can be of seconds to minutes—due to the penetration of the sun through the canopy, and to wind induced movements. In addition, this fluctuating regime may vary over longer periods. In fact, the pattern of sun and shade changes over days and months, due to the combined effect of the path of the sun—which depends on the latitude of the specific field and the time of the year—and the inherent characteristics of agroforestry systems (plot design, silvicultural practices, tree phenology, etc.).

In terms of light quality, Reifsnyder (1987) mentions that the radiation available underneath crops is a combination of at least four components: "direct beam radiation coming through gaps in the canopy; diffuse radiation from the reflection and transmission of the direct beam by leaves and other vegetation elements; sky radiation transmitted through canopy gaps; and radiation reflected off vegetation elements". According to Urban et al. (2007), within the canopy diffuse light presents a lower extinction coefficient than direct light, leading to a deeper penetration of diffuse light within the tree canopy. Thus, in terms of the proportion of direct and diffuse light, the light composition below the trees results from the inherent characteristics of the light above the trees. In addition, the penetration of solar radiation through the tree canopy changes its spectral composition. Tree crowns preferentially absorb light in the 400–700nm wavelengths, resulting in a reduced proportion of blue and red light as compared to green and far-red ones (Nobel, 2005). This leads to a reduction in the red to far-red ratio (R/FR) under the canopy, as compared to full sunlight conditions, and this property is influenced by the shade source. Feldhake (2001) observes a decrease in the R/FR ratio under black locust trees from 1.16 to 0.2, while under a rubber tree plantation this reduction reaches 0.62, as compared to full sun light conditions (Wilson and Ludlow, 1990). Finally, all these factors combined lead to a diversity of possible light environments for understorey species, and it remains difficult to distinguish one factor from another when trying to characterise the light resource availability for crops.

## 4. How do crops deal with dynamic shade?

Usually, studies addressing the effect of shade on crop development within agroforestry systems show that tree shading generally leads to reduced growth and yield repercussion for crops. Early physiological studies have shown that, when water and nutrient resources are not limited, the amount of dry matter accumulated by the crop during vegetative growth relies on the amount of photosynthetically active radiation (PAR, 400–700 nm) intercepted by the canopy, and on the efficiency with which it is converted by photosynthesis (radiation use efficiency) (Monteith, 1977). Final yield then depends on the partitioning efficiency (harvest index), defined as the amount of total biomass partitioned into the harvestable organs of the crops.

The amount of radiation intercepted by the crop results from the differences between the amount of incident radiation and the amount that penetrates below the canopy. This will vary with sun angle and proportion of direct/diffuse light, as well as with the crop canopy architecture (size, shape, and orientation of the plant organs). Several studies have reported that the negative influence of a decrease in global radiation can be compensated for by increasing the proportion of the diffuse light which appears to be advantageous for crop photosynthesis, because leaves receive a photon flux density (PFD) below the light saturation point of photosynthesis (Gu et al., 2002; Li et al., 2014; Way and Pearcy, 2012; Zhang et al., 2011; Zhu et al., 2010). From a physiological point of view, the responses of $CO_2$ assimilation rates to a sunfleck environment are complex. In fact, the different components of the photosynthetic apparatus do not react with the same lag time to quick variations in photon flux density (PFD). As highlighted by Way et al. (2012), sunfleck induces an instantaneous change in the PFD, while the dynamic of adjustment of the photosynthetic mechanism following a change in PFD is variable and depends on species, growth conditions, and environment.

With respect to crop architecture, Zhu et al. (2008) indicate that for crop species with a leaf area index (LAI) higher than 2, the greatest light interception is achieved by a combination of vertical leaf angle at the top of the canopy and gradual decreases in this angle through horizontal leaves deeper in the canopy. Several studies have shown that a number of physiological and biochemical adaptations occur when crops are subjected to a shady environment, and that some of these adaptations are then translated by the crop into morphological changes in order to optimise light capture and use (Valladares et al., 2007, 2003). It should be noted that these adaptations result not only from the reduction in the total amount of light, but also from variation in spectral quality. By applying shade to winter wheat from the stem elongation stage to harvest, Mu et al. (2010) observe an overall reduction in LAI and a change in leaf shape, with increased fractions of the top and bottom leaf area to the total leaf area. For faba bean plants, Nasrullahzareh et al. (2007) observe an inverse trend from emergence until harvest, with higher LAI and ground cover under shade. In his study, Marrou et al. (2013) has shown that applying intermittent shade during the whole cropping season induces a significant increase in the specific leaf area (SLA—ratio of leaf mass to leaf area, $kg/m^2$) of lettuce. In contrast, Dufour et al. (2011) has shown that winter wheat growing under shade presents significantly lower SLA, when compared to plants growing under full sunlight. Furthermore, the application of a light source with a low red to far red ratio and reduced blue wavelength induces shade-avoidance traits, with higher petiole length or overall plant height, in alfalfa (Peri et al., 2001; Varella et al., 2010), winter wheat (Li et al., 2010), and faba bean (Nasrullahzadeh et al., 2007).

Thus, the extent of such morphological adaptations can vary among species, and relies on the type of shade experienced by the crop. Furthermore, crop growth and final yield do not only depend on the amount and quality of light, but also on the dynamics and duration of the shaded period during the growing season in relation to crop phenology (Fischer and Stockman, 1980; Watson et al., 1972). This observation is very relevant for agroforestry systems, under which crops are subjected to an intensification of shade, following tree phenology and leaf apparition during the growing season.

When shade is applied during vegetative growth, morphological adaptation occurs, together with an adjustment of biomass accumulation. For example, in maize, Villalobos et al. (1992) showed that the final leaf number reduced when shading was applied during the period from emergence to flower initiation, while no difference was observed when the treatment was applied later in the growing season. The same authors observed three different tendencies in LAI evolution, depending on the period of shade application, as compared to their control plot. In fact, LAI was reduced, higher, or similar to the control plot when shade was applied from emergence to flower initiation, flower initiation to anthesis, or emergence to anthesis respectively. In sugar beet, Watson et al. (1972) showed that applying shade over four consecutive weeks starting in mid-July (period II) or mid-August (period III) significantly increased LAI, while sugar beet LAI was unaffected when shade was applied for the same duration but starting in mid-June (period I), and even decreased significantly when subjected to a continuous shade treatment from mid-June until harvest (period IV). Likewise, a decrease in sugar beet laminae and petiole dry matter was reported when shaded during period I, but had no effect in periods II or III.

With regard to the yield elaboration period, field observations on winter wheat have shown that applying a shade treatment over a period of about 20 to 30 days prior to flowering remains critical for grain number establishment (Abbate et al., 1997; Demotes-Mainard and Jeuffroy, 2004; Fischer, 1985). Within this period, the magnitude of the wheat's response varies according to the level and number of days of shade application. Furthermore, applying post-flowering shade treatments impacts the winter wheat grain-filling process. Several authors have observed a decrease in grain weight—and consequently a reduced final grain yield—as compared to an unshaded plot (Demotes-Mainard and Jeuffroy, 2004; Savin and Slafer, 1991; Wang et al., 2003). Similar results have been reported for sunflowers, with a decrease in final grain weight when shade was applied from anthesis to maturity (Cantagallo et al., 2004). The several examples presented above highlight the fact that crops growing in a complex light environment may undergo developmental and dynamic acclimation processes (Evans and Poorter, 2001; Gommers et al., 2013; Retkute et al., 2015), which makes a complex light environment particularly difficult to take into account in modelling efforts. Lastly, the magnitude of final yield decrease and light availability varies greatly according to crop or tree species, soil, and climatic conditions, as well as to plot design and management (Table 2).

# 5. Tree-crop interaction models

Models have become powerful research tools, given the lack of data on the long term dynamics of agroforestry systems and their adaptability to various environmental and economic conditions—as well as the numerous options for possible tree–crop combinations, and plot design and management (Dupraz, 2002). Within this context, models can be used to perform long term predictions, synthesise experimental and conceptual knowledge, generate insight into complex mixed system functioning, guide future experimentation, and provide decision support. In addition, through virtual experimentation models can be used to test a number of species combinations, plot designs, and management approaches, which remain difficult to set up with empirical experiments (Luedeling et al., 2016). Within this wide range of objectives, models' frameworks will differ depending on the context for which they have been built. In fact, models can be classified according to the level of complexity with which they describe the processes. Therefore, we can separate process-based (biophysical laws) from empirical models (mathematical relationships), but we can also classify models according to the spatio-temporal discretisation that is used (eg. a daily to yearly timescale, or whether it is spatially explicit). Overall, models should maintain a balance between the accuracy with which single processes are described, the system approach, and the computation time (Leroy et al., 2009; Malézieux et al., 2009; Roupsard et al., 2008), and the discretisation should therefore be adapted to the modelling objectives. In the last decades, several multi-species models have been designed (Table 3). Nevertheless, according to Luedelling et al. (2016), these models faced a number of constraints, and none of them can be used to reliably predict tree and crop yields. In view of the wide range of agroforestry practices and environmental conditions, these authors highlight the necessity of following a modular modelling approach, allowing for evaluation and validation of the different processes using a step-wise method, without tackling the full complexity of the system. Nowadays, these complex multi-crops systems are a challenge for modellers, and require an important development effort to fulfil the range of promising modelling objectives, as presented below.

**Table 2.** Brief insight into the diversity of light and yield reduction recorded under agroforestry systems.

| Crop species | Tree species and age | | Distance to tree rows [m] | Light reduction [%] | Yield reduction [%] | Country | Author |
|---|---|---|---|---|---|---|---|
| Soybean | Hybrid poplar | 10 | 2 | 56 | 62 | Canada | Rivest et al., 2009 |
| Soybean | Hybrid poplar | 10 | 2 / 6 | 23 / 14 | 58 / 24 | Canada | Reynolds et al., 2007 |
| Soybean | Maple | 10 | 2 / 6 | 29 / 2 | 50 / 22 | Canada | Reynolds et al., 2007 |
| Maize | Hybrid poplar | 10 | 2 / 6 | 38 / 11 | 49 / 26 | Canada | Reynolds et al., 2007 |
| Maize | Maple | 10 | 2 / 6 | 52 / 15 | 31 / 27 | Canada | Reynolds et al., 2007 |
| Winter wheat | Paulownia | 11 | 2.5 m | 72 | 21 | China | Chirko et al., 1996 |
| Winter wheat | Paulownia | 9 | average | 63 | 49 | China | Li et al., 2008 |
| Winter wheat | Hybrid walnut | 13 | 3.5 m | 66 | 41 | France | Dufour et al., 2013 |
| Hay | Hybrid poplar | 8 | 1.5 | 65 | 75 | Canada | Bouttier et al. 2014 |

**Table 3.** Description of some multispecies models which are designed to simulate tree and crops interactions (Adapted from (Malézieux et al., 2009)).

| Model | Species diversity | Spatial pattern | Time step | Aboveground interactions | | Belowground interactions | | |
|---|---|---|---|---|---|---|---|---|
| | | | | Canopy | process | Soil | Root system | process |
| Yield-SAFE | 2 | Linear | Annual | 1-D | Light balance | 1-D | | Water, N uptake |
| WaNuLCAS | > 2 | Linear / circular | Day | 1-D | Light balance | 2-D | Roots interaction<br>Tree roots plasticity | Water, N, P uptake |
| Hi-sAFe | > 2 | Spatially explicit | Day | 3-D | Light balance | 3-D slope | Tree roots plasticity | Water, N uptake |
| APSIM | 2 | | Day | 1-D | Light balance | 1-D | No interactions | Water, N uptake |

## General objectives and research questions

The general aim of this thesis is to better understand the processes driving the development of winter wheat and sugar beet growing under spatio-temporal dynamic shade in Belgian soil and climatic conditions, and to quantify final productivity.

We explore the central agroforestry hypothesis stated by Ong et al. (1996) that, within a well-designed agroforestry system, "the tree must acquire resources that the crop would not otherwise acquire".

According to this hypothesis, a high phenological time lag between tree and crop, combined with a north–south tree line orientation, is proposed as the optimal case for light resource use in temperate agroforestry systems. This configuration can be achieved by combining a winter crop and a late-flushing deciduous tree. But, how to deal with conventional crop rotation schemes, including spring crops? To what extent will competition be increased by earlier flushing trees, or by east–west tree line orientations? And what happens when additional tree-crop interactions occur?

In the first two chapters, we describe how we address these questions using an artificial shade system, which was developed in order to isolate light competition from other potential interactions occurring in agroforestry systems. Furthermore, in Chapter III, an arable plot bordered by a tree row was selected to evaluate the effects of real trees on the cropped area (Figure 2).

Using the artificial shade set-up, we aim to answer the following questions:

› **What is the effect of dynamic shade originating from a north–south orientation on the development and yield of winter wheat?** (Chapter I)
› **How are the development and growth of sugar beet affected by dynamic shade produced by different orientations of shade treatment?** (Chapter II)

Using the tree-bordered field, we ask:

› **How does winter wheat respond when growing along a shade gradient induced by poplar trees?** (Chapter III)

In Chapter IV, we complement our experimental approach with a modelling study, in which we have aimed to improve on current agroforestry models. More specifically, we have focused on the ability of crop models to simulate crops growing under dynamic shade (Figure 2).

Using the STICS crop model to simulate winter wheat, we pose the following questions:

- **Is it possible to predict the response of winter wheat to different shade conditions using a single, common plant parameter set?**
- **Is daily cumulated global radiation sufficient as main driver to simulate the growth of winter wheat that is subjected to dynamic shade?**

Finally, we complete this work by making the link between agroforestry and agroecological frameworks (Chapter V) (Figure 2).

Here, we consider:

- **How can agroecology help in planning and supporting the transition of conventional food systems towards more sustainable ones?**

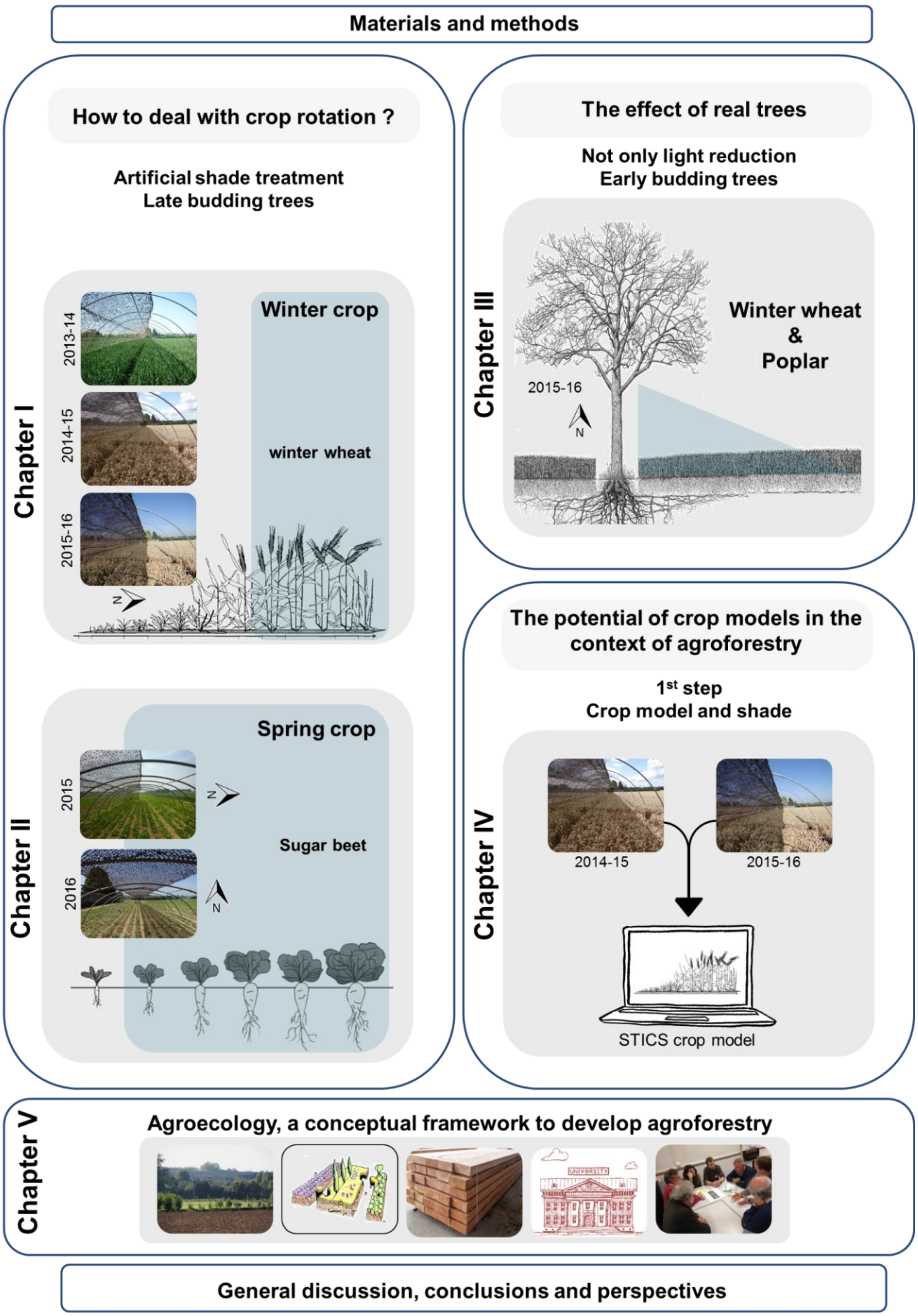



**Figure 2.** Schematic representation of the thesis organization

# Materials and methods

## 1. Field trials and experiment design

### 1.1. Artificial shade experiment

We conducted agronomic field trials for winter wheat (*Triticum aestivum* L., cultivar Edgard) over three growing seasons (2013-14, 2014-15 and 2014-16), and over two growing seasons for sugar beet (*Beta vulgaris* L., var. Lisana KWS in 2015 and var. Leonella KWS in 2016), at the experimental farm of Gembloux Agro-Bio Tech (50°33' N, 4°42'E), in the Hesbaye region, Belgium (Figure 3). All of our experiment's plots were part of the experimental farm, and were similar in terms of soil type, but they were not at exactly the same spot in the field, because different fields in the farm follow a specific crop rotation scheme. In all locations, the soil is classified as a Luvisol (FAO, 2014). The climate is temperate maritime (Figure 4).

A greenhouse tunnel structure was set up in an east–west orientation, over three growing seasons for winter wheat, and for one season (2015) for the sugar beet. For the sugar beet growing season in 2016, a north-west–south-east orientation was followed (Figure 5).

Under the east-west orientation, the shade treatments were obtained by adjusting shade layers on the south face of the greenhouse. This leads to a continuous shade (CS) treatment under which the crop experiences shade throughout the entire day, and a periodic shade treatment (PS) under which the crop is submitted to intermittent shade that varies throughout the day. For the sugar beet under the north-west-south-east orientation, a 2.5 m shade layer band was installed, centred on the top of the structure (Figure 5). This set-up results in two distinct periodic shade treatments, one which leads to a shade period in the morning ($PS_{am}$), and the other in the afternoon ($PS_{pm}$). For all the growing seasons, we also followed a no shade treatment (NS), defined as the control plot, receiving 100 % of the available light.

For the experiments on both winter wheat and sugar beet, we used camouflage nets as shade material to reproduce a rapidly fluctuating sun/shade pattern. The artificial shade was designed to mimic the shade dynamic of a hybrid walnut (*Juglans nigra x regia*) and was adapted to follow the development of tree foliage. We monitored the phenological development of 60 trees in a hybrid walnut plantation in Jenneret, Condroz region, Belgium (50°24' N, 5ﬂ27'E) (Figure 3). Three phenological stages were documented during the growing season (May–November): budburst, end of leaf expansion, and leaf fall. In the artificial shade experiment, the first layer of camouflage net was installed over the crop after budburst, when all buds had a first leaf expanded, and it induced a significant shade (qualitative visual observation). Subsequently, tree foliage expansion was imitated by superimposing an additional layer of camouflage net. For both the two crops, the shade layers and greenhouse structure were removed for harvesting. Figure 6 shows the periods of shade application for the different growing seasons.

## 1.2. Shade from poplar trees, Herzele, Flanders

During the growing season 2015-16, we also conducted an agronomic trial on winter wheat (*T. aestivum* L., cultivar Mentor) at a plot bordered by a poplar tree row (*Populus x canadensis*), in the East Flanders province (Herzele), Belgium (50°52'.88"N, 3°54'19.16"E) (Figure 3). The climate is temperate maritime, and the soil is classified as Cutanic Luvisol (FAO, 2014). In Herzele, the tree row is composed of seven poplars, which are spaced on average 6 m from each other (Figure 5). The trees are located at the west side of the cropped area and follow an approximately north-south orientation. The poplar trees in the row present a homogeneous age, estimated at 35 years old.

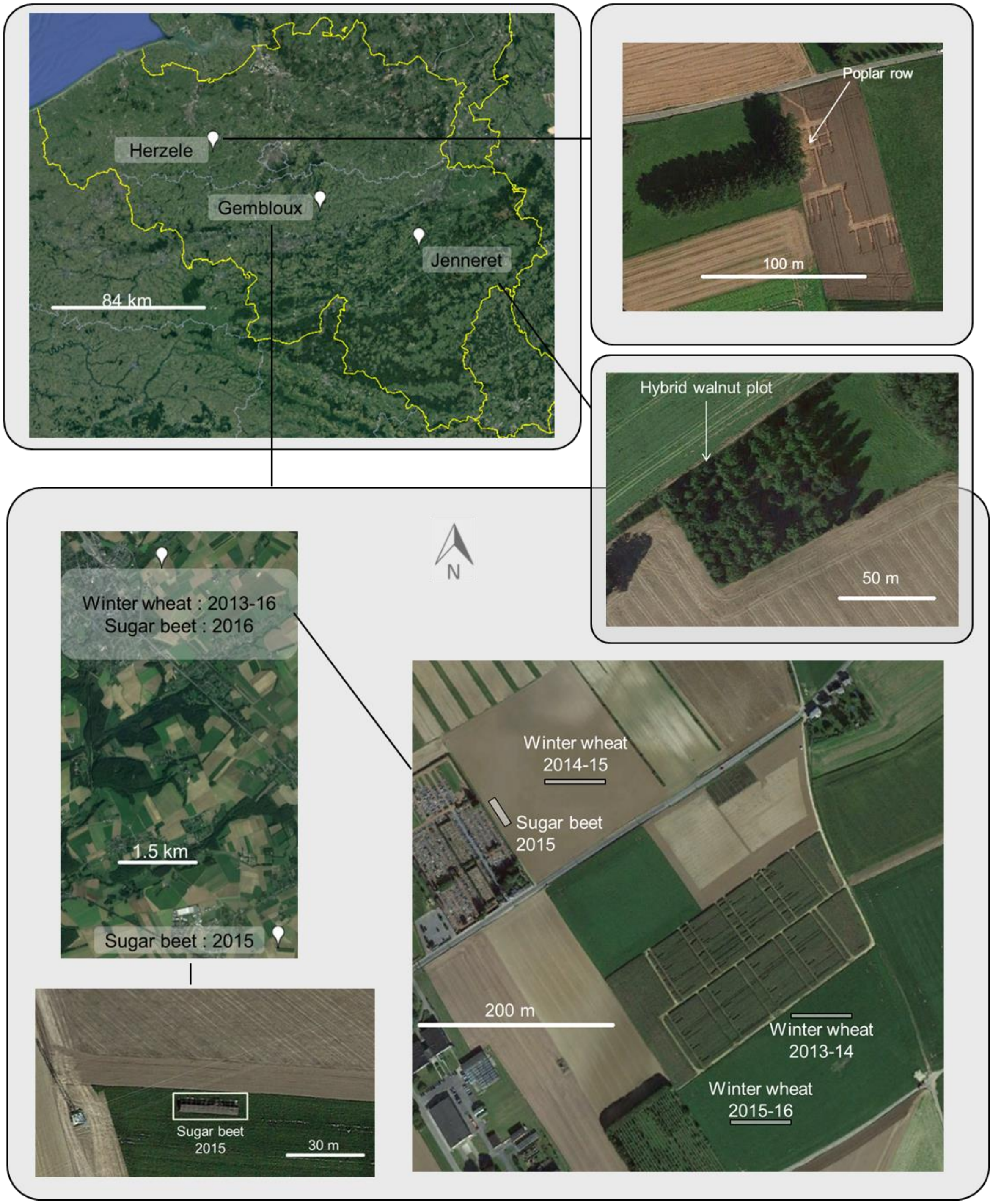



**Figure 3.** Location of the different experimental fields

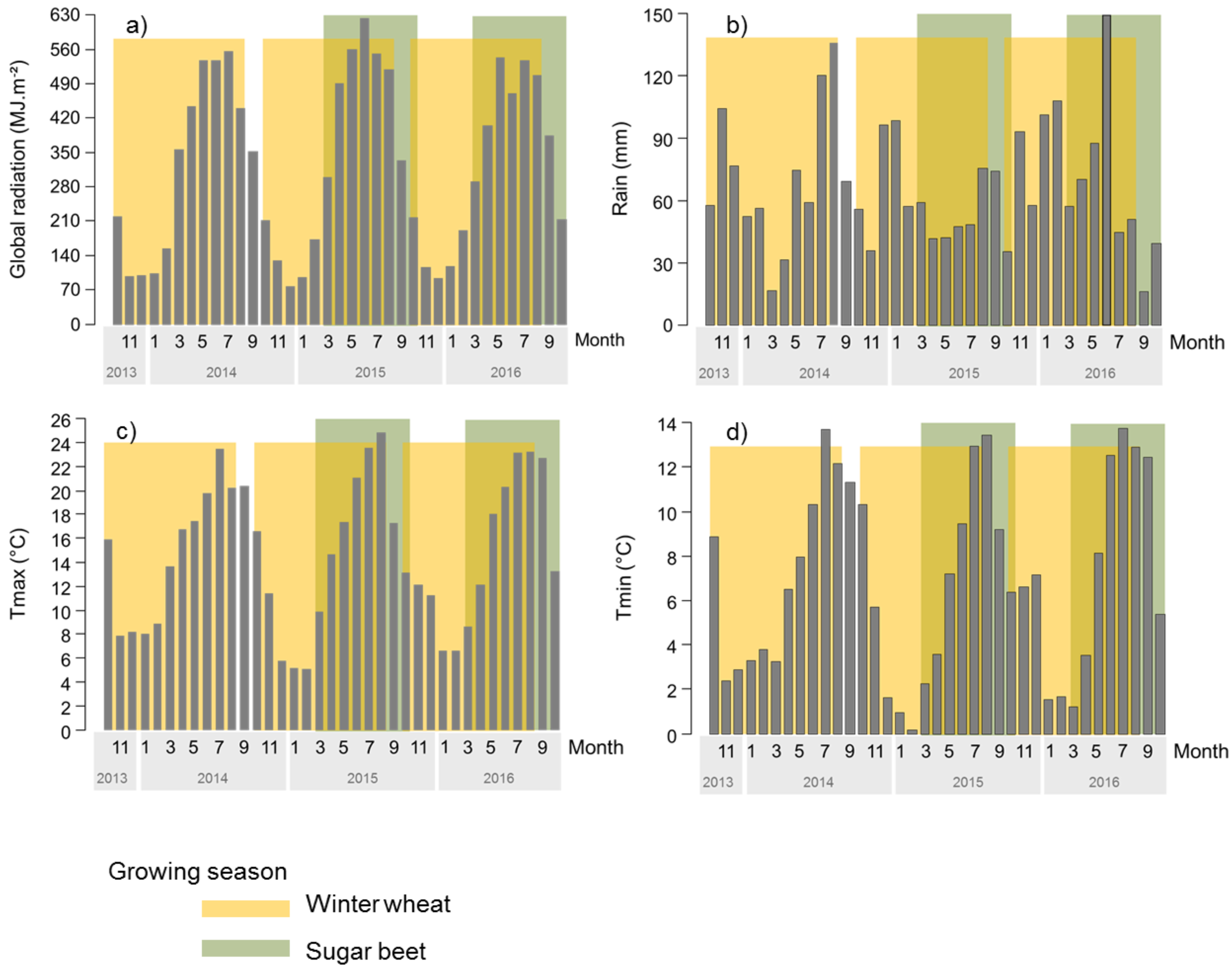



**Figure 4.** Monthly climatic data recorded from October 2013 to October 2016 by the Royal Meteorological Institute's weather station. Chart a) shows the monthly cumulated global radiation; b) shows the cumulated rainfall; charts c) and d) represent the monthly average minimal and maximal air temperature respectively. In the background, orange and green surfaces represent the growing seasons during which winter wheat and sugar beet, respectively were followed.

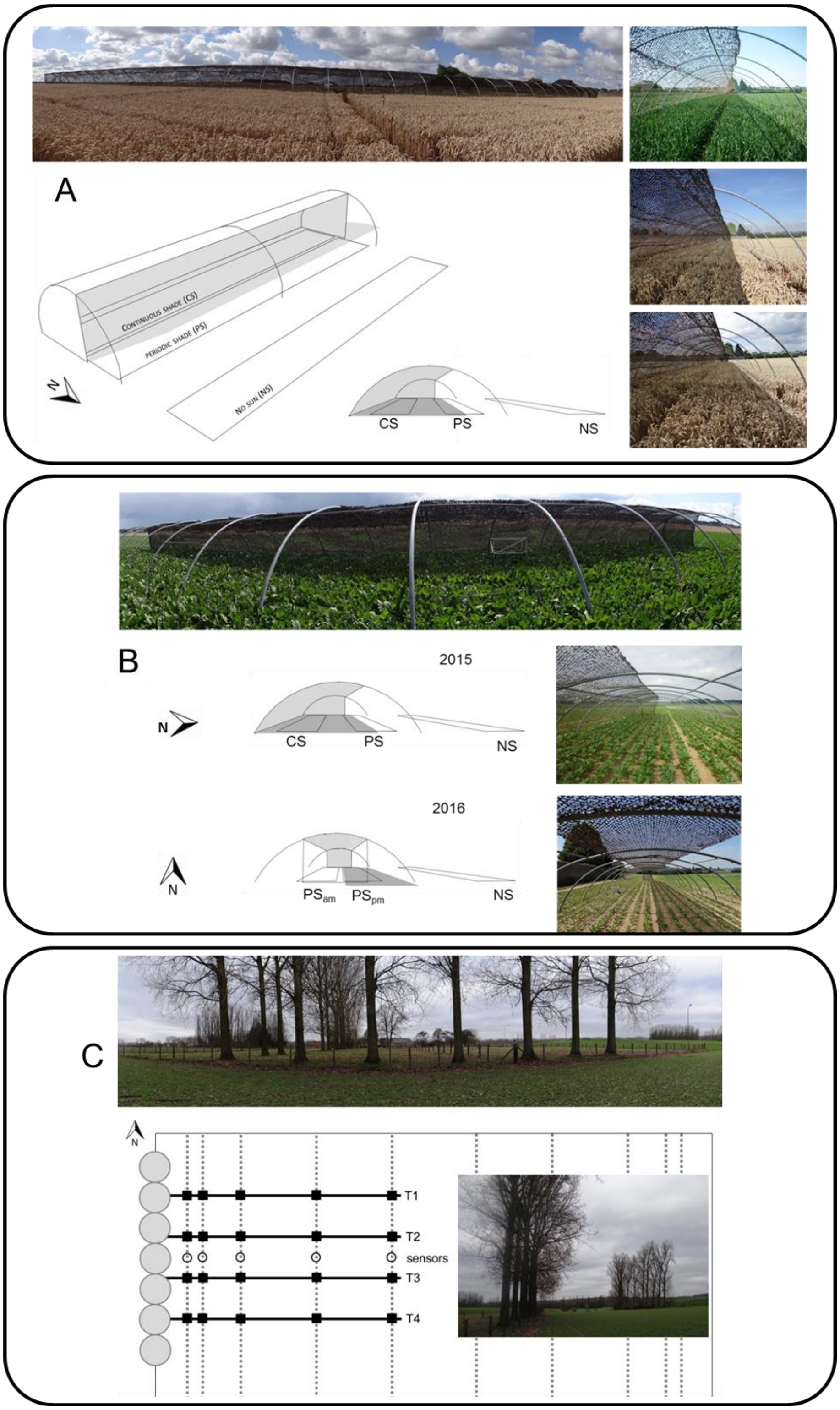



**Figure 5.** Overview of the experiment design. A : for the winter wheat, during the three growing seasons (2013-14, 2014-15 and 2015-16), the three treatments (CS, PS, and NS) are located along a north-south gradient. B : for the sugar beet, the treatment are located along a north-south gradient (CS, PS, NS) during the season 2015, and along an east-west gradient during the season 2016 ($PS_{am}$, $PS_{pm}$, NS). C: for the winter wheat in the tree-bordered field in Herzele during the growing season 2015-16.

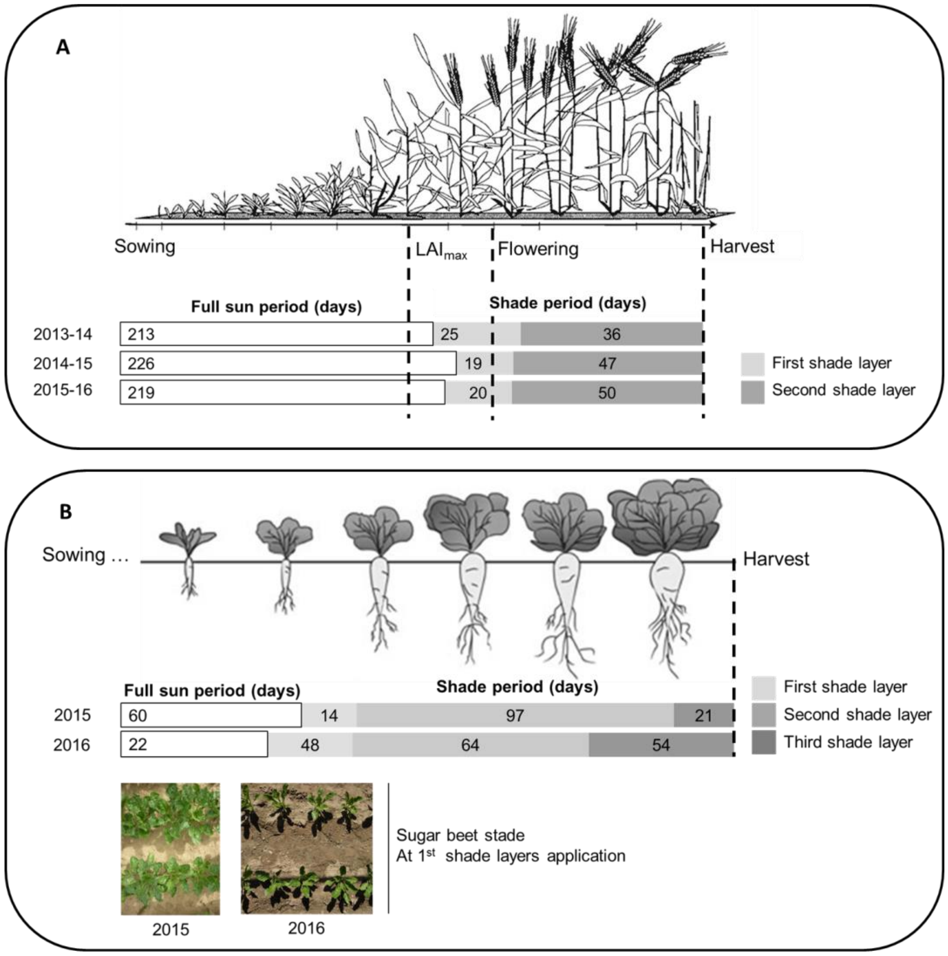



**Figure 6.** Schematic representation of the shade period for the three field experiments. A and B represent the shade layer installation for winter wheat and sugar beet respectively.

# 2. Modelling

Here, we present the sAFe-Light module of the Hi-sAFe model, and the STICS crops model formalism, used in Chapter I and Chapter IV respectively.

## 2.1. General description of the sAFe-Light module of the Hi-sAFe model

In this thesis, we use the Hi-sAFe model (Dupraz et al., 2005) to estimate the long term global radiation availability for crops growing under hybrid walnut trees in the Belgian climate, in order to situate the applied artificial shade fields in an agroforestry system context.

Hi-sAFe is a biophysical process-based model developed to simulate the functioning of silvoarable temperate agroforestry systems. Hi-sAFe simulates a three-dimensional system at a daily time step, coupling a tree model (sAFe-Tree) and a crop model (STICS) through modules of interactions between trees and crop (Figure 7). In Hi-sAFe, the virtual agroforestry plots are defined as rectangles divided into square cells of 1 $m^2$, which can either host crops, trees, or both. Trees are represented by an ellipsoid crown, linked to the diameter at breast height, and to the trunk height by allometric relationships. Within the different modules, sAFe-Light has been designed to assess the daily light repartition within the plot through a spatial average of incident global radiation on each of the crop cells, as illustrated in Figure 7 (Talbot and Dupraz, 2012). This module is based on the “Mountain” model (Courbaud et al., 2003), using a ray tracing model and simple ellipsoids crown description. This module uses a torus approach to avoid artificial edge effects. Detailed explanations of the formalism of sAFe light modules are available in Talbot et al. (2012).

We summarise the functioning of this module in chronological order:

- The daily cumulated global radiation (GR) is used as input climatic variable. This radiation is divided into direct and diffuse radiation using Angström’s empirical formula: fD=1.2-1.3.GR/ERG, where ERG is the extraterrestrial radiation (Allen et al., 1998).
- The sky hemisphere is discretised into a defined number of sectors, each identified by a direction, which is defined by an elevation and an azimuth.
- The position of the sun is defined at regular time steps according to astronomic laws.
- For each position of the sun, the direct radiation is shared between the different sectors in different proportions. The light beams are then calculated for each sky sector and each plot cell.
- Attenuation law is used to decrease the beam energy when it passes through a tree crown (Equation 1). Trunks are considered as opaque to the beams.

  Equation 1.

  $$\frac{I}{Io} = \exp\left(-\left(G(\Omega)\mu\sqrt{\sigma}LAD + WAD\right)L\right)$$

  Where *I/Io* represents the proportion of radiation transmitted through the tree crown, $G(\Omega)$ is the projection factor of leaf area in direction $\Omega$, $\mu$ is a clumping coefficient of leaves, $\sigma$ is the leaf absorptance in PAR wavelength, *LAD* is the leaf area density of the crown ($m^2/m^3$), and *L* the length of the beam’s path (m).
- Light availability is computed at the scale of each cell.

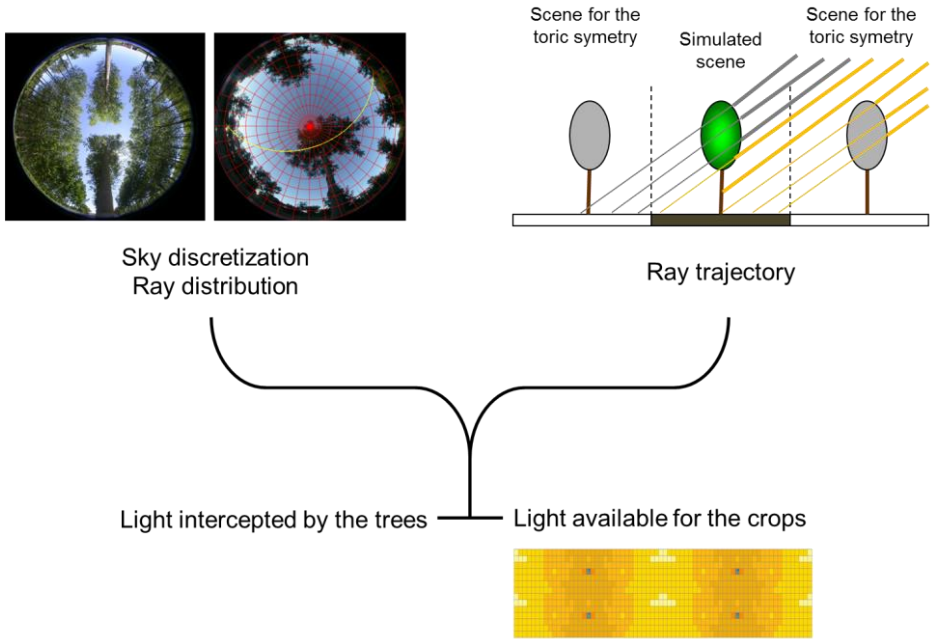



**Figure 7.** Schematic representation of a plot in Hi-sAFe, and illustration of the sAFe-Light module formalism

## 2.2. STICS crop model

### 2.2.1. General description of the model

The STICS crop growth model has been developed since 1996, in order to be: (i) generic in terms of the choice of crop that can be modelled (annuals, perennials, intermediary, as well as tropical crops, and vegetables); (ii) robust in terms of soil and climatic conditions, which can be simulated with satisfactory results (Coucheney et al., 2015), and where the soil and technical itinerary remain simple to implement; (iii) modular in order to facilitate the implementation of new modules.

In STICS, the one-dimensional simulation scene is characterised for each growing season by a homogeneous plot in terms of soil, climate, and practices. Crop rotation can be simulated by defining successive USM. Within each USM, STICS simulates the soil–plant–atmosphere system dynamics on a daily time step.

The processes involved in the model functioning are organised into modules. These modules encompass several options in terms of ecophysiological processes, crop management, and soil functioning, which can be activated by the user depending on the simulated crop, data available, or soil characteristics.

STICS includes: (i) three ecophysiological modules implied in the phenological development, the aboveground crop growth, and the final yield elaboration; (ii) four modules related to the functioning of the soil-root system, including root growth, water balance, and nitrogen balance, as well as heat, water, and nitrogen transfer; (iii) one module in charge of the interaction between the soil-plant system and the technical itinerary; and (iv) one module for the microclimate allowing to simulate the climate and water balance effects on crop canopy temperature and air humidity (Figure 8).

To launch a simulation, STICS requires several input variables and parameters (Figure 8). The input variables are daily meteorological data (global radiation, minimum and maximum air temperature, air relative humidity, wind speed, rainfall), soil properties (texture, organic C and nitrogen content, water-holding capacity at wilting point and field capacity,…) and management practices (sowing date, depth and density, dates and amounts of N supply, date and depth of soil tillage, …). In addition, STICS requires specific plant parameters. The majority of these parameters have been formulated to be generic to a species and others are cultivar-dependent (13 parameters). The complete list of model parameters and inputs variables is given in Brisson et al. (2008).

A large number of output variables are obtained upon a simulation. In this manuscript, the main output variables of interest are the total aboveground biomass, and end-season variables such as grain yield, grain number per $m^2$, and grain weight.

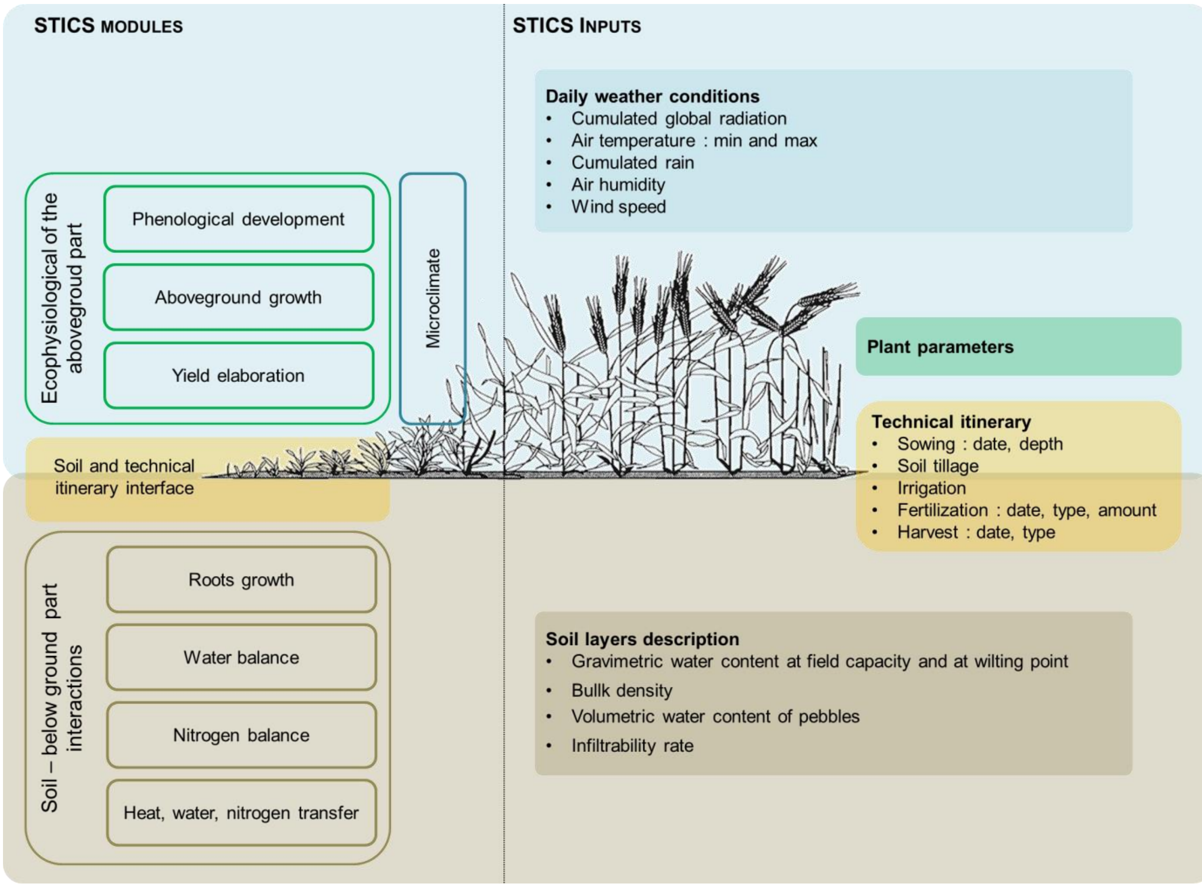



**Figure 8.** Modular organisation of STICS and input data and parameters necessary to launch a simulation. Adapted from Brisson et al. (2008).

### 2.2.2. Description of the ecophysiological modules

In this work, STICS was used to predict growth and final yield of winter wheat under different shade conditions. Therefore, we will mainly focus on the ecophysiological modules.

### Phenological development

This module allows us to define the succession of the phenological stages, with a distinction between the vegetative and reproductive stages. The duration of each physiological stage (eg. emergence, flowering, and maturity) is partly driven by the sum of degree-days, and is based on crop temperature (TCULT, °C), which is derived from air temperature using the energy balance approach. This approach takes into consideration the daily net radiation (RNET, $MJ/m^2$), soil heat flux (G, $W/m^2$), daily evaporation flux (ET, $W/m^2$), and the aerodynamic resistance between the cover and reference level (RAA, s/m). The calculation of TCULT is included in an iterative process, because TCULT is involved in the calculation of the net radiation, which in turn is used in the energy balance approach. Other factors, such as the soil temperature, humidity at the root front level, and vernalisation requirement are implemented as reduction factors in the definition of the daily phasic development of the crop.

## Aboveground growth

For winter wheat, the aboveground dynamics rely on two variables: leaf area index (LAI) growth, and total aboveground biomass (MASEC, t/ha) growth. LAI growth is driven by phenological development of the crop, and by temperature. MASEC growth relies on the accumulation of the daily biomass production (DLTAMS t/ha) (Figure 9). This accumulation is driven by the concept of radiation use efficiency (RUE), through the relationship between DLTAMS and the intercepted radiation (RAINT, $MJ/m^2$). The maximum value of the radiation use efficiency EBMAX (g/MJ) depends on the species and phenological stage of the crop (Figure 10, Equation 2). Finally, both variables takes into account several stress factors known to influence crop growth processes, such as thermal, hydric, and nutritive stresses (Equation 2).

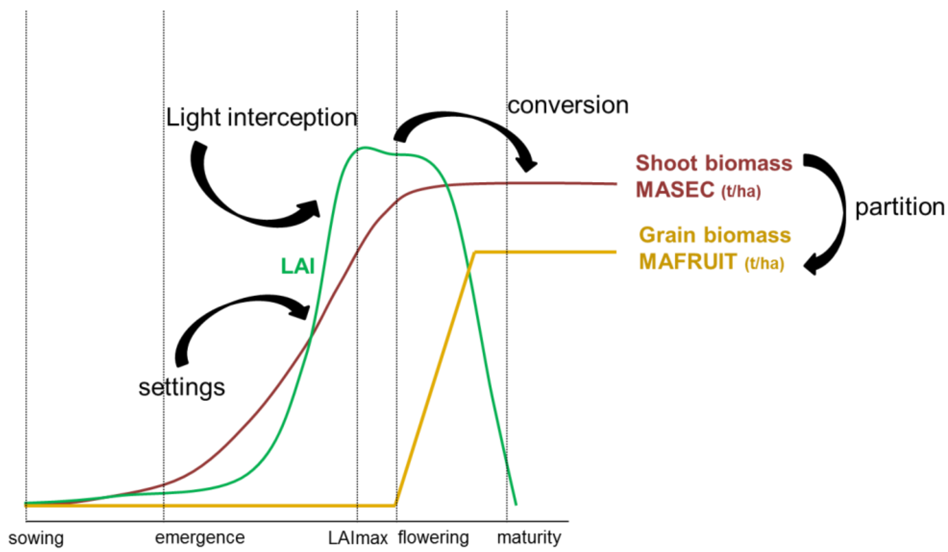



**Figure 9.** Schematic representation of the different occurring for aboveground biomass growth.

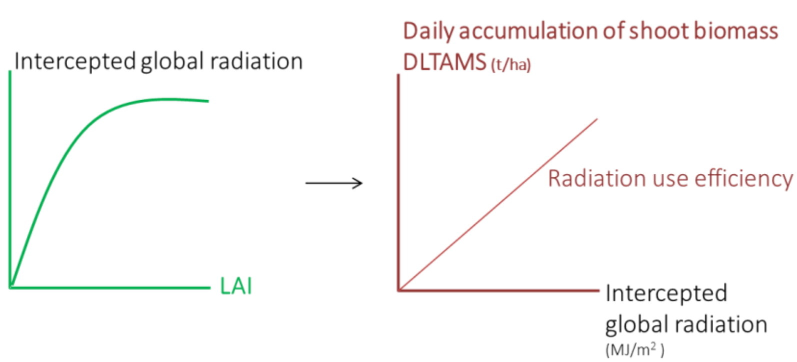



**Figure 10.** Schematic representation of relation between the shoot biomass accumulation and the intercepted radiation.

Equation 2.

$$DLTAMS(I) = \left[EBMAX(I) \times RAINT - COEFB_G \times RAINT(I)^2\right] \times$$

$$FTEMP(I) \times SWFAC(I-1) \times INNS\ (I-1) \times EXOBIOM\ (I-1) \times FCO2 + DLTAREMOBIL\ (I-1)$$

In this equation, EBMAX is the maximum value of the RUE (g/Mg); RAINT the photosynthetic active radiation intercepted by the canopy (MJ/m$^2$, $COEFB_G$ a parameter defining the radiation effect on conversion efficiency; FTEMP the temperature-related RUE factor; SWFAC the index of stomatal water stress; INNS an index of nitrogen stress active on growth in biomass; EXOBIOM an index of water logging active on RUE and transpiration; FCO2 a species-dependent CO2 effect on RUE; and DLTAREMOBIL the remobilization of winter reserves in perennial plants.

## Final yield elaboration

Final grain yield (MAFRUIT, t/ha) is defined in two steps: first, the grain number is determined before flowering and then second,the filling is initiated between flowering and maturity (Figure 11). The grain number (NBGRAINS) is a function of VITMOY (g/m$^2$/d) defined as the aboveground biomass growth rate (DLTAMS, t/ha/d) during a fixed period prevailing flowering (*nbjgrain*, days) (Equation 3 and 4). This relation relies linearly on two species parameters: *cgrain* and $cgrain_{vo}$. The grain number is limited by two parameters, which constrain the number of grains within boundaries: *nbgrmax* and *nbgrmin* (Figure 11) (Equation 4). Final yield (MAFRUIT) is the result of daily cumulated grain filling (DLTAGS in t/ha), which is calculated by applying a dynamic harvest index (IRCARB) to the total aboveground biomass (MASEC) (Equation 5 and 6). In the option we chose, this harvest index increases as a linear function of the thermal time from flowering to maturity and depends on the $viticarb_t$ (g.grain/g/d) parameter (Figure 11, Equation 5). Finally, grain weight (PGRAIN, g) is calculated as the ratio between the variables MAFRUIT and NBGRAINS and cannot exceed a varietal limit *pgrainmaxi* (Equation 8). A complete description of the formalism is available in Brisson et al. (2008).

**Equation 3.**

$$VITMOY\ (IDRP) = \sum_{J=IDRP-NBJGRAIN+1}^{IDRP} \frac{DLTAMS(J)}{NBJGRAIN}$$

**Equation 4.**

$$NBGRAINS\ (IDRP) = cgrain \times VITMOY(IDRP) \times nbgrmax + cgrainvo$$

$$if\ NBGRAINS(IDRP) > nbgrmax\ \rightarrow NBGRAINS(IDRP) = nbgrmax$$

$$if\ NBGRAINS(IDRP) < nbgrmax\ \rightarrow NBGRAINS(IDRP) = nbgrmin$$

**Equation 5.**

$$IRCARB(I) = VITIRCARBt(I - IDRP)$$

$$if\ IRCARB(I) > irmax \rightarrow IRCARB(I) = irmax$$

**Equation 6.**

$$DLTAGS(I+1) = [IRCARB(I+1) \times MASEC(I+1) - IRCARB(I) \times MASEC(I)]FTEMPREMP(I)$$

**Equation 7.**

$$MAFRUIT(I) = \sum_{J=IDRP}^{I} DLTAGS(J) - \frac{PGRAINGELS(I)}{100}$$

$$if\ MAFRUIT(I) > pgrainmaxi \times NBGRAINS(I) \rightarrow MAFRUIT(I) = pgraimaxi \times NBGRAINS(I)$$

**Equation 8.**

$$PGRAIN(I) = \frac{MAFRUIT(I)}{NBGRAINS(I)} \times 100$$

$$if\ PGRAINS(I) > pgrainmaxi \rightarrow PGRAINS = pgraimaxi$$

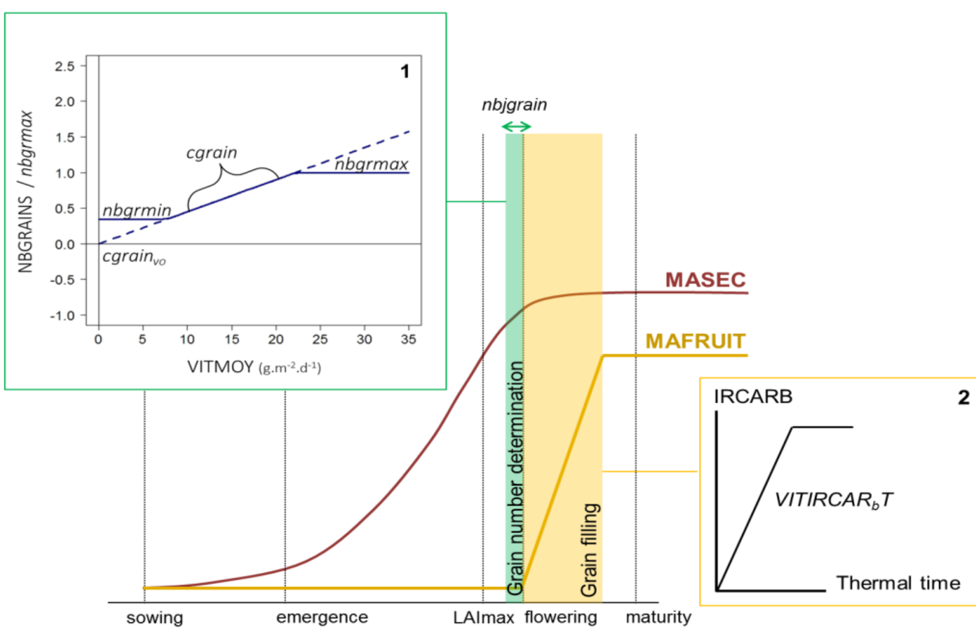
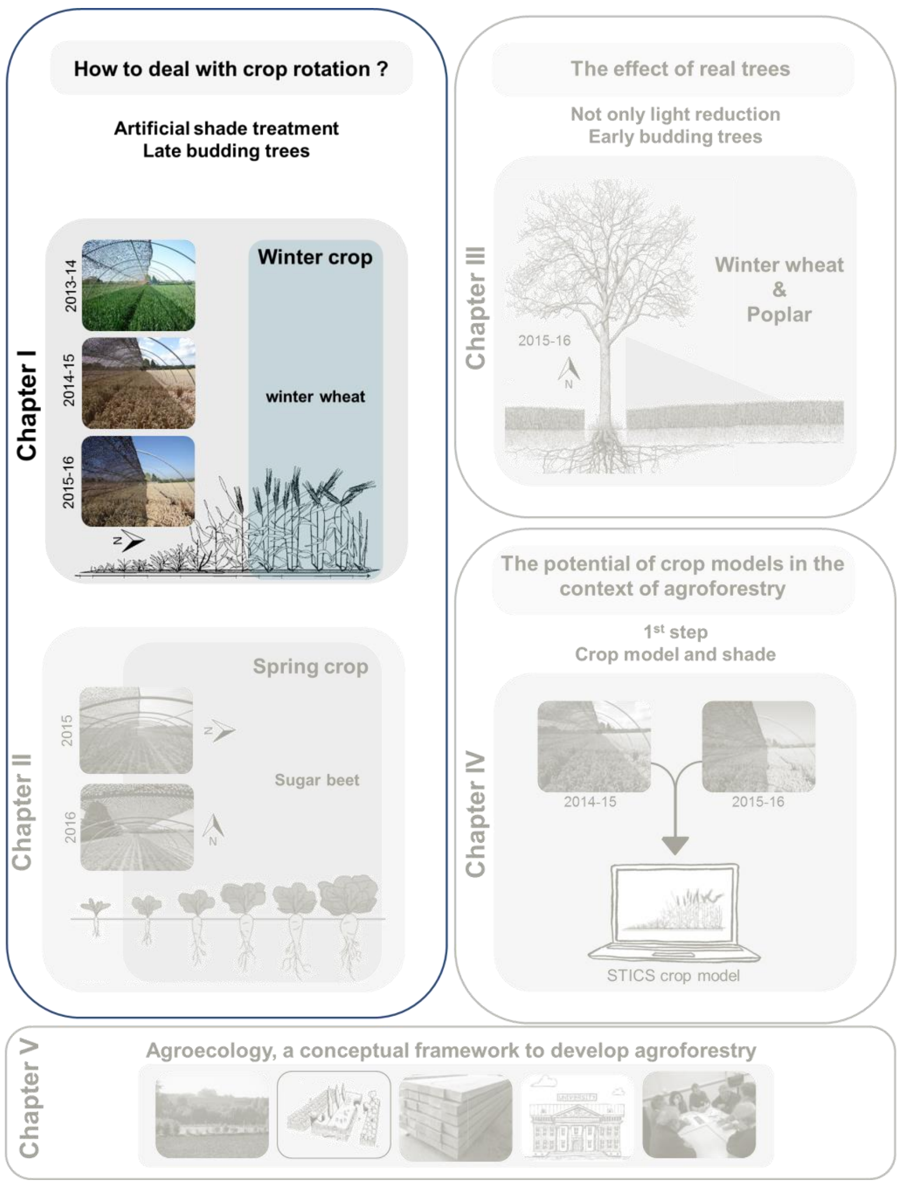



**Figure 11.** Schematic representation of the final grain yield elaboration in STICS.

# Chapter I.

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



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

*Adapted from the article published in European Journal of Agronomy 82 (2017) 60-70*

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# 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 both on the environmental conditions and on shade characteristics. This study addressed the issue by monitoring the growth, productivity, and quality of winter wheat (*Triticum aestivum* L.) under artificial shade provided by military camouflage shade-netting, and by using the Hi-sAFe model to relate these 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), 10 (2014-15), and 12 (2015-16) 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 the three 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 over a period of 66 days (CS: - 61 % and PS: - 43 %) significantly affected final yield (CS: - 45 % and PS: - 25 %), mainly through a reduction in the average grain weight and the number of grains per m². In season 2015-16, the decrease in global radiation reaching the crop over a period of 70 days (CS: -60 %, and PS: -41 %) significantly affected final yield (CS: 44 %, and PS: - 27 %), mainly through a reduction in the average grain weight and the number of grains per m². Grain protein content increased by up to 45 % under the CS treatment in 2015, and only slightly in 2016 (+ 5% under the CS treatment). Nevertheless, at the plot scale, protein yield (t/ha) did not compensate for the decrease in final grain yield.

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 applied in this experiment were compared to those predicted beneath trees growing in similar climatic conditions in Belgium. The levels used in the CS treatment are only likely to occur in real agroforestry conditions on 10 % of the cropped area until the trees are 30 years old, and only with east-west tree row orientation.

## Keywords

Winter wheat; Spatio-temporal shade; Grain yield; Modelling; Agroforestry system

## Highlights

- The artificial shade set-up reproduces the effect of a heterogeneous spatio-temporal light environment at the seasonal and daily time scale.
- Modelling allows us to predict light availability over a 50-year-old tree rotation with an east-west and north-south tree line orientation.
- Reducing global radiation from 10-16 and 12 days before flowering until final harvest reduces the final grain and protein yield of winter wheat.
- This reduction in yield was due to a reduction in both the average grain weight and the number of grains per $m^2$.

# 1. Introduction

In 2014, winter-wheat (*Triticum aestivum* L.) represented around 14 % of cultivated area in Belgium, with a mean yield of 9.9 tonne.ha-1 (Waeyaert, 2014). Winter-wheat represents 29 % of cereal production on the world market (FAO, 2015), 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). Combining crops and woody components in a same field is called agroforestry, and can unite good levels of productivity with sustainable land use (Dupraz, 2002). However, the success of such systems depends on the reinforcement of ecological processes like facilitation and complementarity for resource capture between species (Cannell et al., 1996; Malézieux et al., 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 (eg. different root depths) or in time (eg. different phenology) (Tilman and Snell-Rood, 2014). In this context, research on agroforestry systems aims at quantifying and analysing the spatio-temporal 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 (eg. species choice, stand design), management choices (eg. tree pruning height, tillage depth), and soil and climatic conditions. This makes a clear overview difficult (Batish et al., 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 a crop growing under trees that are subjected to Belgian soil and climatic conditions (Eichhorn et al., 2006). Trees induce a heterogeneous light environment for crop species below them. A tree canopy leads to a typical sunfleck regime, varying on the one hand with a time frame of seconds to minutes, due to penetration of the sun through the canopy and to 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 in the crop.

Previous studies have 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., 2013a; 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 other possible abiotic and biotic interactions occurring between trees and crops in agroforestry systems, several authors have designed and used an artificial shade system (Dufour et al., 2013a; Peri et al., 2002; Varella et al., 2010). Earlier articles have evaluated the ability of artificial shade materials to mimic the fluctuating agroforestry light environment over the day or throughout the cropping season. Varella et al., (2010) demonstrated that wooden slatted structures reproduced well the daily periodic light fluctuations and 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 analyse crop and forage development, yield and physiological responses to shade (Dufour et al., 2013a; 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 which has been replicated by an artificial shade system. In order to take into account the diversity of possible shade environments observed under agroforestry, crops have been subjected to two distinct shade conditions, thus addressing two objectives. The first objective is a worst-case scenario of crop response to an extreme condition of continuous shade under temperate climate conditions. The second objective is to monitor the response of crops to variable shade by changing the shade hourly. Finally, we aim 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 three growing seasons, 2013-14, 2014-15, and 2015-16 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 on exactly the same spot in the field. Soil physicochemical homogeneity within and between the experimental plots had previously been verified using the digital soil map of

Wallonia, and a measurement of soil electrical conductivity (EC) realised using the electromagnetic induction method (EMI) (Bah et al., 2005; Grisso et al., 2005), was conducted prior to the installation of the artificial shade structures.

Winter wheat (*T. aestivum* L., cultivar Edgard) was planted on 24 October 2013 (300 grains/$m^2$), on 21 October 2014 (250 grains/$m^2$) and 27 October 2015 (300 grains/$m^2$) with, drill lines following an east-west orientation in all three cases. The preceding crops were winter wheat in 2013-2014, rapeseed (*Brassica napus* L.) in 2014-2015, and chicory (*Chichorium intybus* L.) in 2015-2016. Fertilisation followed the conventional practice applied in Belgium, which means that three doses of nitrogen fertilisers were applied throughout the growing season. A total amount of 225 (75, 75, 75), 175 (50, 50, 75), and 195 (60, 60, 75) units of nitrogen per hectare and per year were applied for the seasons 2013-2014, 2014-2015 and 2015-2016 respectively. For all the growing 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. The winter wheat was harvested with a combine harvester on 5 August 2014, 10 August 2015 and 16 August 2016.

## 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 throughout the day, and 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, and 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 high) set up in an east-west orientation (Figure 12). 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 the cloth was extended by around 9 % as compared to the initial surface. Under the tunnel structure, the layout included four replicate blocks, each made up of two subplots (6m x 2m). One of the sub-plots was used for periodic destructive sampling of wheat plants during the growing season, and the other was maintained undisturbed for final yield quantification at harvest (Figure 12).

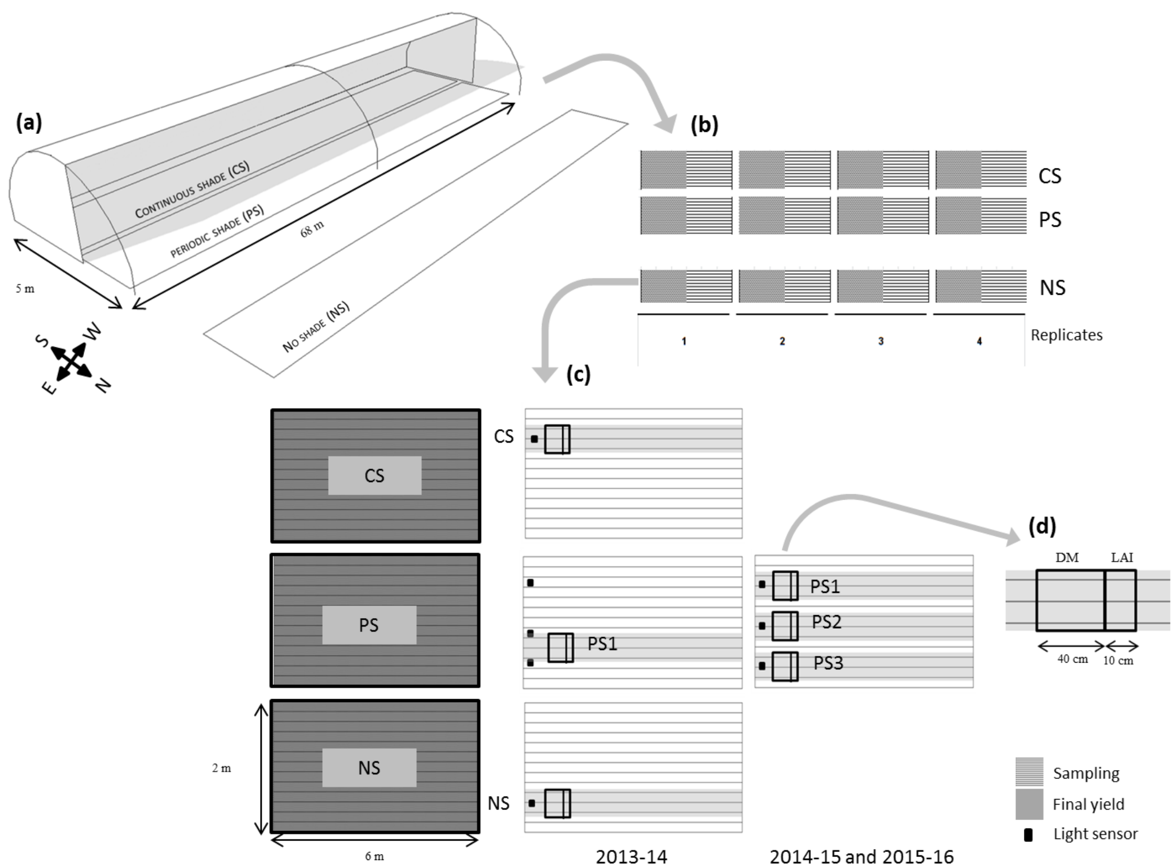



**Figure 12.** General lay-out of the experimental device: a) represents shade structure position and the three modalities (CS, PS, NS) located along a north-south gradient; b) provides further detail on the subplot organisation within modalities and indicates the four replicates of paired subplots; c) corresponds to a zoom in on the subplot featuring the specific location of the light sensors; and d) an example of sampling in the PS plot.

## 2.3. Data collection

### 2.3.1. Tree phenology monitoring and reproduction of shade dynamics

We monitored the phenological development of trees in a hybrid walnut plantation in Jenneret, Condroz region, Belgium (50°24' N, 5°27'E). The 60 walnut trees were planted in 1991, with an average distance of 8 meters between trees. Three phenological stages were documented during the growing season (May-November): budburst, end of leaf expansion and leaf fall. The date at which a phenological stage is achieved was defined as the date when 50 % of the trees in the plantation reached that stage.

In the artificial shade experiment, the first layer of camouflage net was installed over the crop after budburst — when all buds had a first leaf expanded — and this induced a significant shade (qualitative visual observation). Subsequently, tree foliage expansion was imitated by superimposing a second layer of camouflage net. At wheat maturity, the shade layers and greenhouse structure were removed for harvesting. For the season 2013-14, the first layer of camouflage net was applied 213 days after wheat sowing (DAS) (24 May) and the second from 238 DAS (18 June) until 274 DAS (25 July), after which the shade was removed. The wheat was harvested only 11 days later due to rainy conditions (285 DAS, 5 August). A total of 61 days of shade were applied during the growing season 2013-14. In 2014-15, the first layer was applied 226 DAS (4 June) and the second from 245 DAS (23 June) until harvest at 292 DAS (10 August). A total of 66 days of shade were applied during the growing season 2014-15. In 2015-16, the first layer were applied 218 DAS (2 June) and the second from 240 DAS (23 June) until harvest 289 DAS (11 August). A total of 70 days of shade were applied during the growing season 2015-16 (Figure 13).

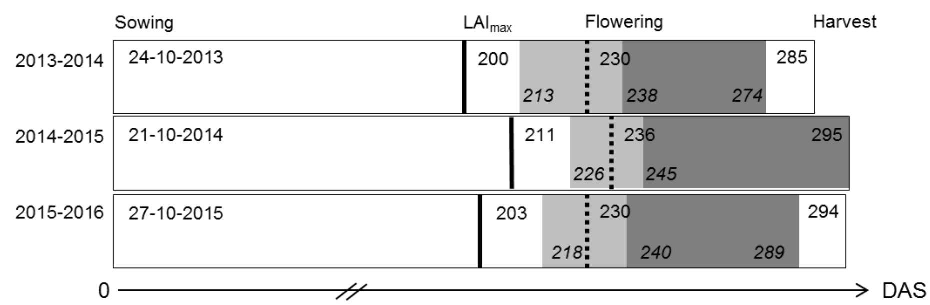



**Figure 13**. Phenological calendar of wheat and period of shade layers applications (grey rectangle) during the growing season 2013-2014, 2014-2015 and 2015-2016. Light and dark grey rectangles represent, respectively, the periods of first and second shade layers installation. The vertical black represents the LAImax stage, and the dashed line represents the flowering stage.

### 2.3.1. Agronomic measurements

We sampled the winter wheat to assess aboveground biomass dry matter (DM) and leaf area index (LAI). Samples were taken from three adjacent sowing lines of 40 cm width for DM and three adjacent 10 cm bands for LAI. For the PS plots, the same three bands were used throughout the four replicates to ensure the same light conditions (PS1, PS2, and PS3) (Figure 12). The final grain yield (t/ha) was obtained by harvesting the entire undisturbed plot (12 $m^2$ per replicate), resulting in one single yield value for the entire PS plot (Figure 12). Dry matter was assessed at four dates in 2014 (158, 178, 199, 220 DAS), seven dates in 2015 (197, 225, 240, 253, 268, 274, 290 DAS), and two dates in 2016 (238, 288 DAS). LAI was measured at three dates in 2014 (158, 178, 199 DAS), four dates in 2015 (197, 225, 240, 253 DAS) and one date in 2016 (238 DAS).

To assess dry matter distribution, the wheat plants were subdivided into spikes and straw, dried at 60°C for 10 days, and weighed. The LAI was determined by scanning the surface of the plant leaves and was defined as the total green leaf area per unit ground surface area. The final yield is expressed in t/ha at 15 % humidity. We assessed grain weight, grain size (using three sieves of 2.8, 2.5, and 2.2 mm), and grain protein content on subsamples from the harvested plots. Protein content (%) analyses were performed with the near-infrared reflectance spectroscopy technique (Rapid Content Analyzer, XM-1100 Series). We calculated the number of grains per $m^2$ from thousand kernel weight (g/1000 grains) and yield (t/ha). Harvest index (HI) is defined as the ratio of the grain weight to the total plant aboveground biomass. It should be mentioned that in 2014, the winter wheat was attacked by the take-all fungus (*Gaeumannomyces graminis* var. tritici).

### 2.3.3. Global radiation measurements

Daily global radiation was recorded from October to April 2014, by a weather station of the Royal Meteorological Institute located 3 km from the experimental site (Ernage, Gembloux, 50°59'N, 172 4°67'E), and from May 2014 to August 2015 by a local weather station (CR800 – Campbell Scientific Inc., USA) installed near the experimental plots (Bordia, Gembloux, 50°56'N, 4°71'E). As soon as the shade structure was set up, global radiation at crop canopy level was measured with quantum sensors (CS300 - Campbell Scientific Inc., USA -accuracy ± 5 % for the daily global radiation) and recorded every minute by data loggers (CR1000 – Campbell Scientific Inc., USA). In 2013-14, two sets of five sensors were installed in parallel along the three shade treatments. For the final analysis, an average value of each sensor pair along the shade gradient was used. For the seasons 2014-15 and 2015-16 only one set of five sensors was used, one was installed under the CS plot, another in the NS plot, and three under the PS plot (Figure 12). During the season 2013-14, two of these sensors (PS2 and PS3) were located close to the three wheat drill rows monitored during the growing season, and the third (PS1) was at the extremity of the plot. Thus, we used the PS2 and PS3 mean global radiation value to analyse wheat growth development (PS). For the seasons 2014-15 and 2015-16, each of the three sensors was located in the sampling area (PS1, PS2, and PS3). Under the PS treatment, the hourly pattern of global radiation varied from one row to another. We therefore characterised the global radiation intercepted by the whole PS plot using a spatial average of the global radiation. Thus, PS was calculated as a weighted average in which global radiation intercepted by the PS1, PS2, and PS3 sensors was weighted corresponding to the proportion of the PS plot area.

## 2.4. Modelling approach

In order to interpret our results in terms of real agroforestry systems, we used the Hi-sAFe model (Dupraz et al., 2005) to predict the long term global radiation availability for crops growing under hybrid walnut in the Belgian climate. This process-based model includes the three-dimensional light competition module sAFe-Light, which has previously been validated by field measurements (Talbot and Dupraz, 2012). The virtual agroforestry plots are defined as rectangles divided into square cells of 1 $m^2$, which can either host crops, trees, or both. Trees are represented by an ellipsoid crown, linked to the diameter at breast height and to the trunk height by allometric relationships. Each tree crown is represented by a volume assimilated to a turbid medium. Tree phenology is described by five stages, from budburst to leaf fall, and relies on tree-specific parameters and cumulative daily temperature. Within this configuration, daily incident global radiation at plot scale can be assessed from a spatial average of incident global radiation on each of the crop cells.

In this study, simulations were conducted on a plot where the tree lines are spaced at 35 m and the trees in the line are 7 m apart, with a 1 m uncropped strip along the tree row. For the tree rows orientation, a north-south and an east-west scenario have been followed. The simulations were carried out with weather data recorded from 1980 to 2013 by the Royal Meteorological Institute. Nevertheless, in order to perform simulations over a period of 50 years, a 17-year climatic series was generated through a random selection of the observed data. At the end of the simulation, radiation availability for the crop throughout the evolution of the agroforestry system was assessed at the level of the square cells, in order to have a detailed map of the light repartition within the plots. The radiation proportion was expressed as the ratio between the incident radiation available under the trees to that above the trees.

## 2.5. Statistical analyses

All statistical analyses were performed with R software. Analyses of variance (ANOVA) and Tukey range tests were used to assess the effect of the shade treatments on crop growth (DM, LAI), final yield, yield components (thousand grain weight, grains size proportion and harvest index) and protein rate.

# 3. Results

## 3.1. Global radiation transmitted below the artificial shade treatment

The analysis of global radiation dynamics was assessed both diurnally and seasonally. At the diurnal timescale, the wheat in the CS treatment experienced a continuous shade regime throughout the day, while under the PS treatment the global radiation varied depending on the distance to the shade structure. Figure 14 **Erreur ! Source du renvoi introuvable.**shows an example of the diurnal variation of the global radiation for a transect from NS over PS (PS1, PS2, PS3) to CS on 3 July 2015. It illustrates the spatial gradient and temporal dynamics of the light penetrating the artificial shade structure. Summarising these diurnal variations for each treatment over the entire growing season, we observe the following average behaviour and extremes. During the season 2013-14, a maximum of 283 min of shade was measured per day by the PS1 sensor, and around 35 min by the PS2-3 sensor. On average, these sensors measured 86 min and 11 min of shade respectively. Due to the slightly larger surface of the camouflage net in 2014-15, the PS plot experienced on average a longer period of shade than in 2013-14. The PS1, PS2, and PS3 sensors registered a maximum period of dense shade (as observed under the CS treatment) of 369, 335, and 229 min respectively. Figure 15 shows the cumulated transmitted global radiation from sowing until harvest for both seasons. At the scale of the growing season, we applied shade 61 (2014), 66 (2015), and 70 (2016) days before harvest on a total growing period of 285, 292, and 294 days respectively. The result is a minor reduction in cumulated transmitted global radiation over the whole growing season, ranging from 19 % to 3 % when compared to the cumulative radiation without shade in 2014, from 25 % to 14 % in 2015, and from 23 % to 13 % in 2016, depending on the distance to the shade structure.

With respect to the phenological development of the crop, we observed different cumulative radiation for the three main periods in the growing cycle with distinct shade patterns (sowing to $LAI_{max}$, $LAI_{max}$ to flowering, and flowering to harvest). The $LAI_{max}$ stage is reached when all leaves are fully expanded (Table 4). Thus, winter wheat experienced similar light conditions before its $LAI_{max}$ stage across the three years. Then, from flowering to harvest the global radiation received by the crop in the CS treatment was reduced by 45 % in 2014, 65 % in 2015, and 56 % in 2016. For the PS treatment, it varied from 6 % to 14 % in 2014, from 35 % to 55 % in 2015, and from 31 % to 46 % in 2016 (Table 4).

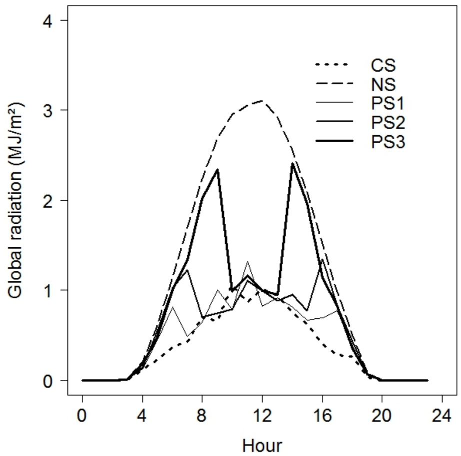



**Figure 14.** Global radiation (MJ/m$^2$) measured in no shade (NS), continuous shade (CS) and periodic shade ($PS_1$, $PS_2$, $PS_3$) treatment during the season 2014-2015.

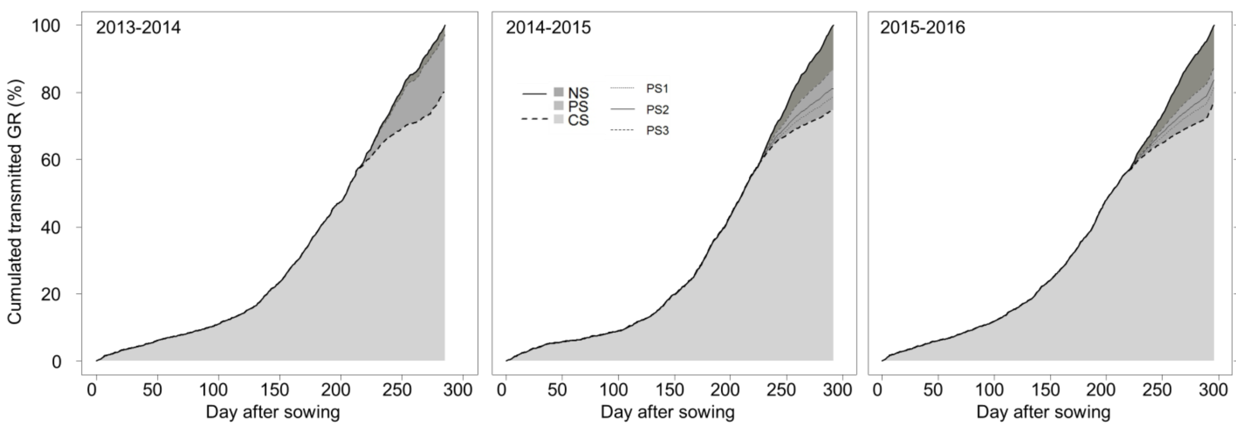



**Figure 15.** Cumulated transmitted global radiation (GRc, %) under the different shade treatments during the two cropping seasons. Transmitted GRc is expressed as a percentage of the GRc cumulated in full sun (NS) at the end of the cropping seasons.

**Table 4.** Cumulated transmitted global radiation during the whole cropping season (from sowing to harvest), during the whole shade period (from to first layer installation until layers were removed) and during the three phenological periods for the artificial shade treatments (PS, PS1, PS2, PS3, CS) and the control plot (NS).

| | | Cumulated transmitted global radiation ($MJ/m^2$) – Percentage of transmitted global radiation (%) | | | | |
|---|---|---|---|---|---|---|
| | | **Cropping season** | **Whole shades period** | **Sowing to $LAI_{max}$** | **$LAI_{max}$ to flowering** | **Flowering to harvest** |
| **2013-2014** | Days after sowing | 0 to 285 | 213 to 274 | 0 to 200 | 201 to 229 | 230 to 285 |
| | NS | 3174 – 100 | 1177 – 100 | 1511 – 100 | 612 – 100 | 1051 – 100 |
| | PS | 2986 – 94 | 988 – 84 | | 566 – 82 | 909 – 86 |
| | PS1 | 3084 – 97 | 1084 – 92 | | 589 – 96 | 983 – 94 |
| | CS | 2565 – 81 | 567 – 48 | | 479 – 78 | 574 – 55 |
| **2014-2015** | Days after sowing | 0 to 292 | 226 to 292 | 0 to 211 | 212 to 235 | 236 to 292 |
| | NS | 3398 – 100 | 1414 – 100 | 1698 – 100 | 565 – 100 | 1135 – 100 |
| | PS | 2788 – 82 | 804 – 57 | | 477 – 84 | 613 – 54 |
| | PS1 | 2664 – 78 | 680 – 48 | | 458 – 81 | 508 – 45 |
| | PS2 | 2755 – 81 | 771 – 55 | | 474 – 84 | 583 – 51 |
| | PS3 | 2936 – 86 | 953 – 67 | | 501 – 89 | 737 – 65 |
| | CS | 2535 – 75 | 551 – 39 | | 438 – 78 | 399 – 35 |
| **2015-2016** | Days after sowing | 0 to 296 | 219 to 289 | 0 to 203 | 204 to 230 | 231 to 294 |
| | NS | 3134 – 100 | 1226 – 100 | 1572 – 100 | 436 – 100 | 1125 – 100 |
| | PS | 2629 – 84 | 722 – 59 | | 368 – 84 | 689 – 61 |
| | PS1 | 2542 – 81 | 634 – 52 | | 356 – 82 | 613 – 54 |
| | PS2 | 2615 – 83 | 707 – 58 | | 368 – 84 | 674 – 60 |
| | PS3 | 2727 – 87 | 819 – 67 | | 380 – 87 | 774 – 69 |
| | CS | 2404 – 77 | 496 – 40 | | 342 – 78 | 490 – 44 |

## 3.2. Wheat biomass and LAI responses under shade

Due to the lag in phenological development of hybrid walnut as compared to winter wheat, for both experimental years the shading treatment did not affect $LAI_{max}$, and no significant difference emerged when quantifying the LAI dynamics of the different treatments.

Looking at the aboveground biomass dynamics, the straw and spike dry matter followed a similar trend over the growing season under the different global radiation conditions for the three experimental years. Straw biomass increased until mid-June and then decreased upon leaf senescence, while spike biomass increased gradually from mid-June until grain maturity. During the first year (2013-14), straw and spike biomass were not significantly affected by the shading treatments at flowering (Figure 16). In the same season, straw biomass measured 20 days before harvest was significantly higher under the CS treatment than under the PS and NS treatments (*p.value*: 0.01), while no significant difference was observed for spike biomass (*p.value*: 0.19).

In 2014-15, straw and spike biomass were affected by the shading treatments at the same sampling date, but the pattern of biomass reduction with light availability did not follow a clear trend (Figure 16). In fact, the CS straw and spike biomass were significantly reduced at flowering (- 37 %, *p.value*: 0.004) as compared to the PS2 treatment. The PS1, PS3, and NS treatments led to an intermediate biomass reduction. At harvest, no significant difference between the treatments was observed for straw biomass (*p.value*: 0.19). Nevertheless, the CS spike biomass was significantly reduced (*p.value*: 0.004) as compared to the NS and PS2 treatments, while the PS1 and PS3 treatments led to an intermediate biomass reduction (Figure 16). At harvest, there were no significant differences between the PS (1246.88 $g/m^2$) and NS treatments (*p.value*: 0.001) when looking at the PS treatment as a whole.

In 2015-16, straw dry matter biomass was not significantly affected by the shading treatments at flowering (*p.value*: 0.19) and harvest (*p.value*: 0.18) (Figure 16). For the spike dry matter biomass, no differences were observed at flowering, while this significantly reduced at harvest when shaded (Figure 16). At harvest, the maximal spike dry matter reduction was reached under the CS (-33 %) and PS1 (-22 %) shade treatments (*p.value*: $1.3.10^{-4}$) as compared to the NS treatment. The PS2 and PS3 treatments led to an intermediate biomass reduction, and remained significantly different from the NS treatment (*p.value*: $3.77.10^{-4}$) when looking at the PS treatment as a whole (690.50 $g/m^2$).

Finally, the shade treatment influenced the relative contribution of the different parts of the plant (grain, straw, and glume) to the final aboveground DM. In 2015, the grain biomass at harvest time accounted for 52 % of total aboveground DM under NS, and 38 % under CS (Figure 17). In 2016, the grain biomass at harvest time accounted for 44 % of total aboveground DM under NS, and 37 % under CS (Figure 17). The large differences in biomass components observed between the three years of the experiment can be explained by the occurrence of take-all disease in 2014, particularly favourable weather conditions for winter wheat in 2015, and adverse weather conditions during the spring in 2016.

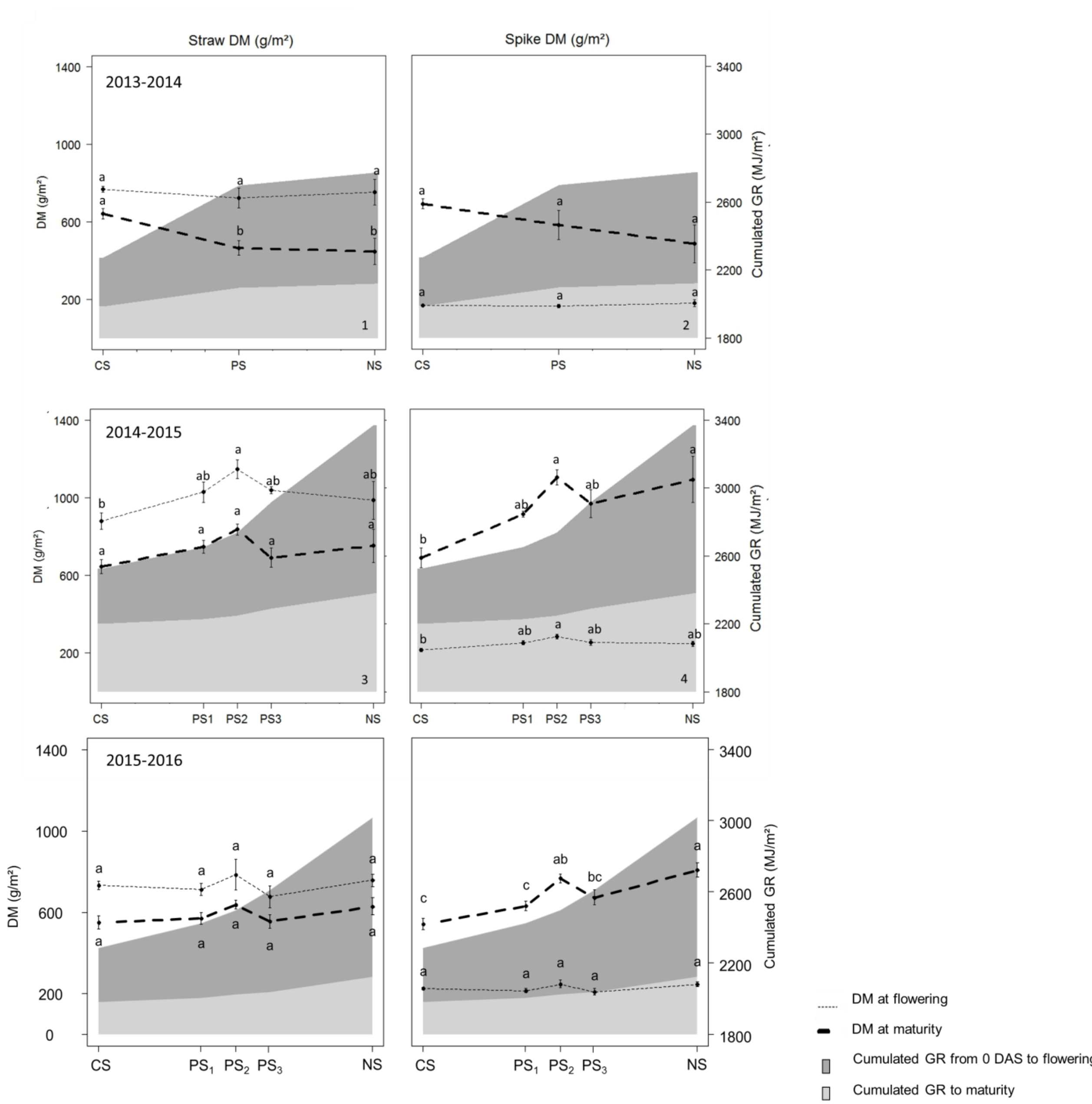



**Figure 16.** Mean straw and spike dry matter (DM, $g/m^2$) for the growing seasons 2013-14, 2014-15 and 2015-16 under the different light regimes (CS, PS, PS1, PS2, PS3, NS) on two sampling dates. In the background, grey surfaces represent the cumulated global radiation (GR, $MJ/m^2$) from sowing up to the two sampling dates. Vertical bars represent the standard error of the means.

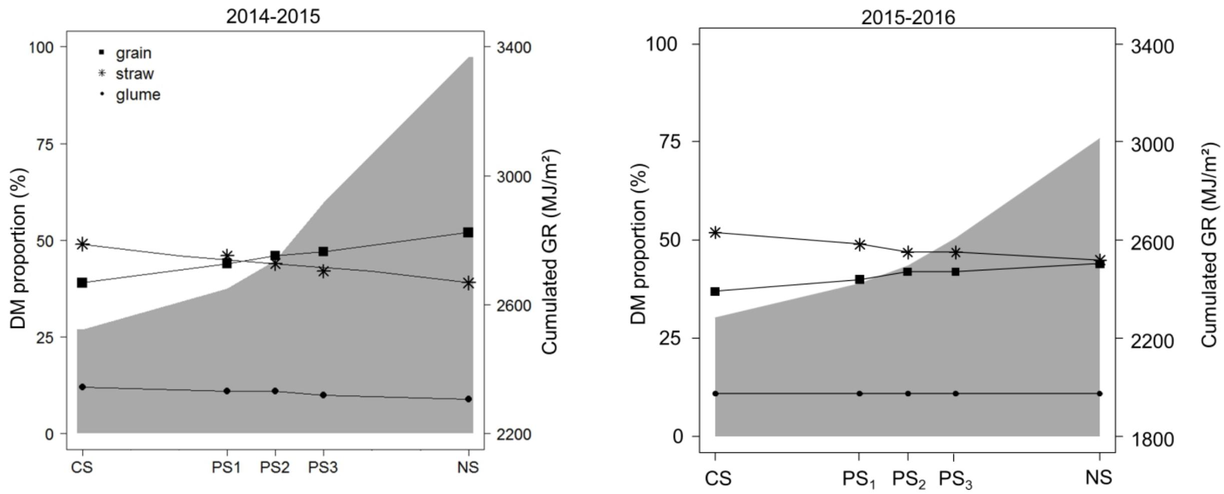



**Figure 17.** Proportion of grain, straw and glume DM (%) to the total aboveground biomass under the different shade treatment at harvest for the season 2014-2015 and 2015-2016. In the background dark grey plot represents the cumulated global radiation (GR, MJ/mffl) from sowing to harvest.

## 3.3. Shading effect on wheat production and yield components

In the three years, final grain yield was highest under NS conditions and declined with increased shade. The CS treatment induced the maximum yield reduction (-29 % in 2014, - 45 % in 2015, and -44 % in 2016), while the PS treatment led to intermediate productivity, as presented in Table 5.**Erreur ! Source du renvoi introuvable.** The correlation between final grain yield and shade intensity was not linear. Using the three sensors in the PS treatment, we can study this relationship in more detail. In 2015, grain yield was higher under PS2 (10.27 t/ha) than under PS1 (8.37 t/ha) and PS3 (9.12 t/ha), although it received an intermediate global radiation reduction (45 %) compared to the PS1 (52 %) and PS3 (33 %) treatments (Table 4, Table 5). Likewise, in 2016, grain yield was higher under PS2 (6.62 t/ha) than under PS1 (5.39 t/ha) and PS3 (5.79 t/ha), although it received an intermediate global radiation reduction (42 %) compared to the PS1 (48 %) and PS3 (33 %) treatments (Table 4, Table 5).

Shade treatments not only influenced the total yield, but also the yield components (ie. number of grains per $m^2$, number of grains per spike, grain dry weight, and grain size). In the three experimental years, the CS treatment reduced the number of grains per spike (by 30 % in 2014, 20 % in 2015, and 9 % in 2016), as well as the thousand grain weight (by 10 % in 2014, 32 % in 2015, and 26 % in 2016) (Table 5). Moreover, the CS treatment led to a reduced proportion of large grain sizes (sieve 2.8 mm), and a large proportion of medium (sieve 2.5 mm) and small (sieve 2.2 mm) grain sizes, as compared to NS and PS (Figure 18). Within the PS treatment, the different shade intensities (PS1, PS2, and PS3) of the three years were not significantly different in terms of the number of grains per spike, but in 2015 and 2016 the thousand grain weight and the number of grains per $m^2$ decreased with increasing shade. Overall, shade application had a negative impact on the proportion of large and medium grain sizes, favouring smaller ones (see Figure 18). Finally, there was a positive influence of shade on the quality of the winter wheat grains. In the three years, the protein concentration in the grain increased with increasing shade (Table 5), but the trend was only significant in 2015 and 2016. Nevertheless, at the plot scale this protein content gain did not compensate for the decrease in final grain yield. In 2015, winter wheat under the CS and PS treatments achieved significantly lower total protein yield than the NS treatment (-20 % and - 8 % respectively, pvalue: $1.42.10^{-6}$). Similarly, in 2016, the total protein yield decreased by 42 and 17 % for the CS and PS treatments, respectively, as compared to the NS treatment.

**Table 5.** Mean value of yield, yield components and protein content of winter-wheat for each treatment. The intervals are ± the standard errors. Parameters with the same letter are not significantly different from each other at the chosen level (Tukey's HSD, $P < 0.05$).

| | **Nb grains per spikes** | **Nb grains per m$^2$** | **Thousand grain weight** | **Yield** | **Harvest Index** | **Protein** | **Protein yield** |
|---|---|---|---|---|---|---|---|
| | [#/spikes] | [#/m$^2$] | [g] | [t/ha] | [-] | [%] | [t/ha] |
| **2013-2014** | | | | | | | |
| NS | 41 ± 3.46 $^{a}$ | 13997 ± 1171 $^{a}$ | 46.50 ± 0.67 $^{a}$ | 6.52 ± 1.24 $^{a}$ | | 12.25 ± 0.39 $^{a}$ | 0.80 ± 0.12 $^{a}$ |
| PS | | 13581 ± 767 $^{a}$ | 46.37 ± 1.03 $^{a}$ | 6.31 ± 0.91 $^{a}$ | | 12.65 ± 0.33 $^{a}$ | 0.80 ± 0.17 $^{a}$ |
| CS | 29 ± 4.12 $^{b}$ | 11120 ± 609 $^{a}$ | 42 ± 0.23 $^{b}$ | 4.67 ± 0.55 $^{a}$ | | 13.52 ± 0.34 $^{a}$ | 0.63 ± 0.06 $^{a}$ |
| ANOVA-*p.value* | 0.001 | 0.09 | 0.003 | 0.042 | | 0.002 | 0.16 |
| **2014-2015** | | | | | | | |
| NS | 59 ± 2.5 $^{a}$ | 26375 ± 1106 $^{a}$ | 49.19 ± 0.95 $^{a}$ | 12.96 ± 0.14 $^{a}$ | 0.52 ± 0.045 $^{a}$ | 10.97 ± 0.17 $^{a}$ | 1.42 ± 0.01 $^{a}$ |
| PS | | 22762 ± 1182 $^{b}$ | 42.95 ± 1.87 $^{b}$ | 9.76 ± 0.2 $^{b}$ | 0.47 ± 0.027 $^{a}$ | 13.30 ± 0.31 $^{b}$ | 1.30 ± 0.01 $^{b}$ |
| $PS_1$ | 41 ± 5.31 $^{b}$ | 20574 ±2643 | 40.71 ± 4.06 | 8.37 ± 0.21 | 0.43 ± 0.018 | | |
| $PS_2$ | 45 ± 3.86 $^{b}$ | 23633 ± 2032 | 43.51 ± 1.35 | 10.27 ± 0.77 | 0.46 ± 0.009 | | |
| $PS_3$ | 41 ± 6.29 $^{b}$ | 19385 ± 2979 | 47.08 ± 1.72 | 9.12 ± 1.38 | 0.47 ± 0.006 | | |
| CS | 47 ± 0.96 $^{b}$ | 21519 ± 452 $^{b}$ | 33.20 ± 0.99 $^{c}$ | 7.14 ± 0.14 $^{c}$ | 0.38 ± 0.022 $^{b}$ | 15.92 ± 0.47 $^{c}$ | 1.14 ± 0.02 $^{c}$ |
| ANOVA-*p.value* | 0.00013 | 0.00015 | $1.46.\ 10^{-7}$ | $1.37.\ 10^{-10}$ | 0.01 | $3.09.\ 10^{-8}$ | $1.42.\ 10^{-6}$ |
| **2015-2016** | | | | | | | |
| NS | 35 ± 0.75 $^{a}$ | 16824 ± 411 $^{a}$ | 50.78 ± 0.73 $^{a}$ | 8.53 ± 0.09 $^{a}$ | 0.43 ± 0.01 $^{a}$ | 13.08 ± 0.17 $^{c}$ | 1.12 ± 0.03 $^{a}$ |
| PS | 34 ± 0.50 $^{ab}$ | 14064 ± 390 $^{b}$ | 44.48 ± 1.10 $^{b}$ | 6.24 ± 0.06 $^{b}$ | 0.40 ± 0.01 $^{ab}$ | 14.09 ± 0.07 $^{a}$ | 0.93 ± 0.01 $^{b}$ |
| $PS_1$ | 33 ± 0.48 | 12208 ± 727 | 44.38 ± 1.74 | 5.39 ± 0.18 | 0.38 ± 0.01 | | |
| $PS_2$ | 36 ± 1.31 | 14501 ± 656 | 45.89 ± 2.45 | 6.62 ± 0.23 | 0.40 ± 0.01 | | |
| $PS_3$ | 35 ± 1.11 | 12600 ± 938 | 46.14 ± 1.06 | 5.79 ± 0.32 | 0.40 ± 0.01 | | |
| CS | 32 ± 1.04 $^{b}$ | 12634 ± 369 $^{c}$ | 37.6 ± 1.36 $^{c}$ | 4.74 ± 0.08 $^{c}$ | 0.36 ± 0.01 $^{b}$ | 13.7 ± 0.14 $^{b}$ | 0.65 ± 0.01 $^{c}$ |
| ANOVA-*p.value* | 0.031 | $6.66.10^{-5}$ | $3.65.\ 10^{-5}$ | $3.51.\ 10^{-9}$ | $4.76.10^{-3}$ | $3.89.10^{-5}$ | $5.17.10^{-7}$ |

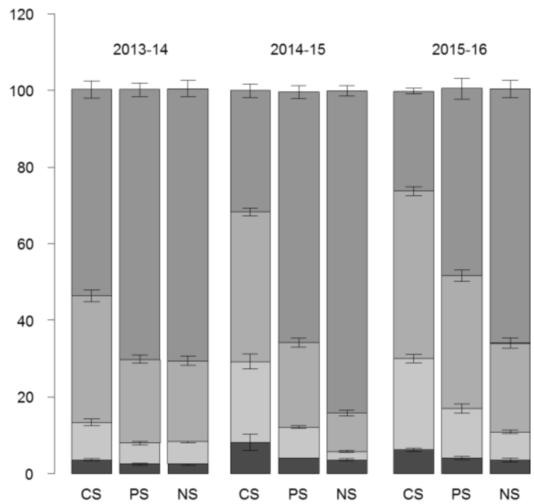



**Figure 18.** Proportion of grain size (2.8 mm; 2.5 mm, 2.2 mm and less than 2.2 mm) under the different shade treatment for the three growing seasons 2013-14, 2014-15 and, 2015-16. Vertical bars represent the standard error of the means.

## 3.4. Long term radiation availability under an agroforestry system: modelling approach

Figure 19 tracks the distribution—in terms of proportion of cropped area—of the predicted relative global radiation available for the understory crop, over 50 years under east-west and north-south tree orientation. Here, the available global radiation corresponds to the mean of the cumulated global radiation received during the months of June, July, and August, under 10-, 20-, 30-, 40-, and 50-year-old trees. During the first decade, the cropped area as a whole receives between 100 % and 80 % of light. After that, the proportion of area affected by reduced light availability increases with tree growth, whatever the orientation of the tree lines. Nevertheless, under the east-west orientation, a more heterogeneous distribution of light availability is to be expected, with a strong gradient ranging from 20 % to 100 % in the 40th year. The crops growing under the north-south tree lines never experience a reduction of light availability lower than 40 %. In fact, the area of strong shade is mainly located in an uncultivated zone under the tree lines. Comparing this simulation to our field data, we can state that the conditions recorded under the PS treatment during the whole shade period (57 % of light availability) would only be reached on a small proportion of the cropped area (less than 10 %) in a real agroforestry system and this from the second and third years onward for the north-south and east-west tree line orientation respectively. For 50-year-old trees, the proportion of the area receiving these light conditions is greater under the north-south orientation (80 % of the cropped area) than under the east-west one (40 % of the cropped area). The values recorded under the CS shade treatment

(39 % of light availability) would only be achieved under the east-west orientation from the 40th year onward, and on 10 % of the cropped area.

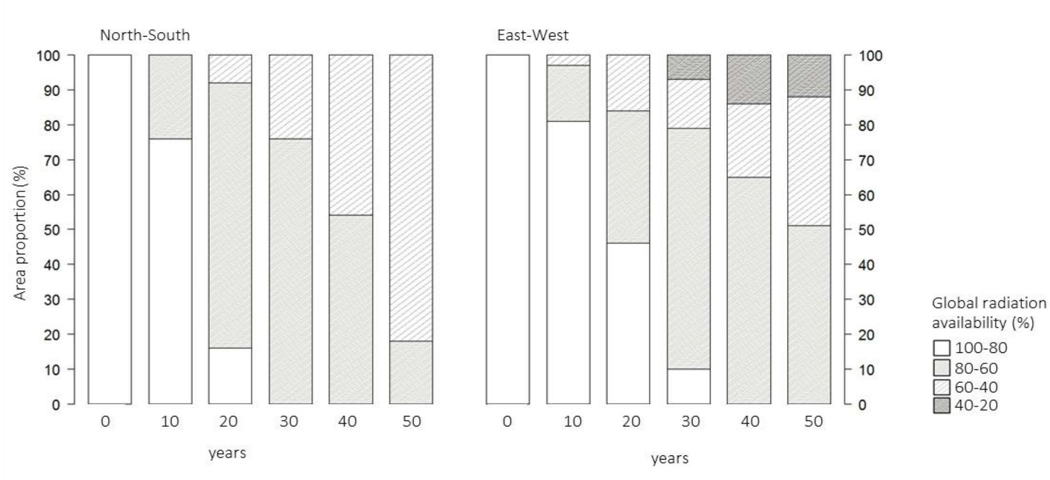



**Figure 19.** Proportion of cropped area (%) versus predicted relative global radiation availability (%) for the understory crop over 50 years for two agroforestry plot designs: east-west and north-south tree line orientation.

# 4. Discussion

Several authors have shown that reducing incident light on a wheat crop leads to growth and yield repercussions, and our study is no exception (Chirko et al., 1996; Dufour et al., 2013; Li et al., 2010; Mu et al., 2010). According to these studies, the magnitude of wheat response varies with the level and period of shade application. Furthermore, the crop components, such as final grain yield, are related in a non-linear way to the reduction in cumulative global radiation from sowing date to harvest. Dufour et al. (2013) and Li et al. (2008) reported that an average reduction of transmitted cumulated global radiation by 17 % or 34 % led to an average yield depression of 20 % and 51 % respectively. Here, we have demonstrated that in 2015, a reduction of 61 % and 43 % of the global radiation cumulated during the shade period induced a final yield reduction of 45 % and 25 % respectively under CS and PS treatment. Under the PS1, PS2, and PS3 treatments the pattern is somewhat more complex, since in 2015 and 2016 the PS2 treatment remains not significantly different from the NS treatment, although the global radiation available for the winter wheat reduced by 45 % in 2015 and 41 % in 2016, as compared to the NS treatment. In these studies and in our experiment, the wheat plants grew in a complex light environment, which varies in intensity, frequency, and space. Therefore, daily carbon gain and final yield cannot only be estimated from an average value of the global radiation over the whole cropping season. In fact, studies have highlighted the non-linear response of photosynthesis to light, particularly for plants growing in fluctuating and heterogeneous environments (Pearcy et al., 1996; Retkute et al., 2015). In fact, a developmental and dynamic acclimation process takes place to maintain a specific level of photosynthesis (ie. changes in LAI or leaf shape during the leaf development, in relative concentration of proteins, in chlorophyll content, etc.), which is related to both the instantaneous environmental signal and to information from the past (Li et al., 2010; Murchie and Niyogi, 2011; Retkute et al., 2015). This raises questions about the potential to generalise results from our experimental design, in which the shade treatments applied induced a sharp change in global radiation for the crop, whereas in a real agroforestry system shade intensity increases progressively. In their field experiment, Li et al. (2010) found that applying shade between jointing and maturity leads to increases in the area of the upper leaves, length of the internode, and pigment content. Under the low intensity shading treatments (ie. reduction of 8 and 15 % of full radiation), the responses of these traits led to an increased final yield for the shade-tolerant wheat cultivar. These physiological and morphological compensations allow yield to be maintained even under heavy shade, and therefore relative yield loss (5.9 %) was significantly lower than relative global radiation reduction (27 %). In our experiment, no morphological adaptation was observed on wheat, because the shade treatment was applied after the $LAI_{max}$ phenological stage. Photoacclimation could have occurred under our shade treatment, but to assess that correctly we would have needed complementary measurements, such as photosynthetic rates. Furthermore, while Murchie et al. (2011) emphasise that the photosynthetic adaptation (photoacclimation) of a plant to a new light environment takes place on a timescale of days, uncertainty remains in fluctuating light environments (Retkute et al., 2015). In addition, several authors have shown that dynamic photoacclimation is highly dependent on species (Athanasiou et al., 2010; Murchie and Niyogi, 2011; Retkute et al., 2015). Retkute et al. (2015) argues that crop breeding programs should take acclimation traits into consideration in order to select shade tolerant cultivars. This suggestion is highly relevant in the context of agroforestry as most of the crop species currently used were selected in full light conditions, and have potentially inefficient photoacclimation traits. Several authors concluded that the success of agroforestry systems depends on the selection of shade-tolerant species (Barro et al., 2012; Ehret et al., 2015). This last point highlights that crop cultivar is an important factor which may explain the differences found in the literature considering crop response to light environment. Furthermore, the effect of global radiation reduction on final yield depends on the phenological stage during which shade is applied, as well as the duration of the period in which the incident light is reduced. In wheat, several authors have demonstrated that imposing a shade treatment during the pre-flowering period (i.e. Around 30 days before-to flowering) mainly affected final yield through the number of grain per m2 component because of a change of numbers of grains per spike (Abbate et al., 1997; Demotes-Mainard and Jeuffroy, 2004; Fischer and Stockman, 1980). However, shade from flowering to maturity reduced both number of grain per m2 and grain weight (Estrada-Campuzano et al., 2008). Our results support these observations. In fact, both yield components were affected as shade was applied 10 to 16 days before flowering until maturity. Additionally, several authors show that post-flowering shade may impact on grain weight through alteration of the current photosynthetic activity as well as the redistribution of the vegetative reserve to the grains (Herzog, 1986; Plaut et al., 2004; Schnyder, 1993). In this study, the amount of vegetative reserve mobilized to the grain as well as the relative contribution of this pool to final grain yield were the same even with post-flowering shade. Thus, the reduction of grain weight under shade treatment can most probably be explained by a decrease of the pool of assimilates produced by photosynthesis during grain filling. Finally, grain yield, as well as grain protein concentration, has to be taken into consideration when evaluating the wheat production: quantity and quality (protein content). Just like Dufour (2013), we measured an increase of protein grain content with increasing shade intensity, but the increase did not compensate the final yield decrease. The protein content of the grain resulted from the remobilisation of N accumulated by the plant, and is negatively related to final grain yield due to a dilution effect. Our results from the disease-free year clearly illustrate this process, since under the shade treatment higher grain protein content is associated with a higher proportion of small grain sizes and a lower final yield. The first year did not show this pattern, because the take-all disease caused an overall yield reduction. In 2013-14, there were no significant differences in final yield or protein content between treatments. Take-all disease is known to negatively affect wheat grain filling by disrupting water and nutrient uptake and flow through the plant (Kwak and Weller, 2013). Even though the 2013-2014 results are not representative of a healthy wheat field, they do show the resilience of silvoarable agroforestry systems to disease occurrence. Our data reveal that the shade treatments were less affected by the disease. This can be explained by the fact that, under the CS treatment, the green leaf area of winter wheat was maintained during a longer period than under NS and PS. This persistence of green leaves can enhance the final yield by extending the period of carbon assimilation. The artificial shade implemented in the experiment represented an extreme level of shade. The CS treatment created a strong shade environment, corresponding to old trees and dense plantation densities, or east-west tree orientation, whereas the PS treatments represented lower shade environments, corresponding to younger trees and/or open plantation density. However, in agroforestry, specific pruning practices and other management decisions can greatly influence the light environment of the crop. In view of the great diversity of agroforestry systems, it remains difficult to associate the current experiment to a specific agroforestry system light environment. Keeping this in mind, our observed yield decreases under CS treatment, of 45 % in 2014-2015, and 44 % in 2015-2016, are not very likely to occur under agroforestry, and should be seen as a worst-case scenario. In fact, this configuration of a high-density canopy closure between the tree rows is unrealistic, because these are now planted at wide spacing, matching the width of agricultural machinery. According to the Hi-sAFe simulation, the global radiation available for crops should remain above 60 % on at least 50 % of the cropped area during the first 40 years of growth of a simulated real agroforestry plot with north-south tree line orientation, and will never reach the intensity of the CS shade treatment, even under 50-year-old trees. Thus, under a tree configuration realistic for agricultural practices in temperate regions, large shade effects can be expected only after 30 years of tree rotation with an east-west tree orientation. The data observed under the PS treatment is therefore more realistic of natural sunfleck shade environments in agroforestry.

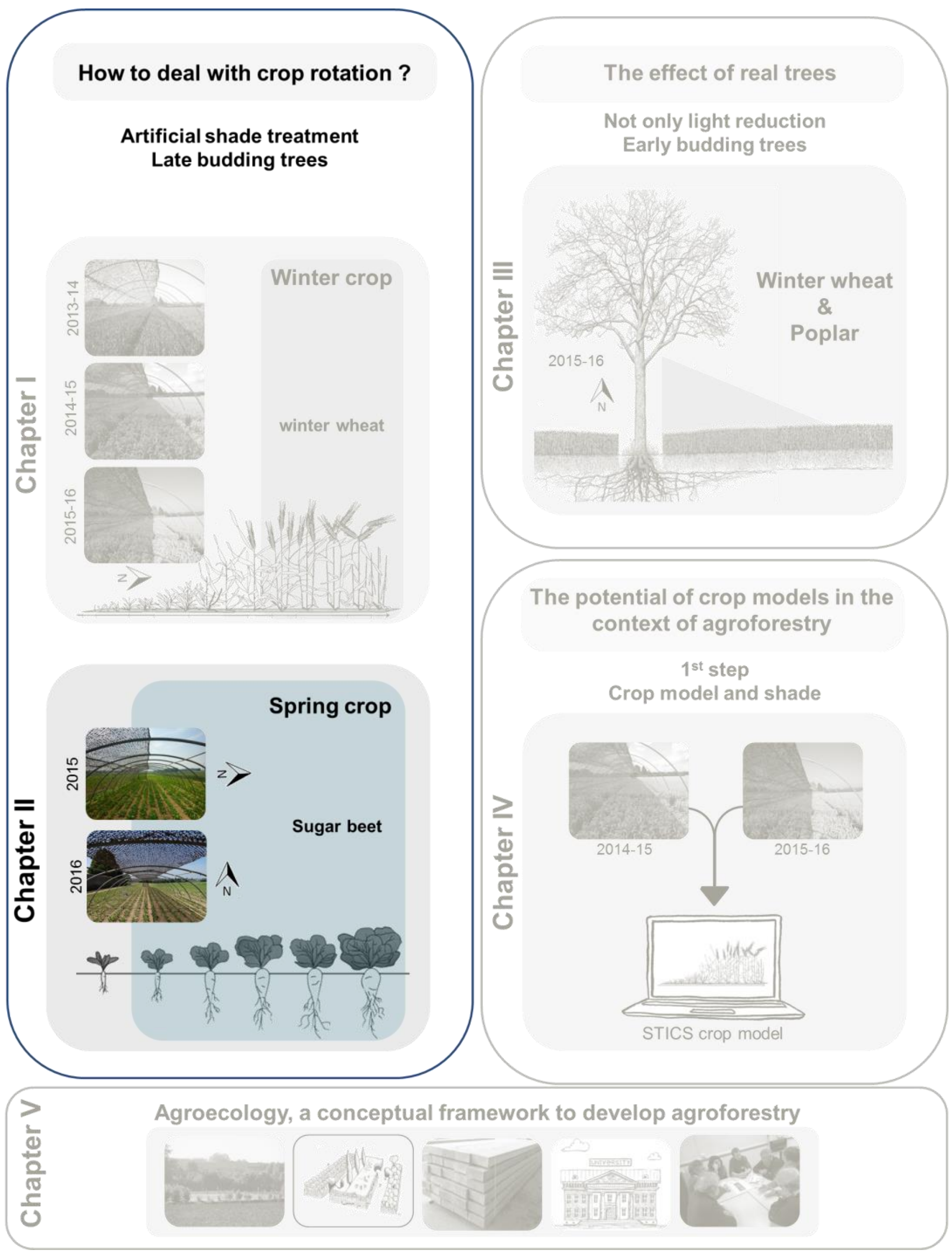
Finally, the artificial shade structure allowed us to separate the effect of light resources from other potential biotic and abiotic interactions in agroforestry systems. Thus, under the artificial shade treatment, we certainly underestimated the effect of a real agroforestry system on crop yield. A number of studies with crops such as soybean (Reynolds et al., 2007; Rivest et al., 2009), corn (Reynolds et al., 2007), winter wheat (Chirko et al., 1996; Dufour et al., 2013; Li et al., 2008), alfalfa (Varella et al., 2010), and forage mixture (Bouttier et al., 2014) have displayed similar trends for relative yield (ratio between intercrops yield and sole crop yield), but the magnitude of competition often differs and has varied from 0.42 to 0.83. Focusing on wheat, Dufour et al. (2013) provide some insights into yield responses to shade, and to other possible interactions, by comparing durum wheat growing under a real agroforestry system and under artificial shade treatment, in the south of France. In this study, the reduction of final yield under the real agroforestry treatment in Restinclières was higher (-20 %) than under the artificial shade treatment (-16 %), even though the light reduction integrated over the whole growing season was comparable for both scenarios (-17 % and -19 %, respectively). Thus, field trials testing the same annual crops intercropped with deciduous trees have established contrasted relative yield results, even in contexts where the competition for light was probably of similar intensity. The response of a crop to shade is highly dependent on growth conditions, including climate, species variety, and management practice.

# 5. Conclusion

The experimental set-up presented in this research paper has reproduced the effect of the heterogeneous spatio-temporal pattern of light which can be observed under trees in an agroforestry system, and isolated it from effects of competition for water and nutrients. Winter wheat responded to the late application of shade by a significant decrease in grain yield, which was partly compensated for by an increase in grain protein content. These first results in Belgium provide an understanding of the functioning of wheat under shade in field conditions, and may help adapt agroforestry practices to northern temperate latitudes. Future research should be conducted to integrate other tree-crop-environment interactions, such as nutrient and water availability, or pest occurrence, in order to have an improved view of the complex interactions in agroforestry systems. Furthermore, it remains necessary to monitor tree productivity and economic value in the research, in order to evaluate the extent to which the revenue from the trees can compensate for a modest overall decrease in crop yield.

# Chapter II.

## Sugar beet performance under dynamic shade environments in temperate conditions



# Sugar beet performance under dynamic shade environments in temperate conditions

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# Abstract

Crop rotation remains a common agricultural practice and appears to be a cornerstone for sustainable land management. Agroecological practices such as silvorable agroforestry systems have been put forward to provide additional ecosystem services as compared to monocropped systems. Nevertheless, the implementation of trees within the cropping area adds a level of complexity in terms of resource-use and may entail competition between species and thus result in potential disadvantage for the crops underneath the trees. In Wallonia region (Belgium), almost half of the arable land is managed following a 4-year crop rotation. Within the rotation scheme winter crops often follow spring crops. This is particularly challenging when implementing trees in the cropped area, in terms of species choice, plot design, and tree management, since the periods of crop resource capture clearly differ. Focusing on the light resource, coupling spring crops with trees induces an important overlap of the growing period of both plants. This study addresses the issue by monitoring sugar beet (*Beta vulgaris* L.) growth, productivity and quality under artificial shade in order to isolate the impact of shade from the other possible interactions. The field experiment was conducted over two consecutive years (2015 and 2016) on the experimental farm of Gembloux Agro-Bio Tech, Belgium. We placed the shade structures so as to reproduce a North-South and East-West tree line orientation. The experiment simulated shading from a canopy of late-flushing hybrid walnut leaves above sugar beet by overlapping military camouflage netting. In 2015, the North-South orientation induced two shade conditions: periodic shade (PS) and continuous shade (CS). In 2016, the East-West orientation created two periodic shade treatments, one during the morning ($PS_{am}$) and one in the afternoon ($PS_{pm}$). In both experimental years, shading was imposed from mid-June until harvest, resulting in 132 days of shade in 2015, and 140 days in 2016 on a growing season of 192 (2015) and 188 (2016) days in total. When shaded, sugar beet tends to produce longer petioles in order to avoid tree shade. In 2015, higher specific leaf area and single leaf area have been observed under the CS and NS treatment, while we observed no differences in 2016. At harvest, all the shade treatments significantly reduced the final root dry matter and sugar yield, but the intensity of this decrease depended on the level of the shade applied. Furthermore, sugar beet quality, or more specifically sugar extractability, was affected by shading but to a lesser extent than for the final root dry matter and sugar yield.

These results have to be interpreted with care, since in real agroforestry systems other interactions between tree and crop may occur than the competition for light only. Furthermore, we have to keep in mind that even though the effect of shade cannot be removed when trees are present within a cropped area, only a certain fraction of the field is subjected to this light reduction. Well thought plot design, tree species choice as well as tree management can minimize the proportion of the area affected by the tree shade and modeling studies may help to optimize agroforestry implementation.

## Keywords

Sugar beet, Spatio-temporal shade, Sugar yield, Agroforestry systems

## Highlights

- An artificial shade experiment was set up to mimic the effect of a North-South and East-West tree line orientation on sugar beet.
- The artificial shade treatments allow to reproduce a heterogeneous spatio-temporal light environment at the seasonal and daily time scale.
- Reducing global radiation during 132 and 140 days before harvest induces aboveground morphological changes
- The shade treatments reduced the final root dry matter and sugar yield of sugar beet significantly.

# 1. Introduction

Over the last decades, agroforestry systems have received a renewed interest from farmers, scientists, and politicians, also in temperate regions (Mosquera-Losada et al., 2012). Despite the potential of this practice in enhancing biodiversity, reducing the use of external inputs and increasing ecosystem services delivery as compared to monocropped systems (e.g. climate regulation, pest and disease control, food and fiber production), it remains rarely implemented in North-western Europe. Among different bottlenecks (Borremans et al., 2016), uncertainties regarding crop growth and productivity remain an important issue (Wezel et al., 2014b). Implementation of trees within the cropping area adds a level of complexity in terms of spatio-temporal dynamics for resource-use, since different types of competition can occur and potentially hinder crop growth. Nevertheless, competition can be limited and complementary use of resources optimized with a well-thought system design as the relative importance of individual resource needs is site-specific and depends on the development stage of both trees and crops (Cannell et al., 1996). For instance, Dufour et al. (2013) suggest that a high phenological time-lag between trees and crops optimizes the use of light resources in temperate pedoclimatic conditions. They therefore recommend the use of late deciduous trees (budburst around April to June) in association with winter crops (October-August). Nevertheless, in Europe crop rotation remains a common agricultural practice and a winter crop often follows a spring crop in the order of appearance (Leteinturier et al., 2006). Coupling spring crops with trees in an agroforestry context is particularly challenging, since this implies a significant overlap of growing period between tree and crop. This leads to simultaneous demands for resources in time and space in some parts of the field. Sugar beet (*Beta vulgaris* L. ssp. *vulgaris*) is one of the common spring crops cultivated in Europe and represents around 50 % of the global sugar beet production, ranking the EU among the world leaders (Eurostat, 2015). In Belgium, this crop accounted for 5 % and 4 % of the utilized agricultural area in 2014 and 2015, respectively. According to Leteinturier et al. (2006), sugar beet remained the principal crop preceding winter wheat within the crop sequence between 1997 and 2003, whatever the crop rotation duration. Previous work on sugar beet quantified the influence of individual weather variables or different weather conditions on growth and yield in a monocropped situation throughout the growing season (Albayrak and Çamaş, 2007; Kenter et al., 2006; Milford et al., 1985; Scott and Jaggard, 2000; Werker and Jaggard, 1998). Nevertheless, few attempts have been made to describe the performance of sugar beet as part of agroforestry systems and the transferability of results from monocropped field situations to mixed systems remains limited (Mirck et al., 2016). The effect of the individual weather variables is often tested by applying a stress condition during the whole crop development rather than at a specific time during the growing season or at a specific time of the day, as observed under trees. For example, in agroforestry systems the light available for the crop varies over the 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). Several studies have investigated the agronomical impact of the light availability experienced by winter wheat (Artru et al., 2017; Chirko et al., 1996; Dufour et al., 2013; Mu et al., 2010), soybean (Rivest et al., 2009), corn (Friday and Fownes, 2002; Gillespie et al., 2000; Reynolds et al., 2007) or spring wheat (Reynolds et al., 2005) under temperate agroforestry. Most of these studies concluded that a key point to optimize the productivity of agroforestry systems is to minimize the competition for the limiting resources. With respect to the light resource, using a well-thought planting design of trees, i.e. adapted tree density and row orientation, appropriate tree species and optimal management, can thus be an important leverage point (Cannell et al., 1996; García-Barrios and Ong, 2004). According to Dupraz et al. (2016), the levels of light heterogeneity experienced by the crops under agroforestry systems highly depend on the orientation of the tree lines. Throughout the development of an agroforestry site, an East-West tree line orientation induces a high degree of heterogeneity with a crop area subjected to dense and continuous shade conditions near the trees and shade-free zones towards the center of the plot. In the case of a North-South orientation, crops experience shade either in the morning or in the afternoon and there are shade-free zones in the field. Next to the impact of the field design, it remains necessary to develop a better knowledge of the crop response to this specific light environment in order to identify functional traits affected by shade. These insights might then help to select promising varieties, but also to evaluate the extent to which crops can deal with these distinct light reduction patterns.

Within a real agroforestry system, it is difficult to distinguish the effect of different state variables (light, water, nutrients, …) and their interaction throughout the growing season. Therefore, some authors designed and used artificial shade structures to differentiate the effect of light from the other possible abiotic and biotic interactions occurring in agroforestry systems focusing on crops (winter wheat) and forage (cocksfoot and alfalfa) (Dufour et al., 2013a; Peri et al., 2002; Varella et al., 2010). The objective of this study was to quantify the response of sugar beet to a dynamic shade environment using such an artificial shade structure. More specifically, we mimicked both an East-West and North-South orientation with its corresponding light dynamics.

# 2. Materials and methods

## 2.1 Field experiment

Sugar beet (*Beta vulgaris* L., var. Lisana KWS in 2015 and var. Leonella KWS in 2016) was sown on March 10th, 2015 and April 21th, 2016, respectively. The crop lines followed an East-West orientation in 2015 and a Northwest-Southeast orientation in 2016 in order to mimic the pattern of two distinct tree line orientations. The preceding crops were mustard and winter wheat, for the growing season 2015 and 2016 respectively. The sugar beet seeds used in this experiment were protected by a coating, developed by the KWS seed company, composed by two fungicides and one insecticide. Fertilization followed the conventional practice applied in Belgium. In 2015, one dose of liquid nitrogen fertilizer (104) was applied two days before sowing. In 2016, one dose of liquid and one dose of solid nitrogen fertilizer were applied 17 and 8 days before sowing respectively. For both growing seasons, the main agronomic practices are mechanical weeding and the application of herbicides. Sugar beet was harvested on October 19$^{th}$, 2015 and October 26$^{th}$, 2016, respectively.

## 2.2 Experimental design

In both growing seasons, shade levels were obtained by adjusting shade layers on a greenhouse tunnel structure (8 m wide, 35 m long and 2 m in height) (Figure 20**Erreur ! Source du renvoi introuvable.** a). In 2015, the structure was set up in East-West orientation with a shade layer applied on the south face. This orientation leads to a continuous shade (CS) treatment under which crop experienced shade throughout the entire day and a periodic shade treatment (PS) under which the crop was submitted to an intermittent shade which varies during the day. In 2016, the greenhouse structure follows a Northwest-Southeast orientation with a 2.5 meter shade layer band centered on the top of the structure (Figure 20 a). This set up results in two distinct periodic shade treatments, one lead to a shade period in the morning ($PS_{am}$) and the other one in the afternoon ($PS_{pm}$). For both experimental years, we also followed a no shade treatment (NS) defined as the control plot, receiving 100 % of the available light. By changing the orientation and shade structure, we were able to monitor a large range of periodic shade types, which helps us to better understand the different shade environments produced in real agroforestry systems.

Camouflage net was used as shade material to reproduce a fluctuating sun/shade pattern, the holes in the cloth producing 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 through time to follow the development of tree-foliage in a monitoring plot in Belgium (see next paragraph). Hybrid walnut was selected as reference tree given its late-budding characteristic.

The layout included four replicate blocks per treatment each made up of three subplots of four adjacent sowing lines of 1.5 meter width. During both growing seasons three sampling campaigns were performed. At each sampling date, one sub-plot per replicate was harvested, i.e. four subplots per treatment.

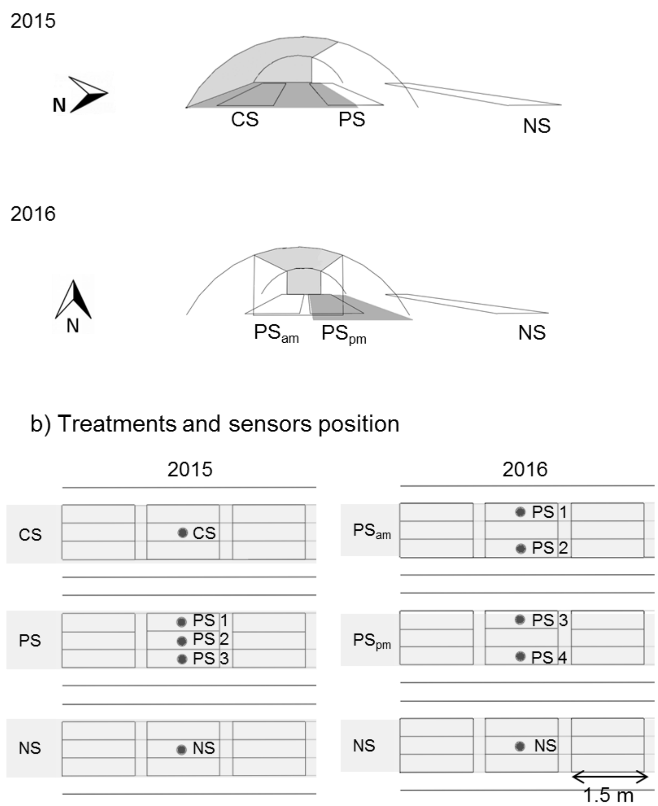



**Figure 20.** Overview of the experimental design. a) the shade structure, its orientation and the shade treatments for the growing season 2015 (constant shade : CS, periodic shade : PS, no shade : NS) and 2016 (periodic shade in the morning : $PS_{am}$, periodic shade in the afternoon : $PS_{pm}$, no shade : NS). b) zooms in to one of the four blocks showing the location of the light sensors within the different treatments in 2015 and 2016.

## 2.3 Data collection

### 2.3.1 Tree phenology monitoring and shade layers application

We monitored the phenological development of 60 hybrid-walnut trees of 20 years old located in a plantation in Jenneret, Condroz region, Belgium (50°24' N, 5°27'E). Four phenological stages were differentiated during the growing season (May-November): budburst, end of first leaf expansion, second flush of leaf and leaf fall. The date at which a phenological stage is achieved was defined as the moment when 50 % of the trees of the plantation reached that stage. In the artificial shade experiment, the first layer of camouflage net was installed over the crop after budburst when trees induce a significant shade (qualitative visual observation). Subsequently, tree foliage expansion was imitated by superimposing an additional layer of camouflage net. In 2015, the first layer was applied 60 days after sugar beet sowing (DAS) (June 9$^{th}$), the second 74 DAS (June 26$^{th}$) and the third from 171 DAS (September 29$^{th}$) until harvest 192 DAS (October

19$^{th}$). For the season 2016, the first layer of camouflage net was applied 48 DAS (June 8$^{th}$), the second 70 DAS (June 30$^{th}$) and the third from 134 DAS (September 02$^{th}$) until 188 DAS (October 26$^{th}$), after which the shade structure was removed.

### 2.3.2 Agronomic measurements

Sugar beets were harvested by hand lifting at three dates. In 2015, the first sampling campaign was performed 115 DAS (August 3$^{th}$), the second 143 DAS (August 31$^{th}$) and the third at harvest 192 DAS (October 19$^{th}$). For the season 2016, the first sampling was performed 111 DAS (August 10$^{th}$), the second 138 DAS (September 6$^{th}$) and the third at harvest 188 DAS (October 26$^{th}$). The number of sugar beets per $m^2$ was assessed by counting the number of sugar beets within each sub-plot sample. From each sub-plot, five sugar beets were randomly selected to perform more detailed measurements. On this subsample, roots, leaves and petioles were separately weighed before and after a drying period (10 days at 60°C in an oven) in order to assess fresh and dry matter of each organ of the plant (kg/plant). Before drying the samples, petioles and leaves of each plant were scanned. Leaf area and petiole length were determined using image J software (Abramoff et al., 2004). Then, leaf area index (LAI) was defined as the total leaf area per unit ground surface area. The specific leaf area (SLA, $m^2$/kg) was calculated for each plant as the ratio of the LAI and the leaf dry weight (kg/$m^2$). From the rest of the sample (subplot sample minus the 5 sugar beet plants used for the previous measurements), plants were separated into root and aboveground part (including leaves and petioles). Roots were washed, then fresh roots and aboveground biomass were weighed, chopped to produce a fine pulp and then frozen for further lab analysis. Root sugar content (%) and non-sugar components (alpha amino N (aN), potassium (K), sodium (Na), mmol per 100 g of sugar beet fresh biomass) were analyzed from the frozen pulp at the IRBAB-KBIVB institute using a polarimetric (Saccharomat Z, Schmidt & Haensch) and a fluorometric method (Venema installation), respectively. Sugar yield (S, t/ha) was calculated from root yield (t/ha) and sugar content (%). Sugar beet quality was defined in terms of potential of sugar extractability (%) and calculated according to the formula defined by Devilliers (1988), also used by the National syndicate of the Belgium sugar factory:

$$Se = S - (0.14 \times (K + Na) + 0.25 \times aN + 0.5)$$

$$Sugar\ extractability = \frac{Se}{Sugar\ content} \times 100$$

### 2.3.3 Global radiation measurements

Daily global radiation was recorded from March to October 2015 by a local weather station (CR800 – Campbell Scientific Inc., USA) installed near the experimental plots (Bordia, Gembloux, 50°56'N, 4°71'E). As soon as the shade structure was set up, global radiation at crop canopy level was measured with quantum sensors (CS300 - Campbell Scientific Inc., USA - accuracy ± 5 % for the daily global radiation) and recorded every 5 minutes by data loggers (CR1000 – Campbell Scientific Inc., USA). In 2015, we assessed light availability for the sugar beet under the CS and NS treatment with one sensor at the center of each subplot (see Figure 20 b). Within the PS plot, the light availability was assessed by measuring light at three locations (PS1, PS2, PS3) along the transect perpendicular to the orientation of the shade structure in the subplot. During the season 2016, light availability under the $PS_{am}$ and $PS_{pm}$ treatment were recorded by two sensors (PS1, PS2 and PS3, PS4) located between the four crop rows monitored during the growing season (Figure 20 b). Light availability under the NS treatment was assessed by one sensor in the middle of the subplot. Under the PS, $PS_{am}$ and $PS_{pm}$ treatments, the hourly pattern of global radiation varied from one row to another. We therefore characterized the global radiation intercepted by the whole PS, $PS_{am}$ and $PS_{pm}$ subplot using an average of the global radiation. PS was calculated as a weighted average in which global radiation intercepted by the different sensors in the treatment was weighted corresponding to the proportion of the PS plot area covered by each sensor. In 2016, a linear model was used to estimate missing values between 08/09 and 14/10 due to the theft of the datalogger equipment in the field.

### 2.3.4 Statistical analyses

All statistical analyses were performed with the R software (R Development Core Team, 2008). Analyses of variance (ANOVA) and Tukey range tests were used to assess the effect of the shade treatments on dry and fresh matter, LAI, SLA, petiole length, final sugar yield, and sugar beet quality.

# 3. Results

## 3.1 Global radiation dynamics under the artificial shade treatment

At a diurnal time scale, the artificial shade structures generated two distinct light regimes within each cropping season. Figure 21 shows an example of the diurnal variation of the global radiation recorded for a given day of the year 2015 and 2016. In 2015, the CS treatment induced a continuous shade regime over the day, while under the PS treatment sugar beet experienced a shade period during the afternoon. In 2016, two distinct periodic shade treatments have been applied. The proportion of global radiation received was reduced in the morning under the $PS_{am}$ treatment and in the afternoon under the $PS_{pm}$ treatment. At the scale of the growing season, a total of 132 days and 140 days of shade was applied during the season 2015 and 2016, respectively.

Table 6 presents a detailed view of the cumulated global radiation received by the sugar beet plants from sowing until harvest as well as between the different sampling dates. The transmitted global radiation cumulated throughout the growing season without the shade treatments was only slightly higher in 2015 (+ 1.8 %) than in 2016. Nevertheless, within the growing season the dynamics of the cumulated global radiation highly differs from one year to another. As presented Figure 22, the cumulated global radiation recorded in June 2016 was well below than in 2015.

The cumulated global radiation under the CS treatment in 2015 was 40 % lower than without shade and the reduction ranged from 24 to 32 % under the periodic shade treatments. Due to a difference in sowing date between the two years, whatever the treatments, the different sugar beet plots experienced the same light conditions during 60 days in 2015, while only during 48 days in 2016. The global radiation cumulated during this period reaches 1138 $MJ/m^2$ in 2015 and 760 $MJ/m^2$ in 2016, representing 38 and 26 % of the global radiation cumulated on the whole growing season, respectively.

We defined three different cumulated radiation periods according to the three crop sampling campaigns throughout the growing season. At the first sampling date, in 2015 the global radiation received by the crop was reduced by 14 and 29 % under the PS and CS treatments, respectively, while in 2016 this reduction ranged from 19 to 24 % under the $PS_{am}$ and $PS_{pm}$ treatments, respectively. During the period from the first to the second sampling date, in 2015 the sugar beet experienced a decrease of the available global radiation of 47 and 68 % under the PS and CS treatments, respectively, while in 2016 it decreased by 32 and 47 % under the $PS_{am}$ and $PS_{pm}$ treatments respectively. For both experimental years, the global radiation reduction reaches a maximum during the third period, with a decrease of 75 % under the CS treatment and from 56, 35 and 48 % respectively for the PS, $PS_{am}$ and $PS_{pm}$ treatments (Table 6).

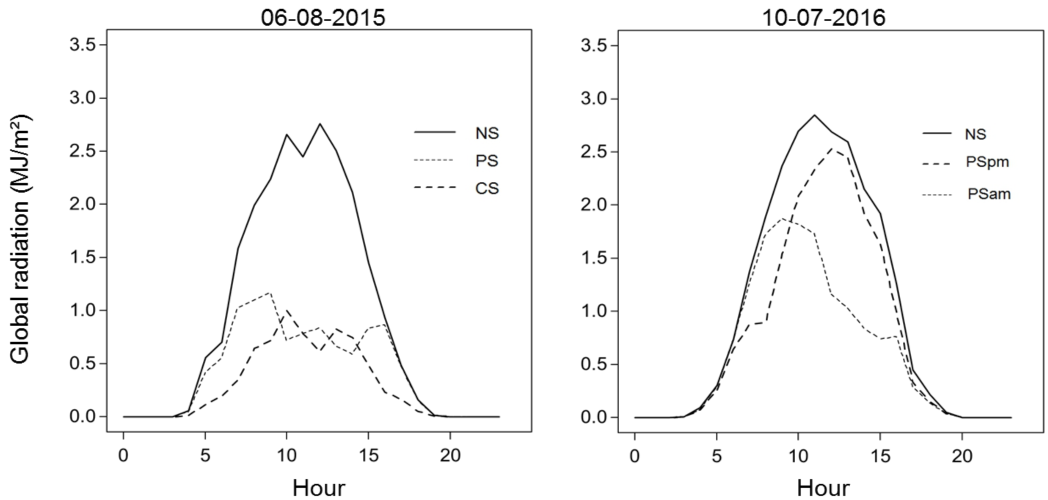



**Figure 21.** Example of hourly dynamics of global radiation (MJ/m$^2$). The presented global radiation was measured on August 6$^{th}$ under no shade (NS), continuous shade (CS) and periodic shade (PS) in 2015 and on July 10$^{th}$ under the NS and the periodic shade ($PS_{pm}$, $PS_{am}$) treatments in 2016.

**Table 6.** Cumulated transmitted global radiation (GR) and percentage of available GR during the whole growing season (from sowing to harvest), before shade application, during the whole shade period (from first layer installation until removal of shade structure) and according to the sampling dates for the artificial shade treatments (CS, PS, $PS_{am}$, $PS_{pm}$) and the control plot (NS).

| | | Cumulated transmitted GR [MJ/m²] – Percentage of available GR [%] | | | | | |
|---|---|---|---|---|---|---|---|
| | | Whole growing season | Before shade | Whole shade period | Sowing to 1rst sample | 1st to 2nd sample | 2nd sample to 3rd sample |
| 2015 | Days after sowing | 0-192 | 0-59 | 60-192 | 0-115 | 116-143 | 144-192 |
| | NS | 2986 – 100 | | 1848 – 100 | 2196 – 100 | 400 – 100 | 390 – 100 |
| | PS | 2263 – 76 | 1138 – 100 | 1135 – 61 | 1879 – 86 | 212 – 53 | 172 – 44 |
| | CS | 1795 – 60 | | 671 – 36 | 1569 – 71 | 130 – 32 | 97 – 25 |
| 2016 | Days after sowing | 0-188 | 0-47 | 48-188 | 0-109 | 110-137 | 138-188 |
| | NS | 2932 – 100 | | 2172 – 100 | 1931 – 100 | 512 – 100 | 489 – 100 |
| | $PS_{am}$ | 2236 – 76 | 760 – 100 | 1475 – 68 | 1568 – 81 | 349 – 68 | 319 – 65 |
| | $PS_{pm}$ | 1994 – 68 | | 1233 – 57 | 1469 – 76 | 270 – 53 | 254 – 52 |

## 3.2 Sugar beet growth and final yield under full sun environment

The weather conditions of both growing seasons were contrasted in terms of rainfall and global radiation (Figure 22). The year 2016 was wetter in the beginning of the growing season and had a rainfall shortage at the end of August-September as compared to 2015 or to the 30-year average. The cumulated rainfall over the growing season was 514.2 mm with a maximum event of 149.3 mm in June. In addition, 2016 had a cumulative global radiation below the 30-year average during the month of June and was characterized by a hot September month. 2015 was characterized by a relatively dry and sunny spring.

Despite the contrasted growth conditions in 2015 and 2016, only slight differences in the growth pattern have been observed under the two NS treatments. In fact, at harvest (sampling date 3), no significant difference in number of leaves per plant (*p-value* = 0.06) and LAI (*p-value* = 0.19) has been observed between the NS treatments in both years, while the final specific leaf area (SLA) was significantly higher in 2016 than in 2015 (*p-value*= $4.10^{-2}$) (Figure II-4). Furthermore, similar root growth rates (*p-value* = 0.68), final root dry matters (*p-value* = 0.18), sugar content (*p-value* = 0.44) and thus final sugar yields (*p-value* = 0.41) were observed under both NS treatments (Table 7**Erreur ! Source du renvoi introuvable.**).

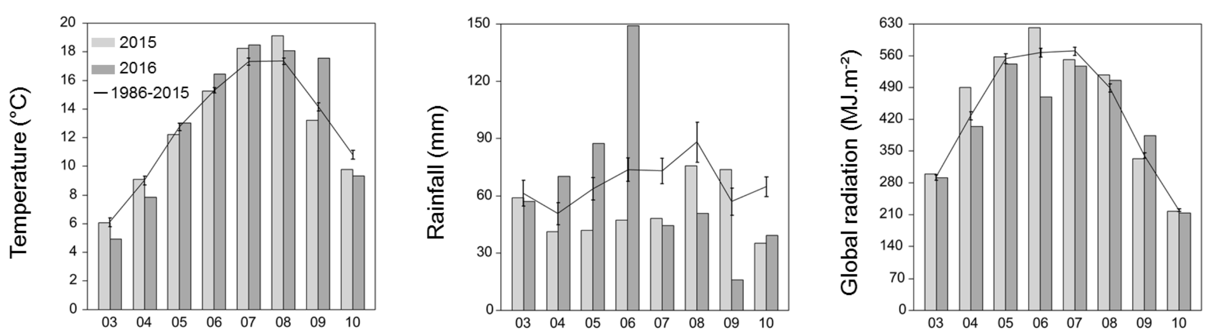



**Figure 22.** Monthly meteorological data recorded from March to October for the growing season 2015 (lightgrey), 2016 (dark grey) and comparison with the average climatic data from 1986 to 2015 (black ligne). From left to right the charts represent the monthly average air temperature (°C), the monthly cumulated rainfall (mm) and the monthly cumulated global radiation ($MJ/m^2$). Vertical bars represent the standard error of the means of the average data.

**Table 7.** Mean value of sugar beet characteristics at harvest under the no shade (NS), the constant shade treatment (CS) and the periodic shade (PS, $PS_{am}$, $PS_{pm}$) treatments for both growing season (2015 and 2016). The intervals ± represent the standard error of the means and the letters represent the statistical significance of the equality between treatments (Tukey, *p-value* <0.05).

| | | Shoot | Roots | | | Sugar | | |
|---|---|---|---|---|---|---|---|---|
| | | Dry matter [t/ha] | Dry matter [t/ha] | Growth rate [t/ha/days] | Water content [%] | Content [%] | Yield [t/ha] | Extractability [%] |
| 2015 | NS | 5.12 ± 0.18 $^{a}$ | 22.39 ± 0.27 $^{a}$ | 0.14 ± 0.01 $^{a}$ | 77.00 ± 0.17 $^{b}$ | 17.96 ± 0.14 $^{a}$ | 17.48 ± 0.32 $^{a}$ | 93.74 ± 0.10 $^{a}$ |
| | PS | 5.06 ± 0.15 $^{a}$ | 14.29 ± 0.39 $^{b}$ | 0.07 ± 0.003 $^{b}$ | 77.36 ± 0.23 $^{ab}$ | 17.18 ± 0.18 $^{b}$ | 10.84 ± 0.27 $^{b}$ | 92.74 ± 0.13 $^{a}$ |
| | CS | 3.91 ± 0.08 $^{b}$ | 6.05 ± 0.36 $^{c}$ | 0.025 ± 0.005 $^{c}$ | 77.91 ± 0.16 $^{a}$ | 16.58 ± 0.16 $^{b}$ | 4.54 ± 0.26 $^{c}$ | 90.81 ± 0.42 $^{b}$ |
| | *p-value* | $8.4.10^{-4}$ | $1.6.10^{-9}$ | $5.8.10^{-3}$ | 0.03 | $1.61.10^{-3}$ | $2.14.10^{-9}$ | $1.14.10^{-4}$ |
| 2016 | NS | 3.82 ± 0.13 $^{a}$ | 20.47 ± 1.17 $^{a}$ | 0.15 ± 0.016 $^{a}$ | 77.62 ± 0.45 $^{a}$ | 18.08 ± 0.06 $^{a}$ | 16.57 ± 1.01 $^{a}$ | 93.01 ± 0.13 $^{a}$ |
| | $PS_{am}$ | 4.08 ± 0.14 $^{a}$ | 16.80 ± 0.45 $^{b}$ | 0.14 ± 0.008 $^{a}$ | 77.08 ± 0.22 $^{a}$ | 17.65 ± 0.1 $^{b}$ | 12.94 ± 0.3 $^{b}$ | 91.92 ± 0.06 $^{b}$ |
| | $PS_{pm}$ | 3.75 ± 0.06 $^{a}$ | 12.98 ± 0.30 $^{c}$ | 0.086 ± 0.002 $^{c}$ | 76.94 ± 0.21 $^{a}$ | 17.64 ± 0.08 $^{c}$ | 9.93 ± 0.17 $^{c}$ | 91.35 ± 0.19 $^{c}$ |
| | *p-value* | 0.22 | $2.3.10^{-4}$ | $6.87.10^{-4}$ | 0.33 | $9.69.10^{-3}$ | $1.01.10^{-4}$ | $1.03.10^{-4}$ |

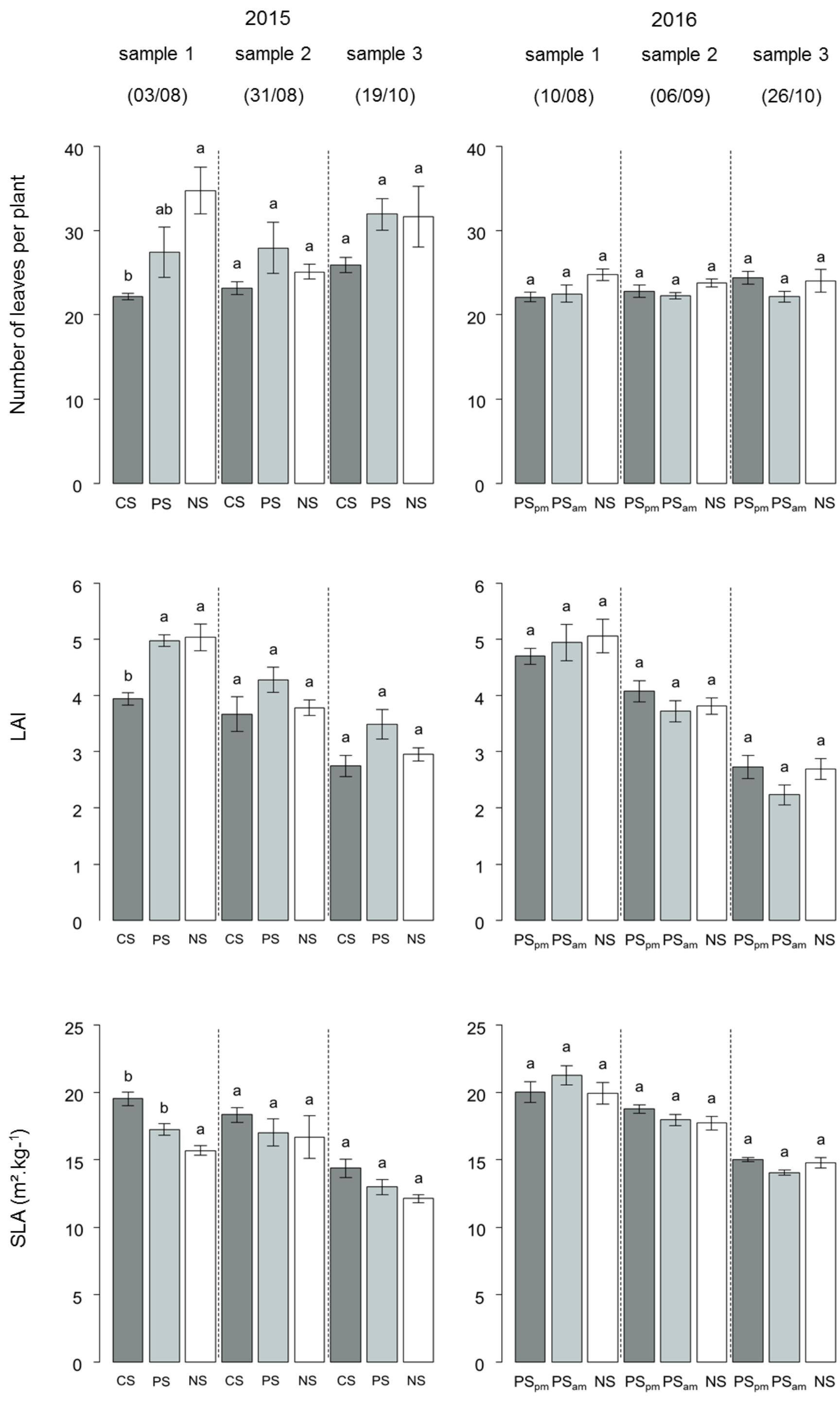



**Figure 23.** Number of leaves per plant, mean leaf area index (LAI) and specific leaf area (SLA) at the three sampling dates for the cropping season 2015 and 2016. Vertical bars represent the standard error of the means and statistical significance of the equality between treatments is represented by the letters above the barplot (Tukey, *p-value* <0.05).

## 3.3 Impact of shade on the aboveground morphology of sugar beet

In both experimental years, the shade treatments induced morphological changes in the sugar beet plants. In 2015, petiole length increased with decreasing available global radiation (Figure 24), resulting in significant taller petioles under shade treatments (CS and PS) than under NS treatments. In 2016, this was only true for the $PS_{pm}$ treatment at the two first sampling dates (Figure 24).

Figure 23 shows that this adaptation goes along with a significant change in the number of leaves per plant, LAI, and SLA under the shade treatments in 2015. Under the CS treatment, the number of leaves per plant as well as the LAI were reduced, while the mean single leaf area and the SLA increased as compared to the NS treatment. Nevertheless, if we look only at the first sampling date, observations are different. No significant differences have been observed in terms of LAI in the PS treatment as compared to NS, but we recorded a significant lower number of leaves resulting thus in a higher average single leaf area and higher SLA at the first sampling date. In contrast, in 2016, over the entire growing season, the number of leaves per plant, LAI, mean single leaf area and SLA were unaffected by both periodic shade treatments ($PS_{am}$, $PS_{pm}$) as compared to the NS treatment.

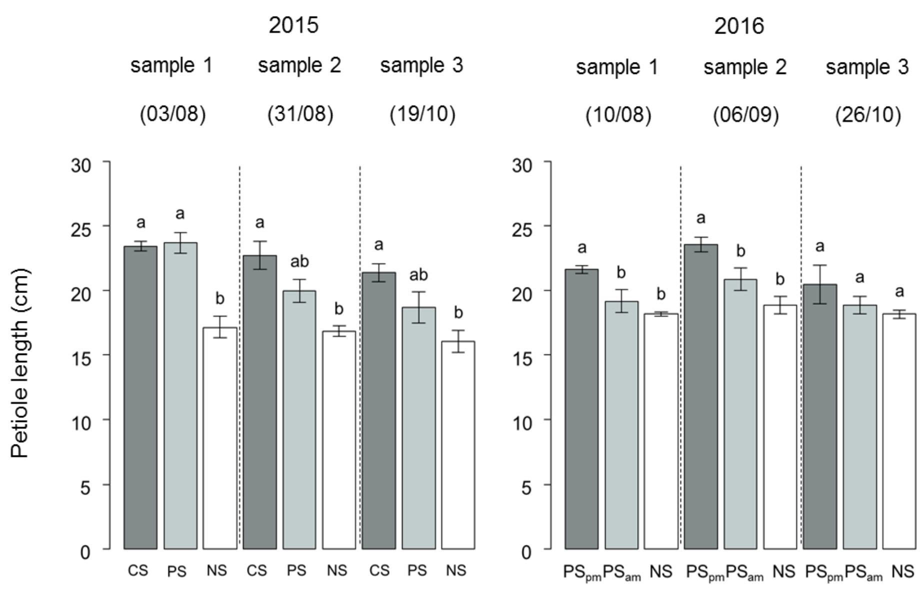



**Figure 24.** Mean petiole length (cm) for the growing season 2015 and 2016 at the three sampling dates. Vertical bars represent the standard error of the means and statistical significance of the equality between treatments is represented by the letters above the barplot (Tukey, *p-value* <0.05).

## 3.4 Impact of shade on sugar beet biomass partitioning, sugar yield and quality

Within the aboveground part of the sugar beet, the allocation of biomass between leaves and petioles changed with the light availability for the crops. Figure 25 shows that after the entire growing season the leaf to petiole ratio decreased with increasing shade. At harvest, the quantity of biomass allocated to the leaves was significantly reduced as compared to the proportion of biomass for the petioles under the shade treatments. This reduction reaches 10 % to 45 % under the PS and CS treatment in 2015, respectively, and 18 to 22 % under the $PS_{am}$ and $PS_{pm}$ treatment, respectively.

In both years, the total dry matter of the sugar beet was highest under the NS conditions and decreased with increasing shade. Figure 25 shows that, under the shaded treatments, root to shoot ratio was significantly lower as compared to the NS treatment. At harvest, in 2015, the quantity of root dry matter formed per gram of shoot dry matter was reduced by 71 % and 34 % under the CS and PS treatments, respectively, as compared to the NS treatment. In 2016, this proportion was decreased by 35 % and 14 %, under the $PS_{pm}$ and $PS_{am}$ treatments, respectively, as compared to the NS treatment. For all the treatments there is an increase of the root to shoot ratio due to the preferential accumulation of biomass into the roots towards the end of the growing season. In fact, apart from the CS treatment, the aboveground dry matter remained unaffected by the periodic shade treatments (PS, $PS_{am}$, $PS_{pm}$) as compared to the NS treatment. Under the CS treatment, the total sugar beet biomass reduction at harvest significantly relies on the reduction of both the total aboveground and the root dry matter, while the periodic shade treatments applied in 2015 and 2016 only affected the root dry matter (Table 7). In 2016, the root dry matter at harvest was 36 and 73 % lower under the PS and CS treatments respectively than without shade, while in 2016, the $PS_{am}$ and $PS_{pm}$ treatments induced a reduction of 18 and 36 %, respectively, as compared to the NS treatment (Table 7).

Furthermore, between the 1$^{st}$ sampling date and harvest, the daily rate of root dry matter accumulation in 2015 was halved under the PS treatment and reduced by 82 % under the CS treatment as compared to the NS treatment. In 2016, this growth rate was unaffected under the $PS_{am}$ treatment, while a decrease of 43 % was observed under the $PS_{pm}$ treatment as compared to the NS treatment (Table 7). Furthermore, as presented Figure 26, the root dry matter is clearly correlated to the cumulated incident global radiation in both years ($R^2 = 0.98$ in 2015 and $R^2 = 0.89$ in 2016).

Within the root, the ratio of dry matter to sugar slightly decreased with the light availability for the crops. In 2015, at harvest, the sugar content reached 17.96 % of the root fresh matter under the NS treatment and was significantly decreased by 4.34 and 7.68 % under the PS and CS treatment respectively (Table 7). In 2016, the sugar content in the roots of the shaded sugar beets was significantly reduced by 2.37 % and 2.43 % under the $PS_{am}$ and $PS_{pm}$ treatments, respectively (Table 7). Looking at the sugar production (t/ha), the pattern of sugar yield reduction with light availability followed the same trend as the root biomass accumulation under shade. The CS treatment induced a maximum yield reduction of 74 % in 2015, while the periodic shade treatment led to intermediate productivity decrease ranging from 38 % for the PS treatment in 2015 to 22 and 40 % for the $PS_{am}$ and $PS_{pm}$ treatments in 2016.

Furthermore, shade treatments do not only influence the final sugar yield, but also the beet quality. The concentration of root impurities, such as amino acids, potassium and sodium, was higher in both years and the amount of extractable sugar was significantly lower under the CS, $PS_{am}$ and $PS_{pm}$ treatments in 2016 as compared to the NS treatments (Table 7).

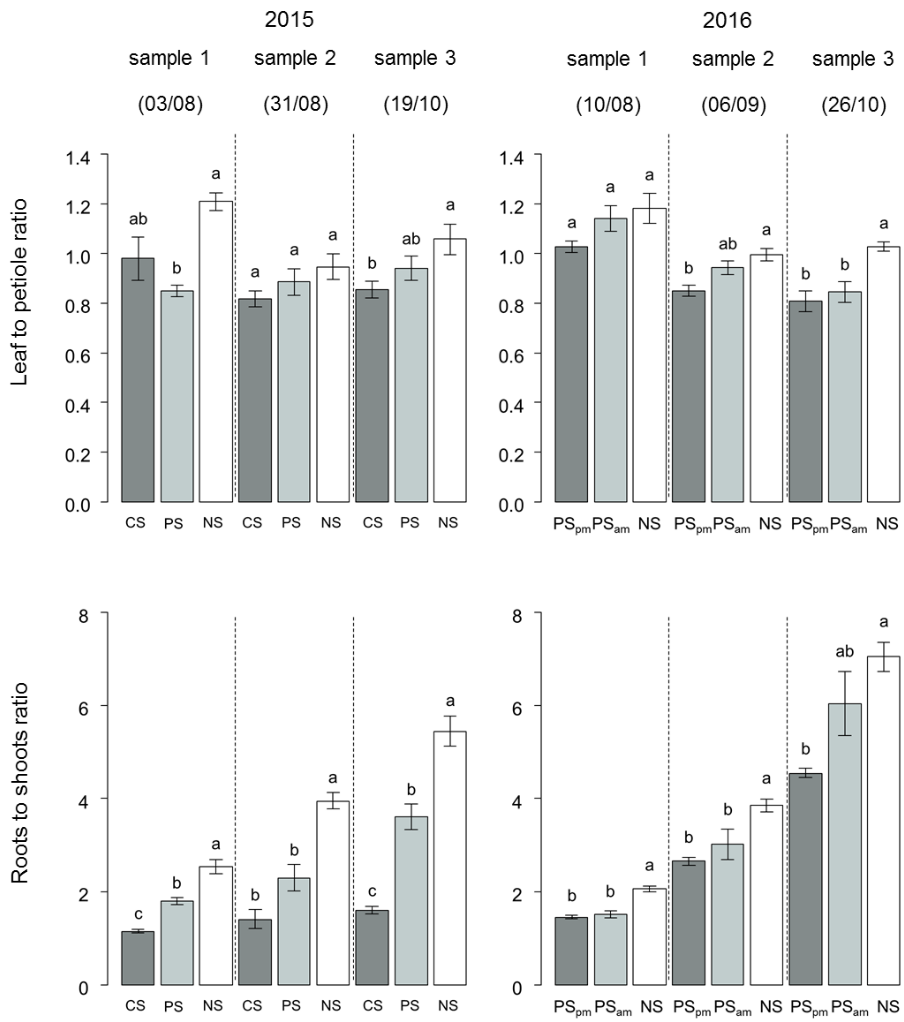



**Figure 25.** Leaf to petiole dry matter ratio and root to shoot dry matter ratio at the three sampling dates for the cropping season 2015 and 2016. Vertical bars represent the standard error of the means and statistical significance of the equality between treatments is represented by the letters above the barplot (Tukey, *p-value* <0.05).

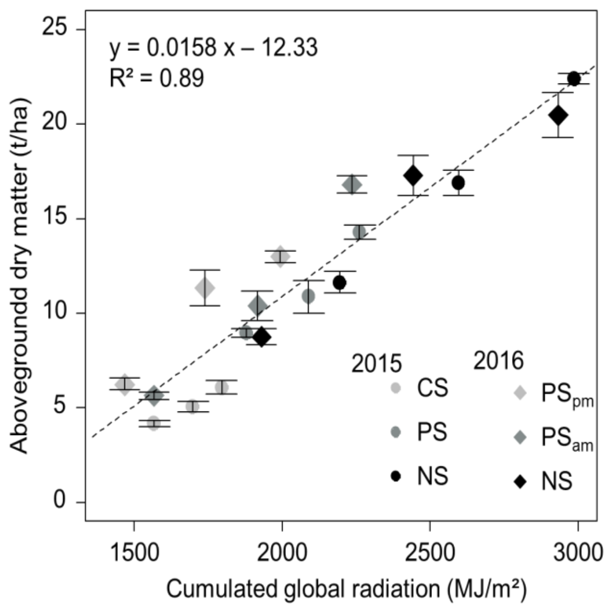



**Figure 26.** Relationship between accumulated roots dry matter (t/ha) and the cumulated global radiation received at the three sampling date under the no shade (NS), constant shade (CS) and periodic shade (PS, $PS_{am}$, $PS_{pm}$) treatments during the growing season 2015 and 2016.

# 4. Discussion

Studies interested in the influence of seasonal weather variability on sugar beet development recognized that amongst the different environmental variables, the amount of available light for the crop is a predominant factor driving the biomass accumulation after crop canopy closure (Scott and Jaggard, 2000). Nevertheless, crop growth not only depends on the global radiation cumulated over the whole growing season but also on the dynamics of its availability throughout the growing season. This observation is even more pertinent for agroforestry systems under which the crops are subjected to an intensification of shade following tree phenology and leaf apparition at the scale of the growing season. Several studies have revealed that crop responses to light reduction depend on the length and the severity of the reduction as well as on the stage of crop development when the reduction occurs (Dufour et al., 2013; Fischer, 1985; Marrou et al., 2013b; Varella et al., 2010). To our knowledge only one study focused on how different timing of light reduction (mid-June, mid-July, mid-August, from mid-June to harvest) affects sugar beet growth and yield (Watson et al., 1972). In the our study, the final root dry matter and sugar yield decreased for sugar beets affected by shade. Nevertheless, within the growing season, several crop growth characteristics (leaf area, water content, growth rate, dry matter partitioning) differed between the treatments according the developmental period within which the shade treatment had been applied. For example, applying shade during four consecutive weeks starting mid-July or mid-August significantly increased sugar beet leaf area index, while sugar beet leaf area was unaffected when shade was applied during the same duration but starting in mid-June and even significantly decreased when subjected to a continuous shade treatment from mid-June until harvest.

When growing under a reduced light quantity and quality (low red to far red ratio and reduced blue) environment, plants respond by adjusting a set of morphological and physiological traits such as petiole length, specific leaf area (SLA), leaf area (LAI), leaf biomass or chlorophyll content in order to optimize light capture and use (Valladares et al., 2007, 2003). Our experiment was no exception to this rule. In fact, sugar beet plants responded to the reduced light availability through elongation of their petioles. This common strategy of shade-avoidance has also been observed for other species such as alfalfa (Peri et al., 2001; Varella et al., 2010) and winter wheat (Li et al., 2010). As mentioned by Liu et al. (2016) this specific trait is established by the plant to overtop the neighboring species and thus alleviate the competition for light resources. Nevertheless, in a context under which the crop cannot escape the shade caused by a high canopy layer, such as within an agroforestry system, this adaptation remains neutral or is even costly for the crop. In our study, the leaf to stem ratio was negatively affected and the morphological adaptation can thus be seen as adverse or costly. In fact, under all shade treatments we applied, sugar beet directed more biomass into the petiole than into the leaves, while leaf area has been recognized as an important determinant of crop growth because it increases the potential of light interception (Milford et al., 1985). Furthermore, we observed that in the CS and PS shade treatments, this adaptation went along with a higher SLA than in the NS treatment at the first sampling date. Evans and Poorter (2001) reported a similar negative correlation between SLA and light available for the crop (Evans and Poorter, 2001). Again, by decreasing the ratio of leaf area to leaf dry mass under shade, the plant presumably increases its potential of light interception per unit of structural biomass invested in the leaves. It is thus an economical strategy to maintain sufficient productivity. In our studies, the higher SLA observed under the CS treatment tends to be related to low leaf dry matter content allocated to the leaves associated with a smaller number of leaves and thus larger and thinner individuals leaves. Likewise, sugar beet maintains a similar LAI under PS as under NS, while creating less biomass in those leaves, resulting in a higher SLA under the PS treatment. Paradoxically, in 2016, even though the shading treatment was applied earlier in the growing season than in 2015, no significant morphological changes of sugar beet leaves have been observed when subjected to periodic shade. Thus, it appears that the degree of adaptation depends on the level and the nature of the shade and it still remains unclear what are the underlying driving processes. Maybe, this can be explained by the fact that two different varieties have been used in both years. Nevertheless, the documented differences between those varieties mainly speak of resistance to nematodes, plant virus and fungi rather than canopy development and the adaptive potential of the plant to various environmental conditions.

In the literature, phenotypic plasticity in response to shade has been recognized as a compensatory process set up by the plant to alleviate the effect of stress and thus maintain an optimal productivity. Plants change over time, they readjust allocation, morphology and leaf physiology. Thus, the rate of leaf appearance, single leaf area, SLA, may change with plant size and growth rate. For sugar beet, the growth of the different parts of the plant and the sugar storage is continuous along the vegetative development period. The distinction between the different growth stages is not clearly noticeable. Nevertheless, Draycott (2006) showed that there is a gradual shift in the partitioning of the biomass accumulation from leaves to roots growth and sugar accumulation at the end of the growing season (Draycott, 2006). In this study, the plant morphological measurements have been performed relatively late in the growing season once the aboveground ground biomass was established. As mentioned by Liu et al. (2016), measuring SLA at harvest doesn't allow to evaluate whether the level of SLA has driven the performance of the plant within the growing season, or if it was a result of further adjustment occurring during the plant growth. Likewise, Milford et al. (1985) show that differences in leaf area early in the season appear to be associated to differences in leaf expansion rate more than to differences in leaf production. Thus, in order to evaluate the exact nature of the morphological adaptations and their influence on the final yield across the different treatments, measurements should be conducted in the early growth stage.

Final sugar yield can be expressed as the product of the total amount of dry matter accumulated during the season, the partitioning of the biomass to the storage roots and the proportion of dry matter stored as sucrose in the roots. When sugar beet copes with shade situations, the storage in the roots and thus the final sugar yield are drastically reduced. Several studies showed that final total dry matter, roots dry matter and sugar yield are proportional to the amount of light intercepted by the foliage along the growing season (Draycott, 2006; Pidgeon et al., 2001; Werker and Jaggard, 1998). Watson et al. (1972) observed a decrease of 50 % of the final root dry matter of sugar beet under continuous shade (44.3 % light reduction from mid-June to -harvest) as compared to full light conditions. These results are consistent with our observations, but the reduction we observed was even more important due to a more intense shade application. Our data showed that a reduction of 64 % of the available light cumulated during a shade period of 132 days induced a final dry matter root reduction of 70 % under the CS treatment in 2015. Under the periodic shade treatment (PS, $PS_{am}$, $PS_{pm}$) we observed a similar pattern: the stronger the reduction of the light availability, the more the final root dry matter decreased. Furthermore, contrary to Watson et al. (1972), root water content significantly increased under the CS and PS treatment in 2015, while there were no differences in 2016 as compared to the NS treatment. Thus, the decrease of the final sugar yield of the plant under the shade treatment is mainly a consequence of the decrease in root biomass and sugar content of the root and this in both experimental years.

Finally, not only final sugar yield, but also sugar beet quality has to be taken into account, since quality affects the extraction efficiency and thus the economic viability of the beet processing (Campbell, 2002). Several authors observed a negative correlation between sugar content and impurities such as potassium, sodium and amino nitrogen (Draycott, 2006; Hoffmann, 2010). Just like these authors, we measured an increase of the content of impurities and thus a decrease of potential sugar extractability with increasing shade.

Although some morphological changes have been observed under the shade treatments, they were insufficient to maintain an optimal root growth and can even be 'costly' for the sugar beet. These observations challenge breeding strategies for agroforestry contexts, because it suggests that genetic factors implied in the plasticity of the plant subjected to reduced light environment should be taken into account to improve the sugar beet growth under a reduced light environment.

Finally, one should not forget that in a real agroforestry context (as compared to the artificial shade structures used in this study), there is not only an interaction for light between tree and crop, but a whole range of biotic and abiotic interactions take place which may also affect crop responses. Studies on the impact of weather variables on sugar beet growth found that temperature strongly influences its early growth, and that drought stress often restricts plant growth (Albayrak and Çamaş, 2007; Kenter et al., 2006; Pidgeon et al., 2001; Werker and Jaggard, 1998). Studying sugar beet in an alley cropping system in Germany during a dry summer, Mirck et al. (2016) shows that yield was reduced near the hedgerow, while higher yield were recorded at an intermediary distance from the row as compared to a nearby reference field. The authors explain this results by the modification of several abiotic factors along a transect from the hedgerow to the middle of the plot. On the leeward side of the hedgerow, due to wind sheltering, higher soil moisture value have been observed as well as change in soil and air temperature and evapotranspiration (Mirck et al., 2016).

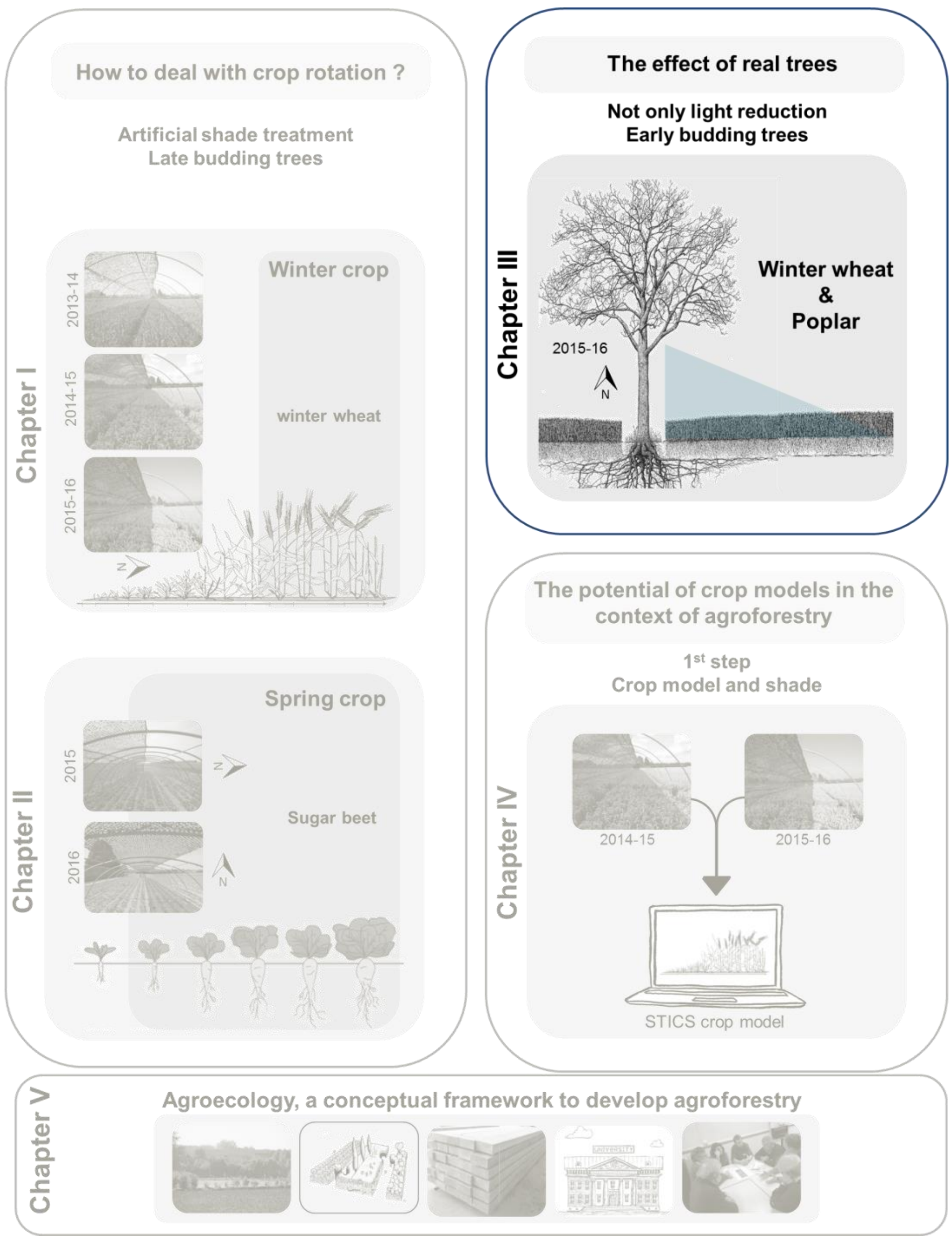
The use of an artificial shade structure allows reproducing a contrasted and dynamic light pattern from extreme shade to different types of fluctuating light environments, but it remains difficult to relate this environment to a specific, similar agroforestry system. The military cloth used here does not entirely reproduce the shade characteristics produced by tree leaves. In addition, various combinations of tree ages, species and plot arrangements could result in the shade treatments we presented. Nevertheless, we showed in a previous study on winter wheat that the CS shade treatment can be expected on only around 10 % of the cropped area under 30 to 50 years old trees within an agroforestry system where the tree lines are spaced at 35 x 7 meter and with tree lines following an East-West orientation (Artru et al., 2017). The proportion of daily cumulated light observed under the periodic shade treatments will occur earlier in the agroforestry revolution and a larger proportion of the cropped area is concerned.

# 5. Conclusion

Dealing with crop rotation containing spring crops within agroforestry systems challenges the stand design and management as well as the crop breeding practices (e.g. shade tolerance). In fact even when implementing late budding tree species, there is an important overlap for the resource use between the tree and spring crops. In this research paper, the artificial shade structure implemented on sugar beet allowed to isolate the effect of competition for light from other types of tree-crop interactions. In 2015 we observed increased SLA and single leaf areas alongside costly shade avoidance strategies (such as taller petioles). This was not visible in 2016. Nevertheless, the negative effect of shade on final root dry matter and sugar yield was consistent over the two years. This means that, unless varieties can be developed with better strategies to increase their efficiency of light use, the potential of sugar beet in agroforestry context is rather limited.

# Chapter III.

## Winter wheat growth under real trees



# Winter wheat response under a gradient of shade from poplar trees, Herzele, Flanders

During the growing season 2015-16, we followed the growth and productivity of winter wheat under poplar trees, in Herzele, Flanders. In Belgium, silvoarable agroforestry systems remain scarce in the agricultural landscape. In order to circumvent this drawback, we selected as a proxy an arable plot bordered by a tree row, to evaluate the effects of trees on a cropped area under Belgian soil and climatic conditions. This study is part of a larger project in Flanders, "Agroforestry Vlaanderen" (http://www.agroforestryvlaanderen.be/), coordinated by the *Instituut voor Landbouw- en Visserijonderzoek* (ILVO) institute.

The objective was to evaluate the growth and productivity of winter wheat under real tree conditions, where potential biotic and abiotic interactions other than only light reduction may occur.

## 1. Materials and methods

### 1.1 Field experiment

We conducted a final agronomic trial on winter wheat using real trees in order to assess the difference between artificial and real shade. The trial was conducted during the growing season 2015-16, at a plot bordered by a poplar tree row (*Populus x canadensis*), in the East Flanders province, Belgium (50°52'.88'' N, 3°54'19.16''E). The climate is temperate maritime and the soil is classified as Cutanic Luvisol (FAO, 2014).

Winter wheat (*T. aestivum* L., cultivar Mentor) was sown on 8 November 2015, with drill lines following the tree line orientation. The preceding crop was maize, in 2014-15. A total amount of 162 units of nitrogen per hectare and per year was applied, at one time, in April. During the growing seasons, one herbicide, two plant growth regulators, three fungicides, and one insecticide were applied in spring. The winter wheat was harvested on 5 August 2016 on sub-samples, and then on 7 August 2016 with a combine harvester.

The tree row is composed of seven poplars spaced on average 6 m from each other. The trees are located at the west side of the cropped area and follow an approximately north-south orientation. The poplar trees in the row present a homogeneous age, estimated at 35 years old.

## 1.2 Experimental set-up and measurements

Measurements were taken at five locations, along four transects (T1, T2, T3, T4) perpendicular to the tree row, as well as along two transects (NT1, NT2) in a part of the plot without trees (Figure 27). The transects without a tree row (NT1 and NT2) were used as a reference. Within each transect, sampling was performed at 3, 5, 10, 20, and 30 m from the tree row.

Global radiation at the crop canopy level was recorded from 1 April 2016 to harvest on 5 August 2016, using five quantum sensors (CS300 - Campbell Scientific Inc., USA -accuracy ± 5 % for the daily global radiation), and recorded every minute by a data logger (CR1000 – Campbell Scientific Inc., USA). At each of the sampling distances, a sensor was installed along the transect (see Figure 27).

During the growing season, winter wheat was sampled at flowering (14 June) and at harvest (5 August), at each distance and each transect. At flowering, the aboveground dry matter biomass (straw and spike DM) and the total leaf area index (LAI) were assessed from samples taken from three adjacent sowing lines of 40 cm length and three adjacent 10 cm bands. At harvest, the aboveground dry matter biomass (DM) and the grain weight were obtained from samples taken from three adjacent sowing lines of 50 cm width. The final grain yield (t/ha) was also gathered, by harvesting three replicates of around 9 $m^2$ (1.5m by approximately 6 m) under the trees for each location, and two replicates of around 22.5$m^2$ (1.5m x around 15 m) in the reference area, using a combine harvester. To assess dry matter distribution, wheat plants were subdivided into spikes and straw, dried at 60°C for 10 days, and weighed. LAI was determined by scanning the surface of the plant leaves using image J software, and was then defined as the total leaf area per unit of ground surface area. On the last samples at harvest, we assessed the number of spikes per $m^2$, the grain number per spike, and the grain size (using three sieves: 2.8, 2.5, 2.2 mm). The final yield is expressed in t/ha at 15 % humidity. We calculated the number of grains per $m^2$ from thousand kernel weight (g/1000 grains) and grain weight (t/ha). Again, the harvest index (HI) was defined as the ratio of grain weight to total plant aboveground biomass.

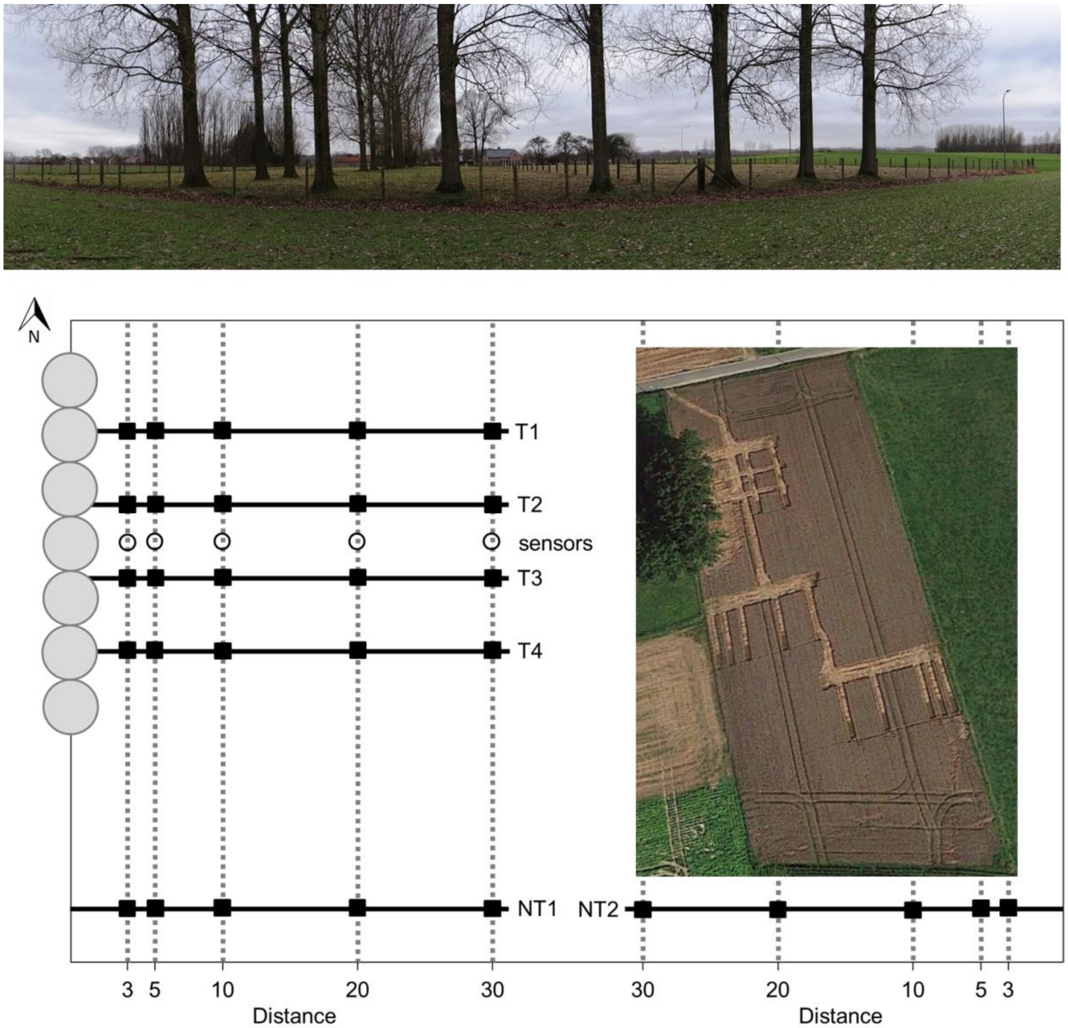



**Figure 27.** Overview of the experiment design. The black lines indicate the transect location in the part of the plot with trees (T1, T2, T3, and T4) and in the reference part without trees (NT1 and NT2). The black squares represent the sampling area at different distances from the border, and the open circles represent the light sensor positions along the transect. Aerial photography was taken in August 2016, after harvest with the combine harvester.

## 1.3 Statistical analysis

All statistical analyses were conducted using R (R Development Core Team, 2009). Analyses of variance (ANOVA) and Tukey range tests were used on the no tree part (NT) dataset to assess the effect of the heterogeneity of the plot, and on the tree (T) treatment dataset to evaluate the effect of distance on crop and productivity. Generalised linear mixed models were then used for each variable, with 'distance' (3, 5, 10, 20, 30 m) and 'treatment' (with tree (T), without tree (NT)) as fixed effects, and the replicate at each distance as random criteria (vegan package). The interaction between distance and treatment was also tested. All the models were first evaluated with only treatment as a fixed effect.

# 2. Results

## 2.1 Global radiation transmitted below artificial shade treatment and trees

We analysed the global radiation dynamics diurnally and seasonally. Under the poplars, the wheat experienced shade conditions during the afternoon, with variable duration depending on the distance to the tree line. Figure 28 gives an example of the diurnal variation of global radiation along the transect from 3 m to 30 m from the trees, on 7 July 2016, and illustrates the spatial gradient and temporal dynamics of light penetrating through the trees. Figure 28 shows the cumulative transmitted global radiation from sensor installation (1 April 1 2016) until harvest (5 August 2016). The intensification of shade at the different locations depends on the poplar tree leaf appearance, since sensors were installed before tree budburst. At the end of this period, the result is a reduction in cumulated transmitted global radiation, ranging from 38 % at 3 m, to 8 % at 20 m, compared to the cumulative radiation at 30 m (shade-free).

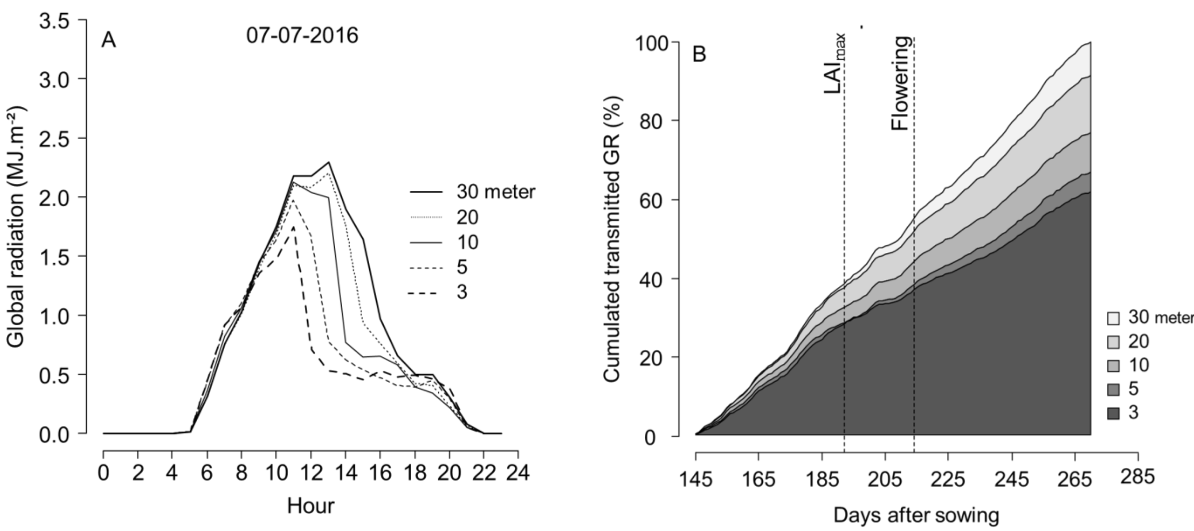



**Figure 28.** A: example of the daily dynamics of global radiation (MJ/m²) under the poplar trees, measured on 7 July 2016 along a transect at 3, 5, 10, 20, and 30 m from the tree line. B: daily cumulative transmitted global radiation (GR %) under the poplar trees; transmitted GR is expressed as the percentage of the cumulated GR in full sun at the end of the cropping seasons; vertical bars indicate the date of $LAI_{max}$, and the flowering stage of wheat.

With respect to the phenological development of the crop, we observed different amounts of cumulative radiation for the three main periods in the growing cycle with distinct shade patterns. Under the poplar trees, from $LAI_{max}$ to flowering, the global radiation received by the crop was reduced by 14 %, 30 %, 42 %, and 48 % respectively at 20, 10, 5, and 3 m, as compared to the cumulated global radiation at 30 m. Then, from flowering to harvest the reduction varied from 12 % to 44 % (Table 8).

**Table 8.** Cumulated transmitted global radiation under the alley cropping system. Under the alley cropping system, the global radiation was cumulated for the period from sensor installation to harvest, from $LAI_{max}$ to flowering and from flowering to harvest along the transect from the tree to the middle of the plot (3, 5, 10, 20, 30 m).

| | | Cumulated transmitted global radiation ($MJ/m^2$) – Percentage of transmitted global radiation (%) | | |
|---|---|---|---|---|
| | | **Sensor installation to harvest** | **$LAI_{max}$ to flowering** | **Flowering to harvest** |
| **Alley cropping** | Days after sowing | 145 – 270 | 192 – 214 | 214 – 270 |
| | 30 m | 1795 – 100 | 286 – 100 | 825 – 100 |
| | 20 m | 1642 – 92 | 247 – 86 | 727 – 88 |
| | 10 m | 1380 – 77 | 199 – 70 | 602 – 73 |
| | 5 m | 1203 – 67 | 167 – 58 | 524 – 64 |
| | 3 m | 1114 – 62 | 150 – 52 | 458 – 56 |

## 2.2 The effect of shade on LAI and wheat biomass

Although poplar budburst occurred before the $LAI_{max}$ stage, the shade experienced by the winter wheat did not affect $LAI_{max}$ (*p.value*: 0.64). Observing aboveground biomass at flowering and harvest in the tree-bordered part of the plot, there is a gradual reduction in straw and spike dry matter, depending on the distance to the tree line. At harvest, straw dry matter was significantly reduced, by 55 %, 15 %, and 27 % at 3, 5, and 10 m respectively, as compared to the biomass at 30 m (*p.value*: $2.2.10^{-3}$). Likewise, spike dry matter decreased significantly, by 34 %, 13 %, and 18 % at 3, 5, and 10 m respectively, as compared to the biomass at 30 m (*p.value*: $2.4.10^{-3}$). Nevertheless, for both variables, no significant differences were observed between the biomass at 20 m and at 30 m. Furthermore, Figure 29 shows that, with the exception of the biomass at 30 m, at flowering and harvest, straw and spike dry matter remained on average smaller on the part of the plot with trees, as compared to the part without trees. In the part without trees, no significant differences for the straw and spike dry matter biomass at both sampling dates were observed along the transect between the different distances (Figure 29). Nevertheless, the data recorded at 30 m are highly different from the rest. This pattern was observable for all of the other variables measured at this location. Data from soil analysis (Ca, K, Mg, P, Na, C, pH-KCl), performed along the transect no particular soil heterogeneity of the plot at this location was observed. Between flowering and harvest, spike biomass increased in both situations, with a significant influence of the distance and the treatment (Table 9).

**Table 9.** Summary of the significance level (*p.value*) from linear model analysis for the different wheat variables followed at flowering and at harvest.

| | Variables | | Fixed factors | | Interaction |
|---|---|---|---|---|---|
| | | | Distance<br>3, 5, 10, 20, 30 [m] | Treatment<br>Tree *vs* no Tree | Distance x Treatment |
| Flowering | Straw dry matter | [g/m²] | 2.9.10⁻³ | 0.08 | 0.36 |
| | Spike dry matter | [g/m²] | 3.5.10⁻⁵ | 3.3.10⁻⁴ | 0.06 |
| | Spike number | [#/m²] | 3.3.10⁻³ | 0.58 | 0.85 |
| Harvest | Straw dry matter | [g/m²] | 1.7.10⁻³ | 2.3.10⁻³ | 0.03 |
| | Spike dry matter | [g/m²] | 1.1.10⁻³ | 6.1.10⁻⁶ | 1.9.10⁻³ |
| | Spike number | [#/m²] | 1.5.10⁻³ | 2.8.10⁻³ | 0.03 |
| | Grain number | [#/m²] | 1.5.10⁻⁶ | 1.3.10⁻⁷ | 4.3.10⁻⁵ |
| | Grain per spike | [#] | 1.3.10⁻⁸ | 1.8.10⁻⁷ | 4.9.10⁻⁶ |
| | PMG | [g] | 1.9.10⁻⁶ | 2.3.10⁻⁴ | 2.4.10⁻³ |
| | Grain yield | [t/ha] | 1.9.10⁻³ | 2.2.10⁻⁵ | 2.4.10⁻³ |

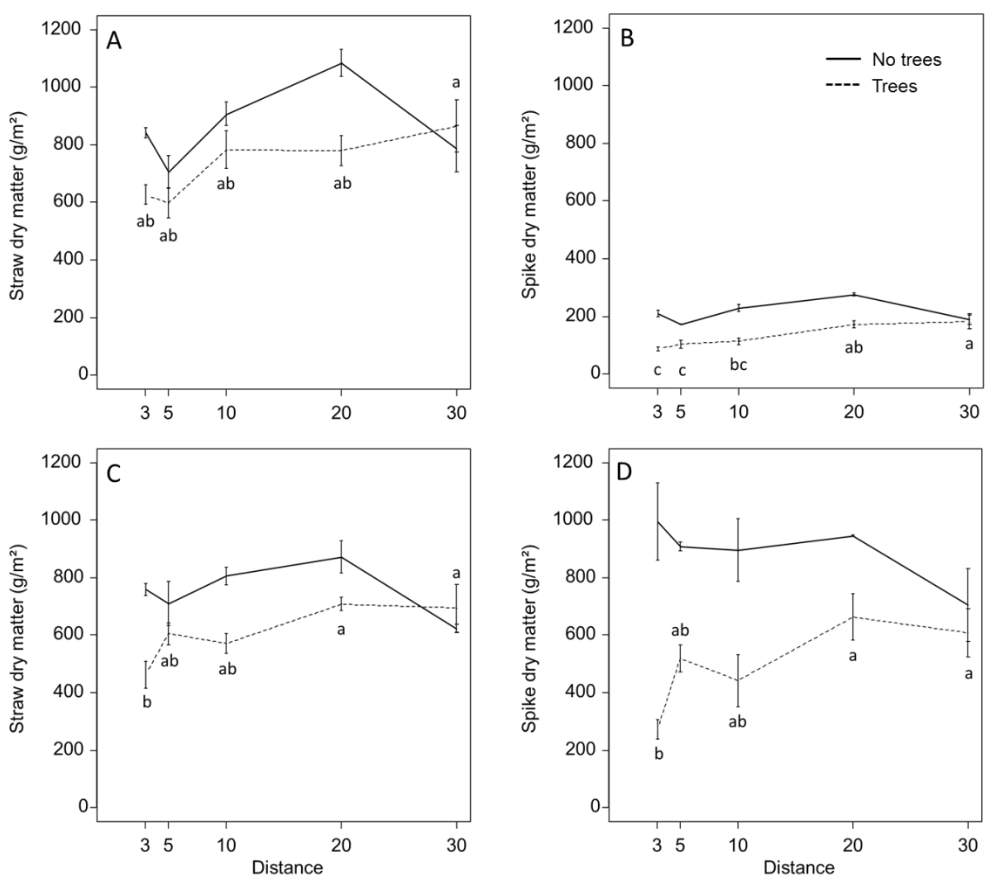



**Figure 29.** Mean straw and spike dry matter (DM, g/m$^2$) at flowering (A and B), and at harvest (C and D), at difference distances (3, 5, 10, 20, 30 m) from the tree row (trees), and from the field edge, in a part of the plot without trees (no trees). Vertical bars represent the standard error of the means. The letters represent the difference in the data between the distances in the part of the plot with the trees (Tukey test, *p.value* < 0.05). For the part without trees, no significant differences were shown between the distances.

## 2.3 The effect of shade on wheat production and yield components

In the tree-bordered field, data from the combine harvester show that final grain yield was significantly highest in the part of the plot without trees, even when compared to the data recorded at 20 m and 30 m from the trees (- 31 % and -29 % respectively), which are under similar light conditions (Table 9, Figure 30). The presence of the trees induced a significant yield reduction at 3 m (-41 %), 5 m (-11 %), and 10 m (-30 %), as compared to the data at 30 m. No significant difference was observed between productivity at 20 m and 30 m from the trees (Figure III-4). The final grain yield, observed from manual sampling, follows the same trend in the part with the trees. In the reference part of the plot without trees, the final grain yield, computed from manual sampling at 30 m, is clearly smaller than that from the combine harvester at the same distance (Figure 30). According to the soil sampling, on average, no particular heterogeneity was observed at 30 m. This difference highlights the limits of small sampling methodology (3 rows of 50 cm), as compared to larger sampling with the combine harvester, since the latter allows us to limit the influence of outliers or extreme observations.

The presence of trees not only influenced the total grain yield, but also the yield components (ie. number of spikes per $m^2$, number of grains per $m^2$, number of grains per spike, thousand grain weight, and grain size), with a significant impact of distance from the trees (Table 9, Figure 31). The number of spikes and grains per $m^2$, as well as the number of grains per spike, follows the same trend in response to the presence of trees. In fact, we observed a significant reduction in the number of grains per $m^2$ and per spike at 3 m (-67 % and -48 %, respectively) and 10 m (-45 % and -37 %, respectively), than at 5 m (-35 % and -26 %, respectively) and 20 m (-3 % and -5 %, respectively), as compared to the data at 30 m. Nevertheless, the thousand grain weight followed the opposite trend, with higher weights near the trees, as compared to the 30 m data. Finally, the presence of the trees had a negative impact on the proportion of large grain sizes, favouring intermediate ones (Figure 32).

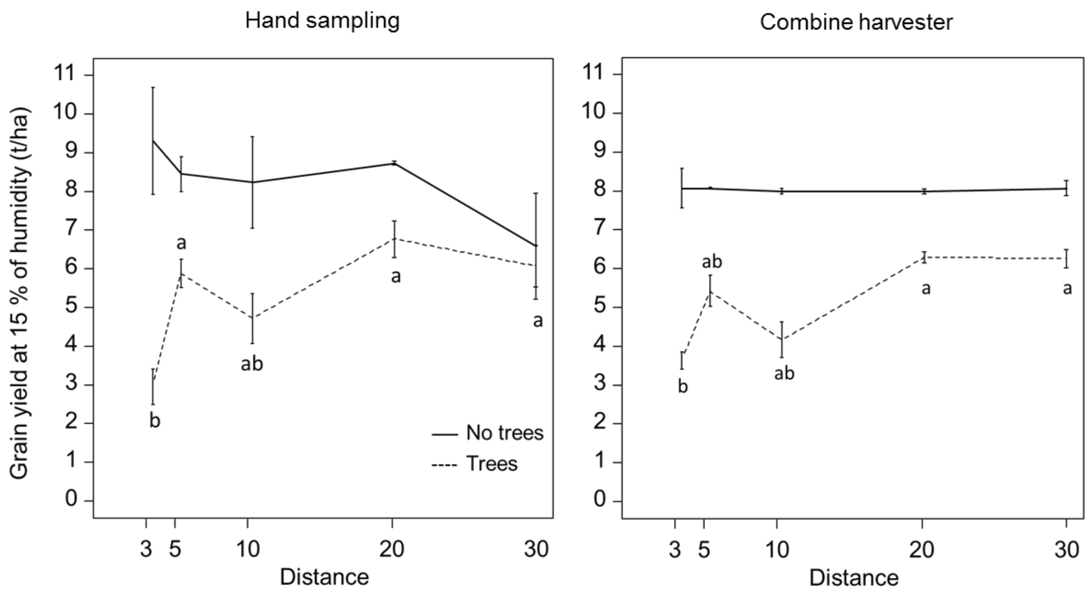



**Figure 30.** Mean final grain yield at 15 % of humidity (t/ha), obtained by hand sampling and combine harvester, at difference distances (3, 5, 10, 20, 30 m) from the tree row (trees) and from the field edge in a part of the plot without trees (no trees). Vertical bars represent the standard error of the means. The letters represent the difference in the data between the distances in the part of the plot with the trees (Tukey test, *p.value* < 0.05). For the part without trees no significant differences were shown between the distances.

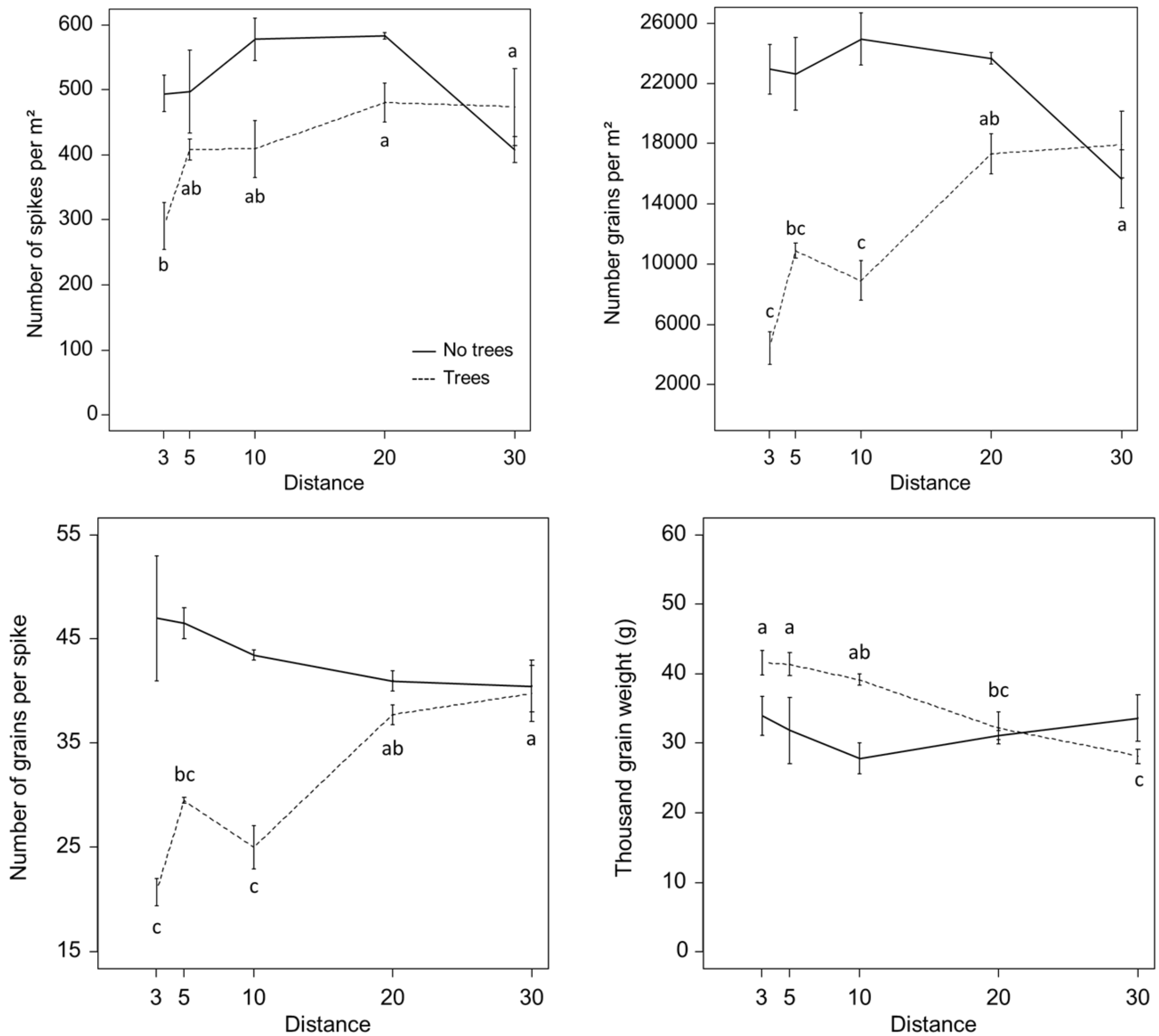



**Figure 31.** Final yield components (number of spikes per m², thousand grain weight (g), number of grains per m², and grain number per spike) at different distances (3, 5, 10, 20, 30 m) from the tree row (trees) and from the field edge in a part of the plot without trees (no trees). Vertical bars represent the standard error of the means. The letters represent the difference in the data between the distances in the part of the plot with the trees (Tukey test, *p.value* < 0.05). For the part without trees, no significant differences were shown between the distances.

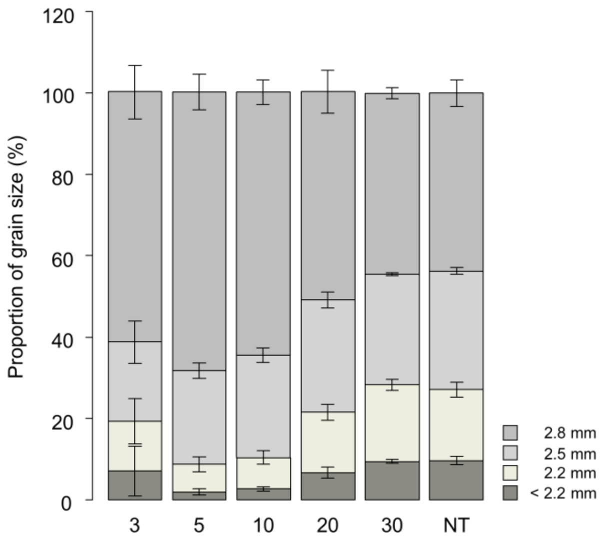



**Figure 32.** Proportion of grain size (2.8 mm, 2.5 mm, 2.2 mm, and less than 2.2 mm) at the different distances from the poplar trees to the middle of the plot (3, 5, 10, 20, 30 m), and from the part of the plot without trees (NT).

# 3. Discussion

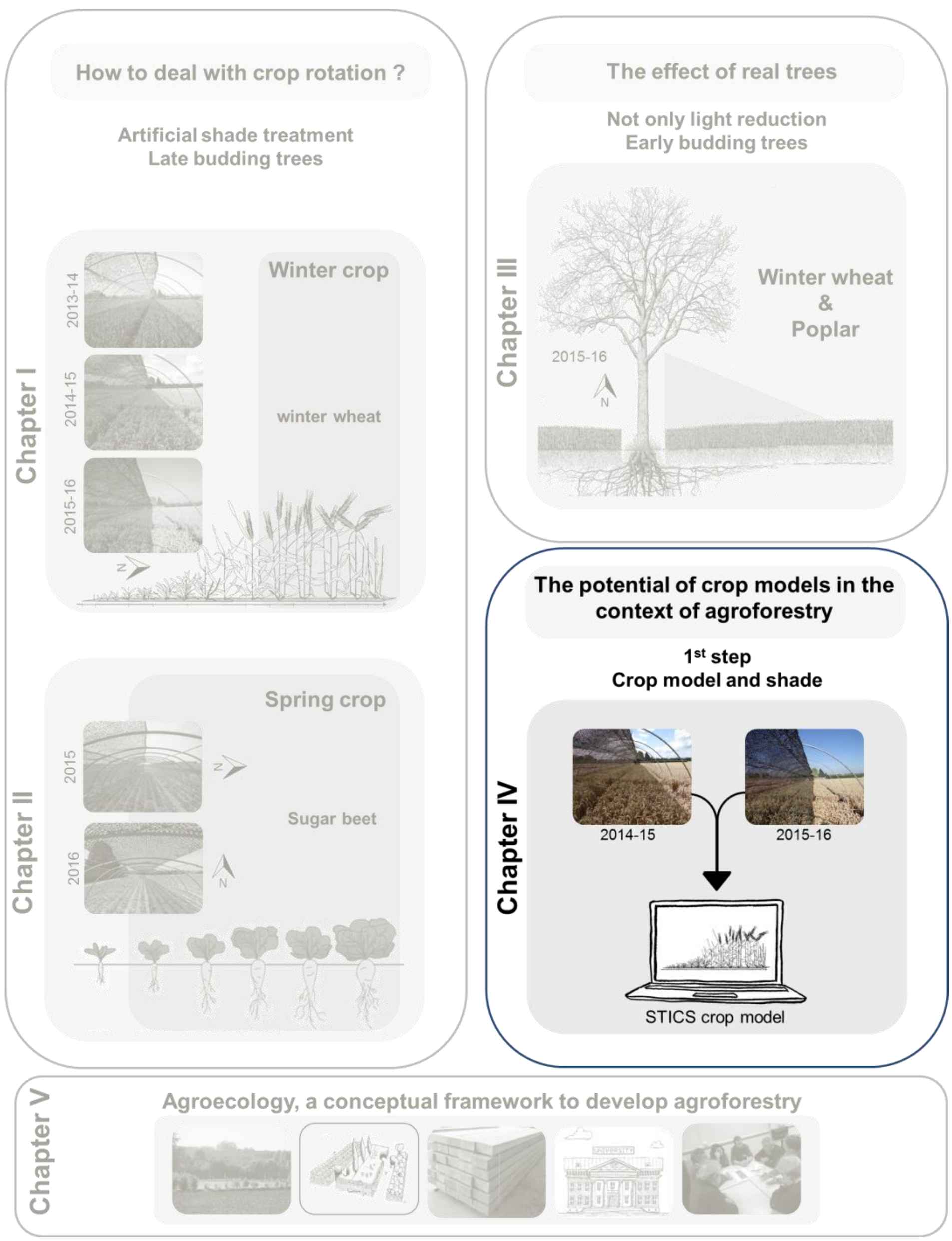
In the tree-bordered part of the plot, the winter wheat plants grew in a complex light environment which varies in intensity, frequency, and space. At the daily timescale, the north-south orientation of the poplar trees only induces shade above the crop in the afternoon. At the scale of the growing season, we observe a progressive increase in shade intensity under the poplar trees with the expansion of the leaves. Furthermore, the crop may already encounter a light reduction from the beginning of the growing season, since even without leaves a tree's trunk and branches induce shade on the cropped area. Using the Hi-sAFe silvoarable model, Talbot et al. (2012) predict that, within an hybrid walnut stand (156 trees/ha), the winter photosynthetic active radiation transmitted can be reduced up to 29 % by leafless trees of 15 m high. Nevertheless, to our knowledge, no studies have been conducted to quantify the light reduction induced by leafless trees, and its impact on crop emergence and growth, while several studies have shown that the magnitude of wheat response to light availability varies with the level and period of shade application (Artru et al., 2017; Demotes-Mainard and Jeuffroy, 2004; Dufour et al., 2013; Fischer and Stockman, 1980).

No morphological adaptation in terms of $LAI_{max}$ was observed along the transect under the poplar trees. Photoacclimation processes might have occurred, but complementary measurements (eg. photosynthetic rate measurement) should have been done to correctly assess this question.

With regard to the final yield components, the results obtained corroborate other research, demonstrating that applying shade over a period of around 30 days before flowering affects final yield through the number of grains per $m^2$, because of the change in numbers of grains per spike (Abbate et al., 1997; Artru et al., 2017; Demotes-Mainard and Jeuffroy, 2004; Fischer and Stockman, 1980). Furthermore—as has been reported by several studies—both the number of grains per $m^2$ and the grain weight decrease when winter wheat is under shade from flowering to maturity (Artru et al., 2017; Estrada-Campuzano et al., 2008). In our study, in the area with trees, the number of grains per $m^2$ is positively correlated with light availability, resulting in a smaller number of grains per $m^2$ under the strongest light reduction, at 3 m from the trees. Nevertheless, thousand grain weights remain higher near the tree, where the shade is more pronounced in the tree-bordered field. According to the literature concerning post-flowering shade, grain weight can be affected by shade through an alteration in photosynthetic activity, as well as by a redistribution of vegetative reserves to the grains (Herzog, 1986; Plaut et al., 2004; Schnyder, 1993). In this experiment, the higher grain weight observed near the trees can probably be explained by the significant decrease in the number of grains per spike, allowing them to be fully filled, even if the pool of assimilate accumulated before flowering and produced by photosynthesis during grain filling was reduced by the shade. This could also be explained by the fact that, near the tree, a delay in physiological maturity was observed, with winter wheat maintaining green leaves for a longer period. This persistence of green leaves can enhance the final yield by extending the period of carbon translocation. Finally, although a number of studies concerned with crops and shade have reported similar trends in relative yield (ie. the ratio between intercrops yield and sole crop yield), the magnitude of the competition often differs, and has varied amongst the systems tested (Artru et al., 2017; Bouttier et al., 2014; Chirko et al., 1996; Dufour et al., 2013; Li et al., 2008; Reynolds et al., 2007; Rivest et al., 2009; Varella et al., 2010). In a real agroforestry system, we should keep in mind that other interactions than light competition may occur, which may result in differing final effects. Furthermore, the system followed in Herzele is only a proxy of an intensive silvoarable agroforestry system. The arable field was only bordered on one side by the tree row, while in an intensive silvoarable agroforestry system the presence of several tree rows within the cropped area may intensify the interactions, depending on the plot design and tree management. Moreover, the trees in the tree-bordered field are not managed as would be appropriate in an agroforestry system. In fact, the poplars had been thinly pruned at around 3 m, and several branches were found in the cropped area, due to significant levels of wind during the growing season, inducing heterogeneity in final yield at the plot scale. Within silvoarable agroforestry systems, formative pruning of the trees is recommended to achieve a straight stem free from branches, both in order to produce valuable wood and to facilitate crop management with agricultural machinery near the tree rows—as well as to prevent branches from falling into the cropped area. The choice of tree management will obviously depend on tree species and production goals. Furthermore, pruning height may influence the microclimatic conditions in the cropped area—such as light availability for the crop—and thus influence the final crop yield. In their study, Dufour et al. (2016) show that poplars (8 years old and around 22 m high), pruned up to 6 m high, induce a reduction of 65 % in final grain yield of durum wheat, while when pruned at 10 m height the reduction decreases to 43 %, compared to sole crop control (Dufour et al., 2016).

# Chapter IV.

## Using a crop model to assess agroforestry practices



# Using a crop model to assess agroforestry practices: does STICS crop model correctly simulate crop growth and productivity under shade?

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# Abstract

Most crop models have been developed with crops growing under full sunlight conditions and they commonly use daily cumulated global radiation as part of the climatic input data. This approach neglects the spatio-temporal dimension of the light reduction experienced by the crop in agroforestry systems. In this study, we evaluate the ability of the crop model STICS to predict winter wheat (*Triticum aestivum* L.) growth and yield under three distinct light conditions using field observations from a two year artificial shade experiment. The shade structure induced a continuous shade (CS) treatment characterized by a reduction of the proportion of light during the entire day and a periodic shade (PS) treatment defined by an intermittent shade varying on the plot throughout the day. These two shade conditions were compared to a no shade treatment (NS) receiving 100 % of the available light. The model accurately predicted the timing of the grain maturity stage under the PS treatment by reducing the daily global radiation only. A correct prediction of this growth stage in the CS treatment required a decrease of the daily maximum air temperature in addition to the reduction of global radiation. Overall, the model accurately reproduces the total aboveground dry matter dynamics under the CS and NS treatments, but did not simulate the reduction observed under the PS treatment correctly. Three parameters (*nbjgrain*, *cgrain* and $cgrain_{vo}$) involved in the determination of the number of grains have been calibrated with the NS treatment data and were then used to predict the crop behavior under the shaded treatments. Using this adjusted parameter set, the STICS model gave a good prediction of the grain number under all treatments. Nevertheless, the simulation of final grain yield under the shade treatments was not satisfactory yet, presumably due to an overestimation of the reallocation of the biomass between shoots and grains. Improving the prediction of these reallocation processes is challenging and critical to improve the simulation of crop behavior under fluctuating light environments such as encountered in agroforestry systems.

# Keywords

STICS model, agroforestry, shade, winter wheat, grain yield, grain number

# 1. Introduction

Within silvoarable agroforestry systems, the presence of a tree canopy reduces the incident light for the crop and induces a heterogeneous spatio-temporal light pattern, next to the competition for water and nutrients. At the daily time scale, the tree canopy induces a dynamic light environment according to the path of the sun, the field configuration, the species choice and tree management (Liu, 1991). At the scale of a growing season, the crop is subjected to an intensification of shade following the tree phenology and leaf apparition. Finally, the light environment evolves over the years according to the tree growth. These effects can be minimized using well-thought implantation of the trees with respect to the sun, an adapted tree density and an appropriate tree species choice and management (Cannell et al., 1996; García-Barrios and Ong, 2004), even though they cannot be totally removed. In order to support a better management of new agroforestry systems in Europe, it is important to quantify and predict the potential impact of this specific light environment on crop productivity, since light is involved in most plant processes (e.g. photosynthesis or transpiration).

Field experiments remain time-consuming and expensive, because of the numerous potential combinations between tree and crop species, the variety of pedo-climatic environments and practices as well as the long term dynamics of these mixed systems (Knörzer et al., 2011). In this context, crop models are powerful research tools that can help to improve our understanding of crop growth under reduced light conditions. Since extended time series and various conditions can be simulated, they can integrate climatic variability and long term effects (Dumont et al., 2015; Palosuo et al., 2011). Crop models can also be used to evaluate different field designs (Talbot, 2012) and management strategies for agroforestry (Chimonyo et al., 2015).

In a recent review, Luedeling et al. (2016) give an overview of eight existing models or modelling frameworks for agroforestry systems. Most of these models share a common general framework, but they can be classified according to the level of complexity with which the processes are described. Firstly, we can separate process-based from empirical models. Process-based models describe the crop and tree growth in interaction with it is environment in terms of biophysical laws, whereas empirical models use mathematical relationships independent from these laws and obtained through experimental observations. A second big difference is the spatio-temporal discretization used by the model. Since questions can arise on the one hand on interactions at the daily timescale and on the other hand on long term effects (> 20 years), the models should maintain a balance between the accuracy with which single processes are described, the system approach and computation time (Leroy et al., 2009; Malézieux et al., 2009; Roupsard et al., 2008) and therefore the discretization should be adapted to the modelling objectives.

In a review comparing representative multi-species system models, Malézieux (2009) separated models implementing a process description at a yearly (Yield-SAFE, COMMIX, SORTIE/BC, SexI-FS) and daily time step (CROPSYS, STICS, GEMINI, WaNuLCAS, Hi-sAFe). However, even the daily time step is rather large if one needs to take into account specific physiological reactions of plants to changes in their environment. Since the light environment in agroforestry systems can change considerably during the day, a time step even smaller than a day could be necessary to take into account the biophysical consequences of this environment. Models running at a daily time scale inherently neglect the daily spatio-temporal dynamics existing in agroforestry systems. Typically, the radiation received by the crop is summarized by the daily cumulated global radiation. Nevertheless, several studies highlighted that under a fluctuating and heterogeneous light environment, light reduction does not lead to a proportional decrease in vegetative growth (Artru et al., 2017; Dufour et al., 2013; Liu, 1991; Pearcy et al., 1996; Peri et al., 2002). From a physiological point of view, daily biomass growth of plants growing in a complex light environment can therefore not be estimated correctly from a daily cumulated value of the global radiation. This raises questions about the ability of the existing agroforestry models to correctly predict crop growth under agroforestry conditions especially in climatic regions where competition for light becomes important.

Within the models presented by Luedeling et al., (2016) the model Hi-sAFe is one of the most advanced, physically-based model linking the different components involved in an agroforestry system. This model was designed to simulate trees and crops species interaction and management strategies in temperate regions. Within Hi-sAFe, the STICS crop model is combined with a tree growth model in order to be able to assess the interactions between the two components.

Furthermore, van Noordwijk and Lusiana (1999) highlighted that linking separately developed models to simulate mixed cropping systems has its limitations, even if these models are process-based. They argued that the effects of above- and below-ground resource competition is generally more pronounced under monocropped systems, since these systems were not forced to develop strategies for resource sharing between species and therefore models developed in this context do not include specific mechanisms to do this. Moreover, plants can respond to environmental changes by undergoing morphological and/or physiological changes compensating for limiting conditions in order to maintain crop growth; e.g. a change in leaf area or leaf shape during the leaf development can occur in response to a reduced light environment (Murchie and Niyogi, 2011; Peri et al., 2002; Retkute et al., 2015). If a part of the mixed cropping model has been previously developed and calibrated under full light monocropped conditions, the risk is to use a model outside its validity range (e.g. a reduced light environment), which can lead to an over- or underestimation of crop growth.

The aim of the present study is to assess the ability of the STICS crop model (Brisson et al., 2008), to accurately predict winter wheat (*T. aestivum* L.) development and final productivity under an artificial reduced heterogeneous light environment. STICS has already been validated under full light conditions (Coucheney et al., 2015) and is used within the agroforestry model Hi-sAFe. Within silvoarable agroforestry system, implementing an east-west tree line orientation induces a high degree of light heterogeneity for the crop. In this configuration, the field can be subdivided in three different shade areas subjected to: (i) a dense and continuous shade during the day near the trees, (ii) a dynamic shade in the afternoon, and (iii) a shade-free zone according to the path of the sun. This paper deals with two specific research questions: (i) Is it possible to predict the response of winter wheat to these different light, using a single and common plant parameter set? (ii) Is the daily cumulated global radiation sufficient as the main driver to simulate the growth of winter wheat subjected to periodic shade?

# 2. Material and methods

## 2.1. Field experiment and data set

During two consecutive growing seasons (2014-15 and 2015-16), winter wheat (*T. aestivum* L., cultivar Edgard) was sown at the experimental farm of Gembloux Agro-Bio Tech (50°33' N, 4°42'E), in the Hesbaye region, Belgium. In the two consecutive years, the experimental plots were not exactly at the same spot in the field due to crop rotation management. Nevertheless, they were both located on a Luvisol (WRB, FAO, 2014). The climate is temperate maritime, with an average annual temperature of 9.96°C and mean annual cumulated rainfall of 805 mm over a 30 year period (1986-2015). The weather conditions of both growing seasons were highly contrasted in terms of rainfall and global radiation. The first growing season was characterized by a relatively dry and sunny spring (mean global radiation: 557 MJ/m$^2$ and mean rainfall 43 mm from April to June), while the second was wetter with lower radiation in spring (mean global radiation: 472 MJ/m$^2$ and mean rain fall 102 mm from April to June) (Figure 33 c & d).

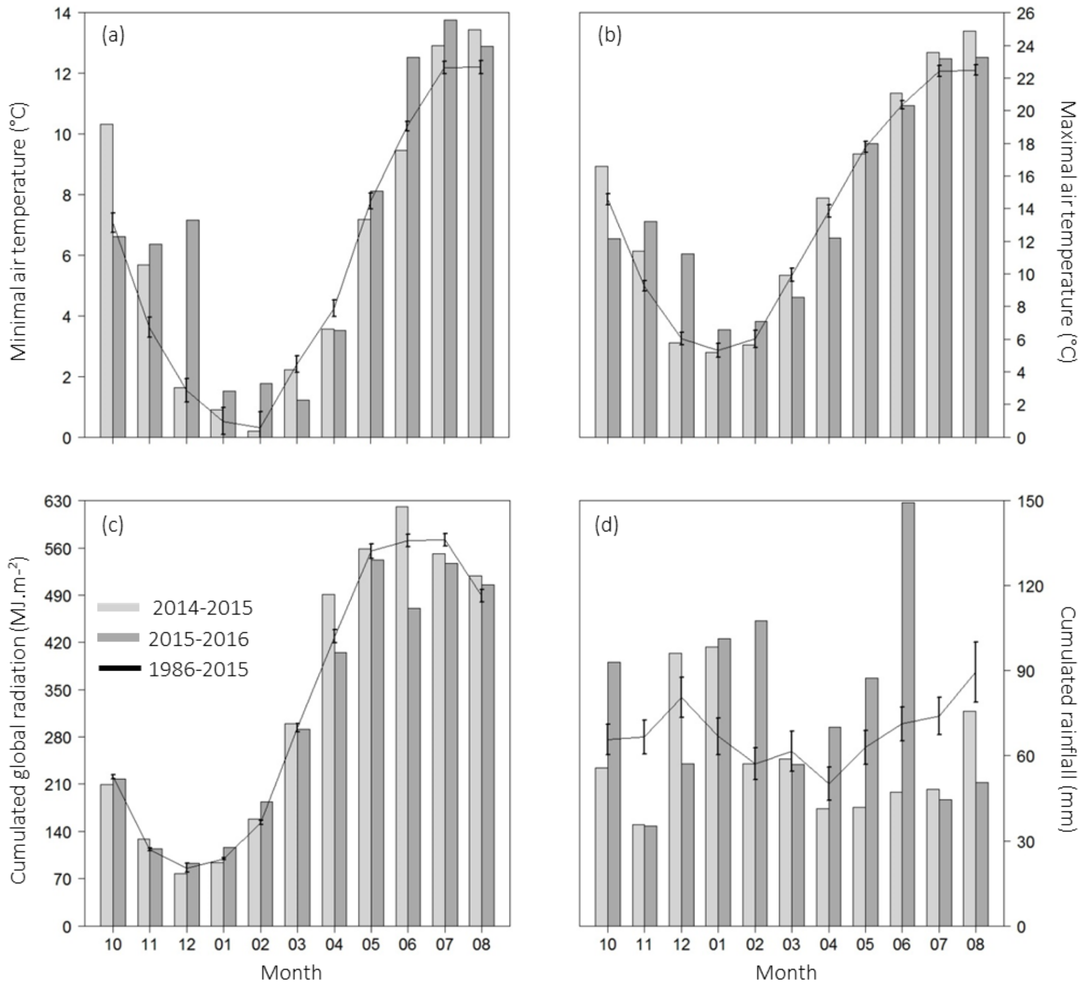



**Figure 33.** Monthly climatic data recorded from October to August for the growing season 2014-15 (lightgrey), 2015-16 (dark grey) and comparison with the average climatic data from 1986 to 2016 (black ligne). Chart a et b represent the monthly average minimal and maximal air temperature respectively, chart c show the monthly cumulated global radiation and d the cumulated rainfall. Vertical bars represent the standard error of the means of the mean data.

The seeds were sown on October 21th, 2014 (250 grains/m$^2$) and on October 27th, 2015 (300 grains/m$^2$) following an East-West orientation in both cases. The preceding crops were rapeseed (*Brassica napus* L.) in 2014-2015 and chicory (*Cichorium intybus* L.) in 2015-2016. Fertilization followed the conventional practice applied in Belgium, which means that three doses of nitrogen fertilizer were applied throughout the growing season (75/75/75 in 2014-15 and 60/60/75 in 2015-16) respectively at Zadoks stages 26, 30 and 58.

In this field experiment, we applied artificial shade to the crop using a greenhouse tunnel (68 x 5 meter) installed in the field with an East-West orientation and military tarps disposed on the southern face of the structure. Based on the path of the sun, this resulted in three shade levels corresponding to three distinct types of daily shade dynamics. The continuous shade (CS) treatment reduces the proportion of light during the entire day. The periodic shade (PS) treatment received an intermittent shade. The shade structure orientation and the path of the sun induce a moving shade on the plot during the day along the north-south gradient. The no shade treatment (NS) received 100 % of the available light. Camouflage net was used as shade material to reproduce a fluctuating sun/shade pattern, the holes in the cloth producing a combination of direct and diffuse light patches. The application of different shade layers followed the increasing shade produced by the canopy of a late-flushing tree. As such, we monitored the phenological development of 60 hybrid-walnut trees located in a plantation in Jenneret, Condroz region, Belgium (50°24'N, 5°27'E). To mimic the walnut tree leaf expansion, we applied a first layer of camouflage net after budburst when tree induces a significant shade (visual appreciation) and a second layer at the end of the maximal leaf expansion. In 2014-15, the first layer of shading was imposed 226 days after winter wheat sowing (DAS, June 4$^{th}$) and the second from 245 DAS (June 23$^{th}$) until harvest 292 DAS (August 10$^{th}$). In 2015-16, the first layer was applied 218 DAS (June 2$^{th}$) and the second from 240 DAS (June 23$^{th}$) until harvest 289 DAS (August 11$^{th}$). According to the observed hybrid walnut and winter wheat phenology, the artificial shade layers were applied 10 days and 7 days before wheat flowering for the growing season 2014-15 and 2015-16, respectively. At the scale of the crop growing season, the artificial shade layers were applied 66 (2014-15) and 70 (2015-16) days before harvest on a total growing period of 292 and 294 days, respectively.

Both growing seasons, daily climatic data (air temperature and humidity, rainfall, wind speed, wind direction and global radiation) were recorded by a weather station from the Royal Meteorological Institute, located 3 km from the experimental site (Ernage, Gembloux, 50°59'N, 172 4°67'E). Under each treatment, incident global radiation was recorded using quantum sensors (CS300 - Campbell Scientific Inc., USA - accuracy ± 5 for the daily global radiation) installed above the crop canopy level. The global radiation intercepted by the whole PS plot was calculated using a spatial average of the global radiation intercepted by three light sensors installed along a North-South gradient. During the growing season, crop phenology, aboveground biomass (sum of straw and spike dry matter biomass), final grain yield and yield components (grain number per m$^2$ and grain weight) were monitored (6 measurements in 2014-15 and 2 measurements in 2015-16). Aboveground biomass (t/ha) was assessed four (June 18$^{th}$) and seven (June 21$^{th}$) days after flowering in 2015 and 2016 respectively, as well as the 7th of August in 2015 and the 8th of August in 2016 when all the treatments had reached maturity. The sampling corresponds to three adjacent rows of 40cm length at flowering and 50 cm at maturity stage. The measurements were performed on dried samples. More details on the experimental setup are published in Artru et al. (2017).

## 2.2. Model set up

### 2.2.1. Structure of the STICS crop model

The STICS crop growth model (STICS v8.4, INRA, France) is fully described in the literature (Brisson et al., 2008) and validated for a broad range of crop species (Coucheney et al., 2015). It is a generic crop model that simulates the soil–plant–atmosphere system dynamics on a daily time step. The crop is characterized by its leaf area index (LAI), its above-ground dry biomass as well as the number and the biomass of the harvested organs. The duration between each physiological stage (e.g. emergence, flowering, and maturity) is partly driven by the sum of degree-days and is based on crop temperature derived from air temperature using the energy balance approach. Other factors such as the soil temperature and humidity at the rooting depth as well as vernalization requirement are implemented as reduction factors in the definition of the daily phasic development of the crop.

In this study, we were interested in the productivity of winter wheat crop under different 'light environments'. The main formalisms of interest are the aboveground biomass dynamics and the grain filling process. Thus, we focused our study on the total aboveground biomass and end-season variables such as grain yield, grain number per $m^2$ and grain weight amongst all the available output variables within STICS. The total aboveground biomass (masec, t/ha) simulated by STICS relies on the accumulation of the daily biomass production (dltams t/ha). This accumulation is driven by the concept of radiation use efficiency and takes into account several stress factors influencing crop growth processes such as thermal, hydric and nutritive stresses. Final grain yield (mafruit, t/ha) is defined in two steps: first the grain number (nbgrains, grains/$m^2$) is determined before flowering and then the grain filling is initiated between flowering and maturity. The grain number is a function of vitmoy (g/$m^2$/d) defined as the aboveground biomass growth rate (dltams, t/ha/d) during a fixed period prevailing flowering (*nbjgrain*, days). This relation relies linearly on two species parameters *cgrain* and $cgrain_{vo}$ and the grain number is limited by two plant parameters that constrain the number of grains with boundaries: *nbgrmax* and *nbgrmin*. Final yield is the result of daily cumulated grain filling (dltags in t/ha) which is calculated by applying a dynamic harvest index (ircarb) to the total aboveground biomass. In the option we chose, this harvest index increases as a linear function of the thermal time from flowering to maturity and depends on the $viticarb_t$ (g.grain/g/d) parameter. Finally, grain weight (pgrain, g) is calculated as the ratio between the final grain yield (mafruit) and the grain numbers (nbgrains). This variable cannot exceed a varietal limit, defined by the threshold parameter *pgrainmaxi*. A complete description of the formalisms is available in Brisson et al. (2008). The variables of interest and parameters presented below are synthetized in Table 16 in appendix.

### 2.2.2. Model parametrization and cultivar selection

To run a simulation with STICS, daily climatic input data as well as soil, management and plants parameters are required. In this study, input weather data files including daily minimum and maximum air temperature, relative humidity, rainfall, wind speed, wind direction and global radiation, were created from the data obtained from the Royal Meteorological Institute weather station, located 3 km from the experimental site (Ernage, Gembloux, 50°59'N, 172 4°67'E). As soon as the shade structure was set up, we used data recorded under the different light treatments (NS, PS, and CS) to replace the daily global radiation of the Ernage station. The potential evapotranspiration was calculated with the Shuttleworth-Wallace equation (Brisson et al., 1998). This equation is based on a resistive approach which accounts for the convective conditions around the plants and is appropriate for crops growing under a fluctuating microclimatic environment such as observed under agroforestry systems.

Soil input parameters were obtained from soil analysis or derived from basic soil measurements (Table 10). Pedotransfer functions have been used to define the gravimetric water content at field capacity and at wilting point for each soil layer (Jones et al., 1991). Moreover, the model is able to take into account the detrimental impact of root zone anoxia due to temporary excess of water on the shallow soil, which was particularly relevant given the high amount of rainfall recorded in 2015-16, especially in June. Furthermore, the *infil* parameter (water infiltrability at the base of each soil layers, mm/day) is estimated as a function of textural classes from the pedotransfer table presented in Brisson et al., (2008) and based on Jamagne et al., (1977). The same soil description was used for all treatments and for both growing seasons.

For each growing season, the same crop management file (sowing date, depth and density, dates and amounts of N rate supply, date and depth of soil tillage …) was used for the three treatments. The climatic, soil and management inputs file used in this study are available in zenodo.org with DOI 10.5281/zenodo.800568.

In addition, STICS requires specific plant parameters. The majority of these parameters have been formulated to be generic to the species and others are cultivar-dependent (13 parameters). The complete list of model parameters and input variables is given in Brisson et al. (2008). Preliminary calibration of the plant parameters set was performed by Dumont el al., (2014, 2015, 2016) on a closely related cultivar within a wide range of management and environmental conditions in the Hesbaye region (same as in the current paper).

## 2.3. Plant parameters calibration

The calibration was performed using only the field data from the NS treatment of both growing seasons. That means that the data set was split in two in order to on the one hand optimize the parameters using regular conditions of crop growth (no shade) and on the other hand to keep an independent data set composed of observations under the shaded treatments for the model evaluation.

### 2.3.1. Phenological stage and grain yield threshold parameters

From the initial set of parameters calibrated by Dumont el al., (2014, 2015, 2016), some cultivar parameters were manually adjusted following field observed values. The cultivar parameters involved in the prediction of the vegetative (*stlevamf*, *stamflax* and *stlevdrp*) and reproductive (*stdrpmat*) phenological stages, as well as yield component threshold parameters (*pgrainmax and nbgrmax*) were adjusted according to field observations done under the NS treatment during both growing seasons as explained above (Table 11). The remaining parameters were fixed to the default value provided in STICS model (Brisson et al., 2008). The complete plant parameter file used in this study is available in zenodo.org with DOI 10.5281/zenodo.800568.

### 2.3.2. Final grain yield parameters

The calibration procedure on which this paper focuses implies the optimization of three species-dependent parameters involved in the grain number prediction, *nbjgrain, cgrain* and $cgrain_{vo}$. First the *nbjgrain* parameter was fixed analyzing the response of the simulated mean canopy growth rate (vitmoy, $g/m^2/d$) to different values of *nbjgrain* ranging from 0 to 30 days before flowering. Second, the two parameters *cgrain* and $cgrain_{vo}$ were optimized by linear regression. These two parameters are involved in the relation defining the proportion of actual grain number to the potential maximum number of grains (nbgrains / *nbgrmax,* axis y) as a function of total aboveground growth rate (vitmoy, $g/m^2/d$, axis x) during the prevailing period of grain filling (*nbjgrain*). To perform this linear regression, the daily biomass accumulation (dltams t/ha) was simulated for the NS treatments of both growing seasons. Then, the vitmoy variable was calculated as the ratio of this simulated dltams and the *nbjgrain* parameter, which was fixed at 12 days. Thereafter, the ratio $nbgrains_{obs}$ / *nbgrmax* was defined using the observed grain number under each treatment in the field ($nbgrains_{obs}$) and a fixed value of the parameter *nbgrmax*.

**Table 10.** Soil description for each layer.

| | Field measurement | | | | Pedotransfer function | | |
|---|---|---|---|---|---|---|---|
| Layer tick | Clay | Silt | Sand | Bulk density | Gravimetric water content at field capacity | Gravimetric water content at wilting point | *Infil* |
| [m] | [%] | [%] | [%] | $g/cm^3$ | [%] | [%] | [mm/d] |
| 0-25 | 10 | 84.5 | 5.5 | 1.3 | 19.38 | 9.23 | 2.25 |
| 25-50 | 15.75 | 80.75 | 3.5 | 1.5 | 16.33 | 7.53 | 6.91 |
| 50-70 | 14.75 | 81 | 3.5 | 1.53 | 16.34 | 7.71 | 7 |
| 70-100 | 14.5 | 82 | 3 | 1.53 | 18 | 9.48 | 3.45 |
| 100-150 | 14 | 83.5 | 2.75 | 1.53 | 20.32 | 11.81 | 3.33 |

**Table 11.** Value of the plant parameters defined in STICS model (initial set) and calibrated on the NS treatment data of both experimental years (calibrated set).

| | Range | Initial set | Calibrated set | Unit |
|---|---|---|---|---|
| Adjustement from field observation | | | | |
| *stlevamf* | 0 - 6000 | 315 | 260 | degree.days |
| *stamflax* | 0 - 6000 | 325 | 275 | degree.days |
| *stlevdrp* | 0 - 6000 | 700 | 790 | degree.days |
| *stdrpmat* | 0 - 6000 | 850 | 800 | degree.days |
| *nbgrmax* | $0 - 1.10^6$ | 28000 | 29000 | $grain/m^2$ |
| *pgraimaxi* | 0.003 - 0.5 | 0.05 | 0.042 | g |
| $viticarb_t$ | $5.10^{-5}$ - 0.002 | 0.007 | 0.0065 | g grain/g plant/degree.days |
| Calibration from linear regression | | | | |
| *cgrain* | 0.01 - 1 | 0.045 | 0.0298 | grains/g.day |
| $cgrain_{vo}$ | $-15.10^3 - 15.10^3$ | 0 | 0.1546 | - |
| *nbjgrain* | 5 - 40 | 30 | 12 | day |

### 2.4. Model evaluation under the shaded conditions

The ability of STICS to predict the total aboveground biomass, final yield and yield components was tested by comparing the model estimation to the experimental field observations including the datasets of the PS and CS shade treatments during the two growing seasons. The statistical criteria used to evaluate the model performance were the root mean square error (RMSE), the Nash-Sutcliffe efficiency (NSE) and the pBias criterion. The RMSE gives the standard deviation of the model prediction error (Equation. 1). The lower the RMSE values are (same unit as the variable), the better is the model prediction. The NSE is a normalized statistic which determines the relative magnitude of the residual variance compared to the measured data variance (Equation. 2). This criterion varies from 1 to the negative infinite value with NSE = 1 being the optimal value. The closer the NSE value is to 1, the more accurate is the model prediction. Values below 0 mean that the mean observed value is a better predictor than the simulated one, and the performance of the model is judged unacceptable.

The pBias measures the average tendency of simulated values to be larger or smaller compared to the observed ones (Equation. 3). The optimal value of the pBias is 0, while positive and negative values indicate a model under- and overestimation.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(yi - \widehat{yi})^2} \qquad (1)$$

$$NSE = 1 - \frac{\sum_{i=1}^{n}(yi-\widehat{yi})^2}{\sum_{i=1}^{n}(yi-\bar{y})^2} \qquad (2)$$

$$pBias = 100 * \frac{1}{n}\sum_{i=1}^{n}(\widehat{yi} - yi) \qquad (3)$$

Where $n$ is the total number of measurements, $yi$ is the measured value for the $ith$ measurement, $\bar{y}$ is the average of the measured value, and $\widehat{yi}$ is the simulated value for the $ith$ measurement.

## 3. Results

### 3.1. Impact of shade on wheat growth and yield: field observations

Winter wheat experienced similar light conditions before its $LAI_{max}$ stage in both years, so no big differences in phenological development should be expected due to that factor. Then, from flowering to harvest, the cumulated global radiation received by the crop under the CS treatment was reduced by 65 % in 2014-15 and 56 % in 2015-16. For the PS treatment, it varied from 55 % to 35 % in 2014-15 and from 46 % to 31 % in 2015-16. In 2014-15, these contrasted conditions resulted in a phenological time lag between the treatments. We observed a mismatch of 7 days between the occurrence of the maturity under the CS treatment (5 August 2015) and the NS and PS treatment (29 July 2015). In other words, under the NS and PS treatment the interval between flowering and maturity was 45 days, while it was 52 days under the CS treatment. In 2016, the phenological delay was observed but not quantified.

This reduction of the available incident global radiation under the CS and PS treatments led to a decrease of the final aboveground biomass as compared to the NS treatment (Figure 34). For both growing seasons, the difference between the treatments was mainly due to a significant reduction of spike biomass under the shade treatments (Table 12). At harvest, the total aboveground biomass under the shade treatments was significantly reduced as compared to the NS treatment (Figure 34).

The reduction of the global radiation received by the crop mainly affected yield elaboration processes with detrimental consequences for the final grain yield (t/ha) and grain number per $m^2$. Table 12 presents the mean value of the final grain yield and the yield components observed under the NS treatment and the relative reduction of the values of these variables under the CS and PS treatments. At harvest, in 2014-15 and 2015-16, we observed a significant yield reduction for the CS and PS treatment in comparison to the NS treatment (Table 12). This decrease was related to a significant reduction of both grain weight and grain number under the CS and PS treatments as compared to the NS treatment. Moreover, grain size calibration reveals that under the NS treatment, the final grain yield mainly relies on large grains (< 2.5 mm and < 2.8 mm: 84 % in 2014-2015 and 66 % in 2015-16) and a small proportion of medium (< 2.5 mm and > 2.8 mm: 10 % in 2014-2015 and 23 % in 2015-16) and small grain sizes (< 2.2 mm and > 2.5 mm: 3 % both growing season). Nevertheless, these proportions change when wheat is exposed to a shade treatment. Under the CS treatments, the final grain is composed by on average 31 to 26 % of large grain, 39 to 44 % of medium grain and by 8 to 6 % of small grain, respectively for the season 2014-15 and 2015-16. Under the PS shade treatment, we observe 65 % to 36 % of large grains, 22 % to 36 % of medium grains and 8 to 21 % of small grains size. As a consequence, shading significantly decreased the harvest index (HI) at maturity (Table 12). The large differences in observed aboveground biomass dynamics and final yield between the 2 years can be explained by a reduction of the available global radiation and an important waterlogging event in 2016 with particularly unfavorable weather conditions for winter wheat during the grain filling period (Figure 34).

**Table 12.** Mean value of total aboveground, spike dry matter, final grain yield, grain number, grain weight and harvest index of winter wheat for the NS treatments. Mean results obtained under the PS and CS treatments are expressed in percentage of the nominal NS treatment. Statistical significance of the equality between treatments is represented by the *p-value*.

| | | Total aboveground dry matter [t/ha] | | Spike dry matter [t/ha] | Grain yield [t/ha] | Grain number [#/m²] | Grain weight [g] | Harvest index [/] |
|---|---|---|---|---|---|---|---|---|
| | | at flowering | at harvest | at harvest | | | | |
| 2014-15 | NS | 12.34 | 18.47 | 10.94 | 9.94 | 23788 | 0.042 | 0.55 |
| | PS [in % of NS] | + 7.77 % | - 6.87 % | - 12.06 % | - 20.82 % | - 9.54 % | - 11.90 % | -16.36 % |
| | CS [in % of NS] | - 11.10 % | - 27.61 % | - 36.83 % | - 49.19 % | - 24.78 % | -33.33 % | -30.90 % |
| | *p-value* | *0.12* | *0.03* | *0.02* | *$7.84.10^{-6}$* | *0.01* | *$1.20.10^{-7}$* | *0.017* |
| 2015-16 | NS | 10.06 | 14.38 | 8.08 | 6.10 | 14407 | 0.042 | 0.42 |
| | PS [in % of NS] | - 6.26 % | - 11.05 % | - 14.60 % | - 17.37 % | - 9.30 % | -7.14 % | -7.14 % |
| | CS [in % of NS] | - 4.57 % | - 23.99 % | - 32.79 % | - 35.90 % | - 19.11 % | -19.04 % | - 14.28 % |
| | *p-value* | *0.35* | *$7.10^{-3}$* | *$3.7.10^{-7}$* | *$1.10^{-4}$* | *0.01* | *$2.10^{-4}$* | *0.0024* |

**Table 13.** Root mean square error (RMSE), model efficiency (NSE) and pBias of the predicted aboveground dry matter at flowering and at harvest for the calibration dataset and validation dataset.

| | Calibration set | | Validation set | |
|---|---|---|---|---|
| | NS treatment 2014-15 and 2015-16 | | CS & PS treatment 2014-15 and 2015-16 | |
| | DM at flowering [t/ha] | DM at harvest [t/ha] | DM at flowering [t/ha] | DM at harvest [t/ha] |
| RMSE | 0.82 | 0.44 | 1.02 | 1.08 |
| NSE | 0.48 | 0.95 | 0.57 | 0.77 |
| pBias | 2 | -1.2 | -2.7 | -5.3 |

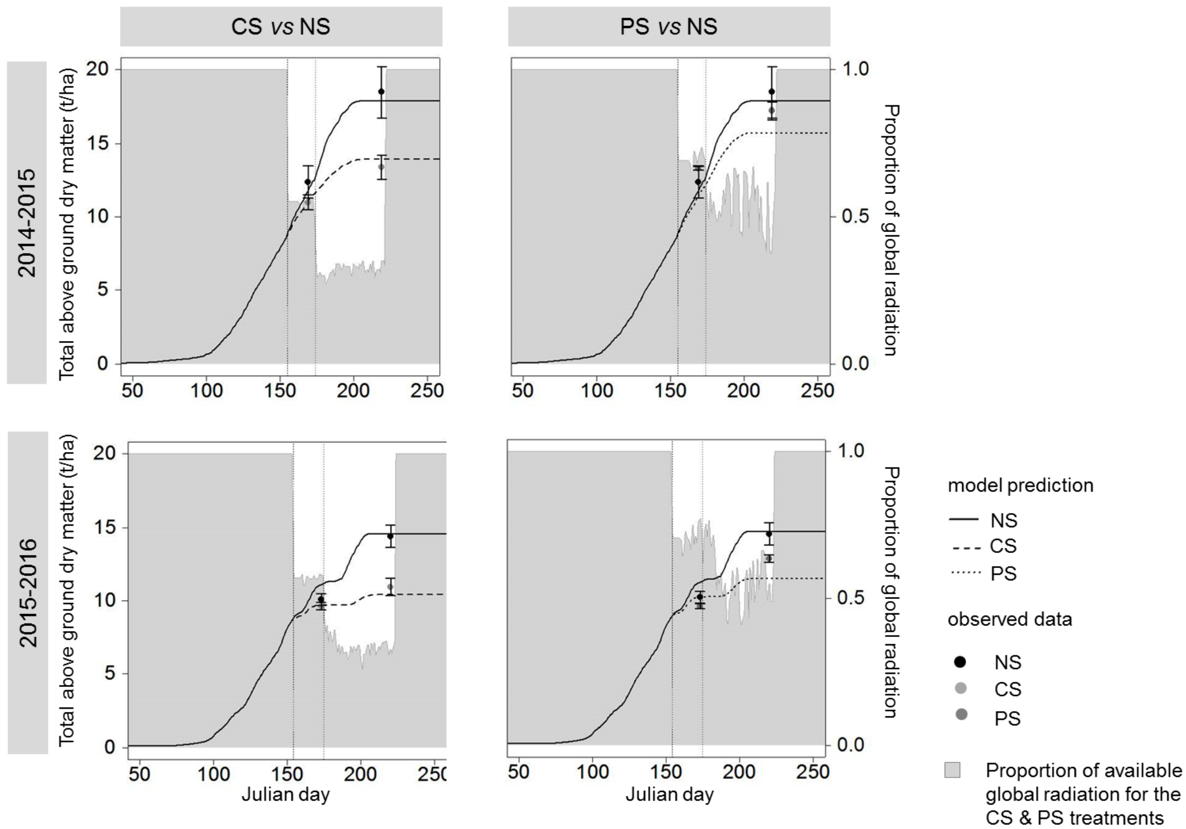



**Figure 34.** Simulated total aboveground biomass dynamics (t/ha) and field observations for the growing season 2014-15 and 2015-16 under the different light regimes (NS, PS, CS). In the background, the grey surfaces represent the daily proportion of global radiation (right axis, %) received by the shade treatments as compared to the NS treatment. Vertical lines indicated the date of the shade layers applications during the cropping seasons. Vertical bars represent the standard error of the means of the observed data.

## 3.2. Plant parameters calibration

### 3.2.1. Phenological stage adjustment

The time to reach maturity for harvest under the PS treatment was well predicted when using the adjusted set of phenological stages parameters (Table 11), while under the CS treatments it was reached seven days earlier in the simulation than observed in the field. To reproduce the delay which occurred in reality, the daily mean air temperatures have been reduced during the shading period, following the equation 4. In the STICS formalism, the duration between two phenological stages, *i.e.* between *idrp* (day of beginning of grain filling, julian day) and *imat* (days of physiological maturity, julian day), is expressed in degree-days and calculated on the basis of crop temperature (TCULT). This crop temperature relies on the daily sum of evaporative fluxes, the calculation of net radiation and the air temperature. This daily crop temperature is calculated as the arithmetic mean of the maximum and minimum crop temperature both depending, amongst others, on the maximum and minimum air temperature

(Tmax and Tmin, °C) assumed to occur at midday and at the end of the night, respectively. According to the literature and given the experimental set up, the main difference between non-shaded and shaded treatments is a reduction of the maximal air temperature rather than of the minimal air temperature. Given the STICS formalism and the literature on the subject, we reduced the daily mean air temperature by 1.96 °C by applying a reduction of 3.92 °C on the sole maximal air temperature input (Equation. 5).

$$Temp\ reduction = \frac{stdrpmat + stshadedrp}{nbshademat\ NS\ treatment} - \frac{stdrpmat + stshadedrp}{nbshademat\ CS\ treatment} \quad (4)$$

$$Temp\ reduction = \frac{800 + 158}{55} - \frac{800 + 158}{62} = 1.96\ °C$$

$$Tmax\ reduction = 2\ x\ Temp\ reduction = 3.92\ °C \quad (5)$$

In this equation, the parameter *stdrpmat* (degree.days) corresponds to the duration between the *idrp* (day of beginning of grain filling, julian day) and *imat* (day of physiological maturity, julian day) stage; *stshadedrp* (degree.days) corresponds to the duration between the first day of shade application and the *idrp* stage; *nbshademat* defines the number of days between the first day of shade application and the *imat* stage for the NS treatment and the CS treatment. The maximal air temperature (Tmax, °C) was computed using equation. 4 and 5 for the CS treatment, while NS and PS did not show delay in phenology. Thus, according to this adjusted value of Tmax and daily global radiation recorded under the CS treatments, TCULT was decreased under the CS treatments during periods with shade. In 2014-15, TCULT was reduced by 2.79 °C on average during the shade period under the CS as compared to the NS treatment. Likewise, in 2015-16, TCULT was reduced by 2.72 °C on average during the shade period under the CS as compared to the NS treatment. Under the CS treatment, the proposed reduction of the daily maximal air temperature showed good efficiency to improve the prediction of the grain maturity stage. This adjustment allowed to extend the grain filling period by 7 days in 2015, maturity reach on the 5$^{th}$ of august and 8 days in 2016, maturity reach on the 2$^{nd}$ of august as compared to the NS treatment, which was close to the field observations.

### 3.2.2. Impact of *nbjgrain*, *cgrain* and *cgrain$_{vo}$* parameters on final grain number

Figure 35 presents the variation of the mean plant growth (vitmoy) to the length of the observed period of growth (*nbjgrain*) for the NS treatments and both growing seasons. The graph shows that in case a value of *nbjgrain* lower than 5 or greater than 18 days would have been used, the predicted VITMOY would have been too slightly responsive. This would have furthermore led to unrealistic optimization of the cgrain and *cgrain$_{vo}$* parameter values. Contrarily, vitmoy appeared highly sensitive when *nbjgrain* ranges from 6 to 17 days. More precisely, vitmoy achieves a maximal value during the season 2014-15 at *nbjgrain* equaling 12 days and a minimal value the following season when *nbjgrain* equals 8. In order to maximize the contrast within the responses of VITMOY we would recommend to select a value in between those thresholds; we arbitrarily fixed the *nbjgrain* parameter at 12 days (vertical solid line in Figure 35). Figure 36 and Table 11 present the default species parameter values proposed in STICS and the adjusted *cgrain* and $cgrain_{vo}$ using linear regression applied on the relationship between vitmoy and $nbgrains_{obs}$ / *nbgrmax*, with the *nbjgrain* parameter fixed at 12 days.

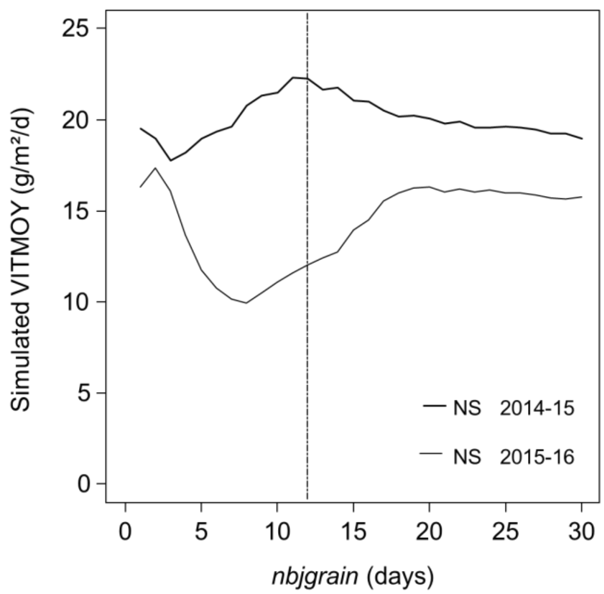



**Figure 35.** Sensibility of the mean canopy growth rate (VITMOY, $g/m^2/d$) to the number of days prevailing grain filling period (*nbjgrain*, days). The vertical bar indicate the number of days fixed in this study to compute the grain number, *nbjgrain* = 12 days.

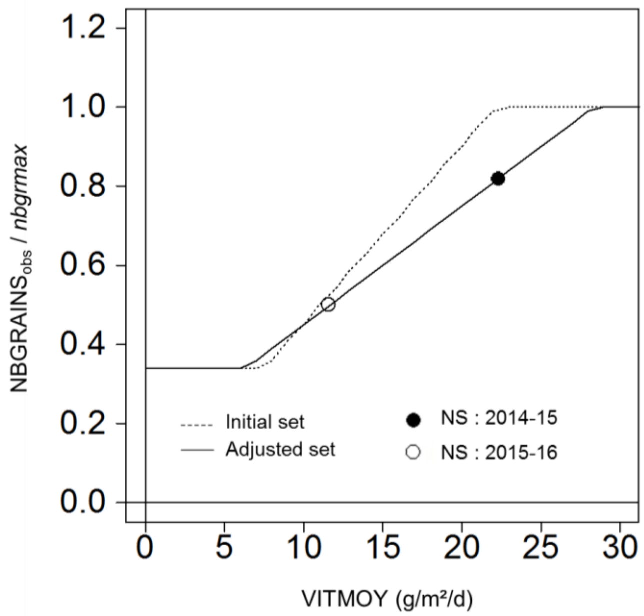



**Figure 36.** Calibration of the parameters *cgrain* and *cgrainvo* from NS treatment observed data. These two parameters are respectively defined as the slope and the intercept of the regression between the proportion of grain number (NBGRAINS$_{obs}$/*nbgrmax*) and plant growth (VITMOY) during the pre-grain filling period. The dashed line represent this relation for the initial set of plant parameter (*cgrain* = 0.045, *cgrainvo* = 0, *nbjgrain* = 30 days) and the solid line result from the adjustment from the observed data (*cgrain* = 0.0298, *cgrainvo* = 0.1546 and *nbjgrain* = 12 days).

## 3.3. Model evaluation

### 3.3.1. Prediction of the aboveground biomass dynamics

Overall, the simulations of the total aboveground biomass dynamics reflected the rank observed in the field experiment between the shade treatments. Nevertheless, detailed examination of the different treatments showed that at harvest the relative reduction of the total aboveground biomass for the PS treatment was smaller in the simulation (-12.19 % in 2015 and -22.29 % in 2016) than in the field (- 6.87 % in 2015 and -11.05 % in 2016). Under the CS treatment in 2015 this reduction was smaller in the simulation (-22.20 %) than in the field (- 27.61 %), while in 2016 is was higher in the simulation (-28.66 %) than in the field (- 23.99 %) (Figure 34, Table 14). On average the total aboveground biomass prediction for the PS and CS datasets was good, the RMSE equaled 1.02 and 1.08 t/ha, the NSE was 0.57 and 0.77, and the pbias was -2.7 and -5.3 %, at flowering and at harvest, respectively (Table 14).

**Table 14.** Root mean square error (RMSE), model efficiency (NSE) and pBias of the predicted aboveground dry matter at flowering and at harvest for the calibration dataset and validation dataset.

| | Calibration set | | Validation set | |
|---|---|---|---|---|
| | NS treatment 2014-15 and 2015-16 | | CS & PS treatment 2014-15 and 2015-16 | |
| | DM at flowering [t/ha] | DM at harvest [t/ha] | DM at flowering [t/ha] | DM at harvest [t/ha] |
| RMSE | 0.82 | 0.44 | 1.02 | 1.08 |
| NSE | 0.48 | 0.95 | 0.57 | 0.77 |
| pBias | 2 | -1.2 | -2.7 | -5.3 |

### 3.3.2. Prediction of final yield and yield components

Overall, the simulations reflected the trends observed in the field experiment, with a decrease of the final grain yield and the grain number per m$^2$ with increasing shade level. The calibration procedures clearly improved the agreement between simulated and measured values for the grain number component (Figure 37): using the adjusted plant parameter set for the shaded treatment allowed to increase the model efficiency up to 0.96 and to reduce RMSE from 4882 to 749 grains per m$^2$ for the validation set (Table 15). A slight underestimation was still present for the season 2015-16 (Figure 37). Nevertheless, the prediction gave very similar results for the final grain yield using both types of parameter sets. Apart from the NS treatment in 2015, yield was overestimated for all the other treatments (Figure 37, Table 15). Furthermore, the model failed to reproduce the field observation trend for the grain weight component and this regardless of the plant parameters used (Figure 37). Likewise, apart from the NS treatment in 2015, grain weight was overestimated for all the other treatments (Figure 37). For the season 2015-16, final grain yield has been bounded the *pgrainmaxi* parameters value and the simulated number of grains (nbgrains). For the growing season 2015-14, grain number was not involved in the grain yield determination as the simulated final grain yield (NS = 9.24; PS = 8.15 and CS = 7.14 t/ha) did not exceed the *pgrainmaxi* x nbgrains limit, equal to 10.68, 9.51 and 8.46 t/ha for the NS, PS and CS treatments respectively. The *pgrainmaxi* parameters have been adjusted from the experimental data observed under the NS treatment. It could have been adjusted on the data from the CS and PS treatment in order to limit the final grain biomass accumulation but in that case the genericity of the plant parameters set would have been lost.

**Table 15.** Root mean square error (RMSE), model efficiency (NSE) and pBias of the predicted yield, grain number and grain weight with the initial and adjusted plant parameters set for the calibration dataset and validation dataset.

| | Calibration set | | | Validation set | | |
|---|---|---|---|---|---|---|
| | NS treatment 2014-15 and 2015-16 | | | CS & PS treatment 2014-15 and 2015-16 | | |
| | Yield [t/ha] | Grain number [#/m$^2$] | Grain weight [g] | Yield [t/ha] | Grain number [#/m$^2$] | Grain weight [g] |
| Initial set | | | | | | |
| RMSE | 1.02 | 4341 | 0.004 | 1.35 | 4882 | 0.004 |
| NSE | 0.71 | 0.12 | | 0.14 | -0.69 | -0.22 |
| pBias | 3.6 | 18.4 | -10.7 | 21.4 | 27.9 | -3.7 |
| Adjusted set | | | | | | |
| RMSE | 0.66 | 299 | 0.003 | 1.25 | 749 | 0.009 |
| NSE | 0.88 | 0.99 | | 0.26 | 0.96 | -4.2 |
| pBias | -0.5 | 0.9 | 0 | 19.4 | -1.7 | 24.4 |

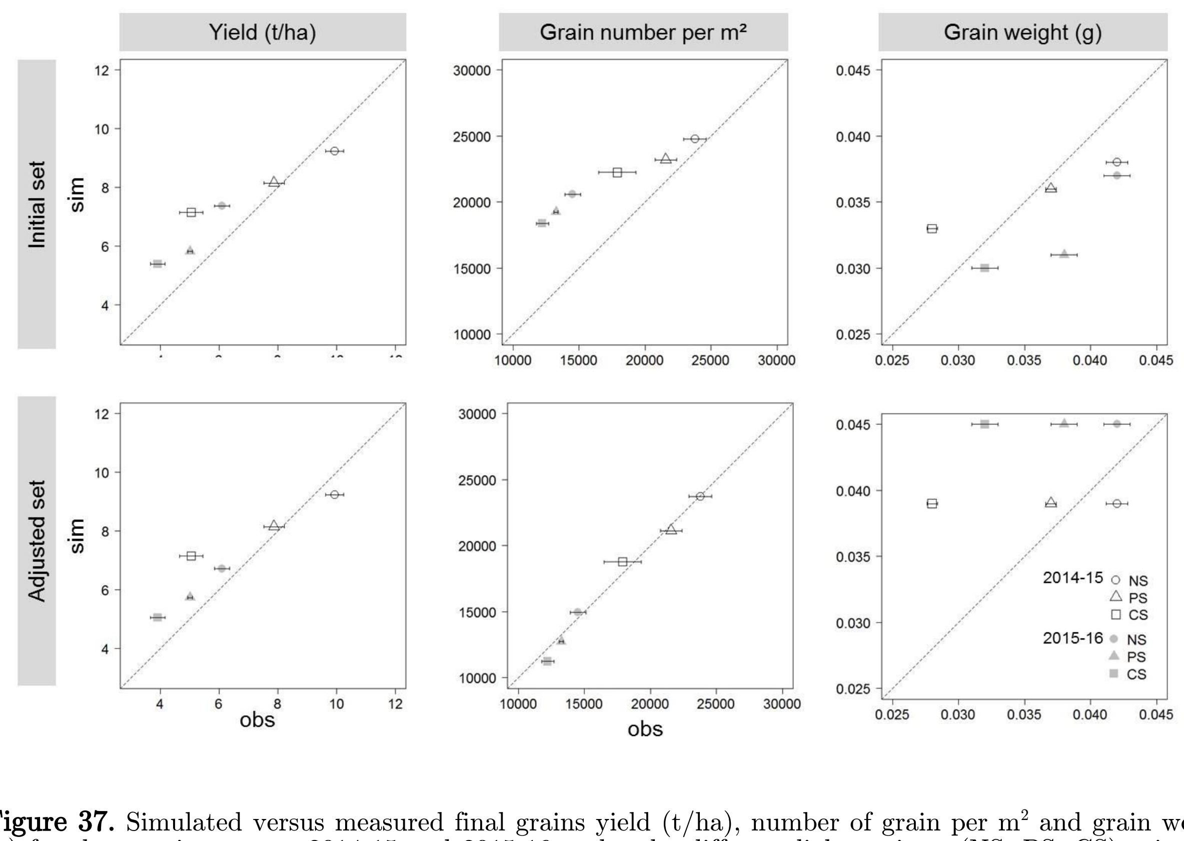



**Figure 37.** Simulated versus measured final grains yield (t/ha), number of grain per m$^2$ and grain weight (g) for the growing season 2014-15 and 2015-16 under the different light regimes (NS, PS, CS) using the initial and adjusted plant parameter sets. Horizontal bars represent the standard error of the mean of the mean observed data.

# 4. Discussion

## 4.1. Impact of shade on winter wheat growth and final yield

Field observations showed that applying a shade treatment during a pre- (7 to 10 days) and post-flowering period of winter wheat leads to a decrease of the overall plant biomass as well as a decrease of the grain number per $m^2$ and the final grain weight. This is in accordance with a large body of literature on the subject (Artru et al., 2017; Demotes-Mainard and Jeuffroy, 2004; Dufour et al., 2013; Fischer, 1985; Sinclair and Jamieson, 2006). The literature suggests that the final grain yield depends on the grain number determination and on the remobilization of the pre-flowering reserve as well as on the photosynthesis occurring during the grain filling period (Bijanzadeh and Emam, 2010; Boiffin and Caneill, 1981; Gate, 1995).

From a physiological point of view, the shade treatment applied in this study occurred during three critical periods for the final grain yield elaboration: (i) the grain number settings period, just before flowering; (ii) the cell production phase, from flowering until around 14 days after flowering; and (iii) the cell expansion phase, from around 14 days after flowering until maturity (Brocklehurst et al., 1978). In our field experiment, the shade treatments influenced the composition of final grain yield in terms of grain number and grain size proportion. The larger amount of medium grain sizes (< 2.5mm) under the CS treatment as compared to the NS treatment may be due to either a diminution of cell productions per grain or a reduction of the cell expansion during the filling stage or both. Nevertheless, large grain size has also been observed under CS treatment certainly meaning that under shade treatment some grains present an equivalent number of cells and assimilate. In fact, field studies have shown that, although these components are developed sequentially, there can be some compensatory processes between the different yields components, with the prior-established components influencing the later-formed ones (Beed et al., 2007; Fischer, 2008; Jocković et al., 2014; Singh and Jenner, 1984). As for the grain number component, there is an unresolved ongoing debate on the relative importance of sink and source functions in the final yield determination. Some authors stipulate that grain number is implied in the regulation of the amount of resources accumulated in the grain during the grain filling period (Fischer, 2008), while others found that the grain number is a consequence of the accumulated resources, just like grain weight (Sinclair and Jamieson, 2006, 2008)..

## 4.2. Model calibration and evaluation

We evaluated the ability of the crop model STICS to accurately predict winter wheat growth and yield under two reduced light environments using a common plant parameter set pre-calibrated on an independent dataset under full light conditions (NS treatment).

This study clearly demonstrates that STICS results in an accurate prediction of the total aboveground biomass dynamics under a constant shade pattern of light using the daily global radiation as climatic input. Nevertheless, the model consistently underestimates the total aboveground biomass when using a daily cumulated global radiation for the PS treatment. These results raise questions about the validity of the relationship between the daily biomass accumulation and the intercepted global radiation for plants growing under intermittent shade regimes within a day. Furthermore, in STICS, the ratio of direct to diffuse irradiance is only computed as a function of the latitude and the date, while under shade treatments this ratio changes with higher proportions of diffuse irradiance as compared to direct light and this may induce variation in crop RUE (Sinclair et al., 1992). In STICS model, the radiation use efficiency parameter defined in the plant parameters set was the same whatever the light treatment.

Differences in crop phenology due to differences in air temperature under shade and full light conditions are important to take into account. When we reduced only the global radiation in the model, the predicted maturity date in the CS treatment was seven days earlier than the date observed in the field in 2015. While doing this, the simulated crop temperature only slightly decreased under the shaded treatments as compared to the NS treatment. This highlights the necessity to take the changes in terms of air temperature into account in the modeling in addition to the light reduction in order to correctly reproduce the effect of shade on the crop temperature and thus on the thermal time that drives the understory crop phenology. In fact, several authors have reported that air temperature at crop canopy level is reduced under agroforestry systems as well as under artificial shade structures. At a daily time scale, temperature decreases at daytime and it gets warmer at night under shade structures than in open air (Gosme et al., 2016; Karki and Goodman, 2015). In mature agroforestry systems (15-20 years old plot), Gosme et al. (2016) found that in spring, when temperatures are high and when the trees have leaves, the daily average air temperature can decrease by 1.2°C in the agroforestry plot as compared to the control plot. Likewise, Karki and Goodman (2015) recorded a maximum decrease of 3.8°C in August under 15-20 years old loblolly pine. However, Marrou et al. (2013) showed that, under photovoltaic shelter, convective air movement allows to homogenize the mean daily air temperature and the crop temperature and thus no differences were observed as compared to the full sun treatment. Similarly to the PS treatment applied in our study, this agrivoltaic system induced periodic shade during the day according to the light movement with the path of the sun. These results confirm the assumption that in our experiment, under CS the wheat probably experiences a lower ambient temperature as compared to the NS, while no differences were observed under the PS treatment. Thus, a decrease of around 2°C to the daily mean air temperature applied in this study under the CS treatment is consistent with the range of values recorded in other studies.

In STICS, the grain number relies only on the rate of carbon accumulation prior to flowering and in our study this formalism allows to accurately predict the grain number under the NS as well as under the shaded treatments, although the calibration of the *nbjgrain, cgrain* and $cgrain_{vo}$ plant parameters was mandatory. By applying shade treatments, several authors have shown that the duration of the critical period of grain number establishment (*nbjgrain* parameter in STICS) lasts about 20 to 30 days prior to flowering (Abbate et al., 1997; Demotes-Mainard and Jeuffroy, 2004; Fischer, 1985). Within this period the magnitude of wheat response varies according to the level and the number of days of shade application. Furthermore, Fischer & Stockman (1980) identified a maximal reduction of grain number when shade was imposed around 10 to 13 days prior to flowering. Within this period, the grain number determination remains highly sensitive to environmental variations. Our results support this finding: the aboveground biomass growth rate appears highly sensitive when the period ranged between 8 to 15 days before flowering.

Thereafter, the grain filling process starts once the grain number has been set and as in most of the current crop models, the final grain yield relies on the partitioning of the pre- and post-flowering resource accumulation using a harvest index increase rate. This approach has the advantage of globalizing the two sources of assimilates (current growth and remobilization), while remaining economical in terms of number of parameters. In STICS, in the option we chose, the proportion of biomass allocated to the grain linearly increases with thermal time through the $vitircarb_t$ (g.grain/g.biomass/dd) parameter. In this formalism, the determination of the grain number (nbgrains) occurs simultaneously with the maximum grain weight parameter (*pgrainmaxi*) to limit the final grain allocation rate and thus avoid simulating unrealistic remobilization levels. The *pgrainmaxi* acts as a threshold parameter. It could have been reduced to fit the grain weight observe under each of the light treatments, but in that case the parameter set would have been different for each treatment, thus losing the genericity of the modelling work. In our simulations, too much biomass was allocated to the grain under the shade conditions for both growing seasons. In 2014-15, the remaining differences between the predicted and observed final yield under the shaded treatment were presumably caused by an overestimation of the reallocation of the biomass between shoots and grains. The STICS yield parameter $vitircarb_t$ is the main parameter in the model that can be involved in the overestimation of the final yield and as a consequence to an overestimation of the grain weight for the shade treatment by inducing a high partitioning rate of the aboveground biomass to the grain. In fact, this parameter has been fixed to $6.5.10^{-4}$ whatever the light treatment, while in the field, several studies have shown that after anthesis this partitioning can be highly variable and depends on environmental conditions (Li et al., 2013; Wheeler et al., 1996). For the season 2015-16, the predicted final yield is bounded: although the number of grains was satisfactorily predicted, final yield was overestimated by using the same *pgrainmaxi* value under the three treatments (fixed here at 0.045 g). These final yield predictions are not consistent with our field observations and results reported in other studies show that applying shade treatments prior to flowering until maturity affects grain number as well as grain weight.

For both components (grain number and weight), the underlying physiological mechanisms remain unclear. The simplest yield formalism proposed in the STICS model allowed to accurately reproduce the grain number, but it overrides the complexity of the grain filling and thus failed to accurately predict the final grain yield under continuous and intermittent shade environments. The formalism failed to reflect possible variations in the contribution of either the reserve build up during the vegetation or the actual photosynthesis, in response to fluctuating growing conditions. To do so, Garcia de Cortazar-Atauri et al., (2010) proposes to use the yield formalism implemented in STICS for indeterminate growing plants. That formalism provides a more mechanistic description of the final grain yield elaboration by making a distinction between the grain number setting period, the cell division phase and the cell elongation phase in the grain.

# 5. Conclusions

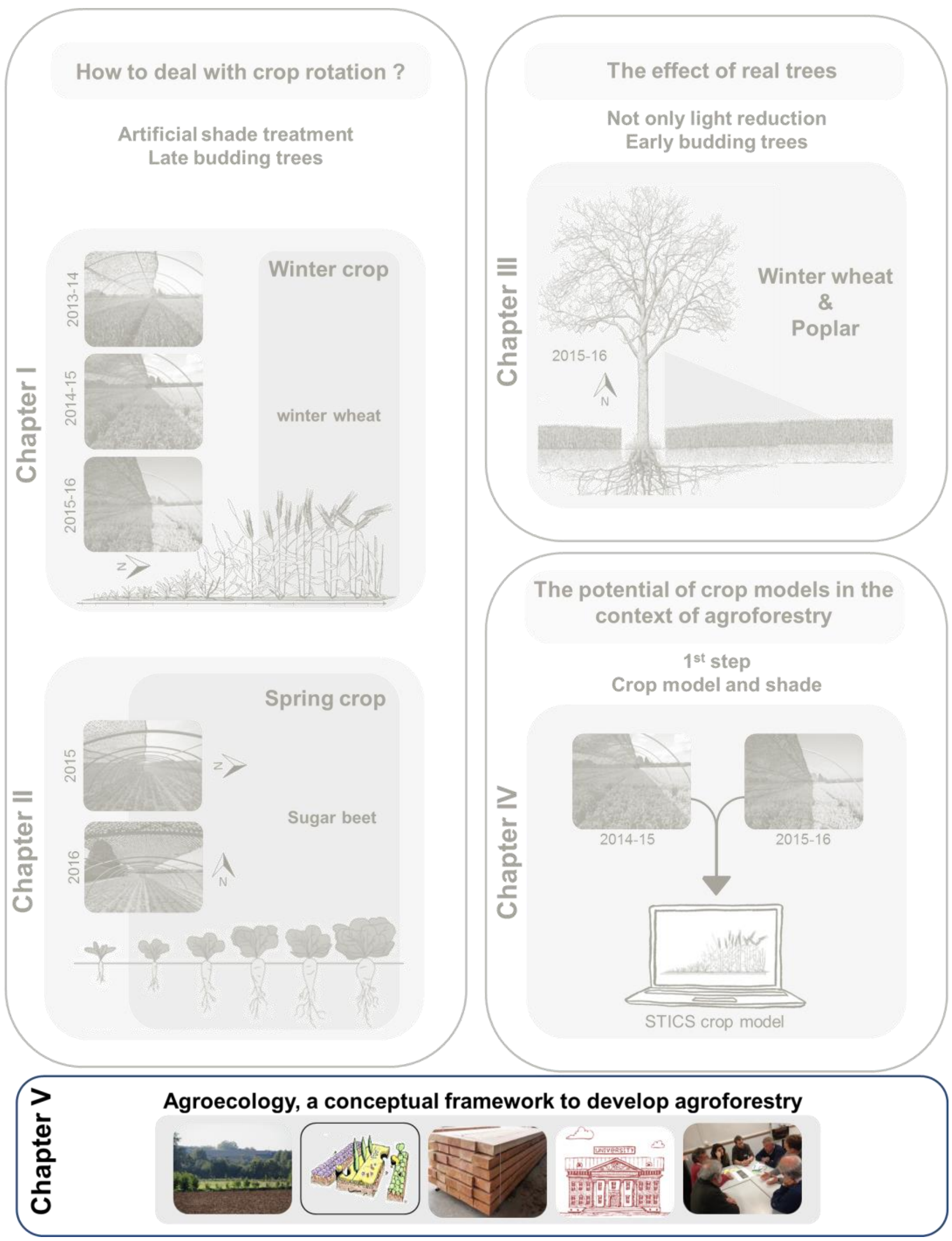
We evaluated the ability of the STICS crop model to simulate the development and the final yield components of winter wheat growing under heterogeneous light environment using a common set of plant parameters. This was performed using field data from an artificial shade experiment producing three contrasted shade treatments (NS, PS, CS) on winter wheat during two growing seasons. We showed that the overall aboveground biomass was well predicted for all three treatments. However, under the CS treatment, the implementation of a reduction of the mean daily air temperature was necessary in addition to the reduction of the incident global radiation to accurately simulate the timing of the phenological stages. Regarding the final yield components, the calibration of three plant parameters involved in the grain number formalism was mandatory to accurately predict the grain number under the NS treatment as well as under the shade conditions. Nevertheless, final grain yield and thus grain weight remained overestimated under the continuous and periodic shade treatment. This inaccuracy relies on the STICS yield prediction formalism. In fact, the present formalism did not allow to adequately reflect the complexity of reserve partitioning occurring for plants growing under fluctuating shade conditions. Therefore, these results highlight the limits of the STICS model when used to simulate crop growth under contrasted shade conditions. Thus, further progress is necessary to accurately predict the complexity of the winter wheat development and yield under shade. An interesting next step would be to use the yield formalism used in STICS for indeterminate growing plants which involves a "sink strength" function and source/sink ratio.

**Table 16.** Definition and units of the variable and parameters

| **Variables** | | |
|---|---|---|
| **Names** | **Definition** | **Unit** |
| dltams | Growth rate of the plant | t/ha/day |
| dtags | Growth rate of the grains | t/ha/day |
| iamf | Day of the maximal leaf growth stage | julian day |
| idrp | Day of the beginning of grain filling stage | julian day |
| ilax | Day of the maximum leaf area index stage | julian day |
| ilev | Day of the emergence stage | julian day |
| imat | Day of physiological maturity stage | julian day |
| ircarb | Carbon harvest index | g grain/ g plant |
| mafruit | Dry matter of harvested organs | t/ha |
| masec | Aboveground dry matter | t/ha |
| nbgrains | Grain number | grains/m$^2$ |
| pgrain | Grain weight | g |
| vitmoy | Average growth rate during the latence phase | g/m$^2$/day |
| **Parameters** | | |
| Vegetative phenological stage | | |
| *stlevamf* | Duration between ilev and iamf | degree.day |
| *stamflax* | Duration between iamf and iflax | degree.day |
| *stlevdrp* | Duration between ilev and idrp | degree.day |
| Reproductive phenological stage | | |
| *stdrpmat* | Duration between idrp and imat | degree.day |
| Yield formation | | |
| *cgrain* | - | - |
| $cgrain_{vo}$ | - | - |
| *nbjgrain* | Period before idrp to compute grain number | degree.day |
| $viticarb_t$ | Rate of increase of the carbon harvest index | g grain/g plant /day |
| Yield components threshold | | |
| *nbgrmax* | Maximum number of grains | grains/m$^2$ |
| *pgraimaxi* | Maximum weight of one grain | g |

# Chapter V.

## Agroecology a conceptual framework to develop multifunctional agroforestry systems in Europe



# Agroecology, a conceptual framework to develop multifunctional agroforestry systems in Europe?

In the previous chapters of this thesis, we have focused our research questions on the competition for light within agroforestry systems, in order to gain insights into growth mechanisms and final yield of shaded crops. Nevertheless, agroforestry can affect a number of ecological processes, beyond the effect of light availability alone. In addition to the production of commodities, it has the potential to provide a number of ecosystem services, including biodiversity conservation, erosion regulation, soil enrichment, pest and disease regulation, air and water quality, and carbon sequestration (Fagerholm et al., 2016; Jose, 2009; Torralba et al., 2016). These multiple outputs, and the flexibility of system design and management, make agroforestry a potentially useful land-use practice to mitigate—at least to a certain extent—current agricultural damage (eg. agrochemical pollution, pesticide poisoning, greenhouse gas emissions, soil erosion) (Zhang et al., 2007). Nevertheless, the effects of agroforestry on the delivery of ecosystem services may vary, and will be a result of the composition, design, and management of the systems, as well as the local context for implementation. This list of potential advantages should therefore be applied with care, and subjected to further research within distinct local contexts. Additionally, agroforestry alone will probably not allow us to solve all damaging agricultural practices. The agriculture of the future should, therefore, probably be a mix of complementary practices. Agroforestry also still requires evolution in the markets for commodities produced by famers. A profitable market for tree products (wood and/or fruits) needs to be developed, while crops cultivated under trees will probably not be exactly the same as those grown without trees.

It would seem that the development of sustainable and profitable agroforestry systems will also imply changes in agriculture and food systems. In this last paper, we present the concept of agroecology, in order reflect upon such a transition based on agricultural practices such as agroforestry, and the development of a tailored food system. We present perspectives on the role of agroforestry in developing sustainable agriculture, and in terms of food production and environmental protection. Finally, we propose the changes to current research and educational systems which will be necessary to empower this transition.

# Towards sustainable food systems: the concept of agroecology and how it questions current research practices (Review)

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## Abstract

Introduction: Multiple environmental and socio-economic indicators show that our current agriculture and the organization of the food system need to be revised. Agroecology has been proposed as a promising concept for achieving greater sustainability. This paper offers an overview and discussion of the concept based on existing literature and case studies, and explores the way it questions our current research approaches and education paradigms.

Literature: In order to improve the sustainability of agriculture, the use of external and chemical inputs needs to be minimized. Agroecological farming practices seek to optimize ecological processes, thus minimizing the need for external inputs by providing an array of ecosystem services. Implementing such practices challenges the current structure of the food system, which has been criticized for its lack of social relevance and economic viability. An agroecological approach includes all stakeholders, from field to fork, in the discussion, design and development of future food systems. This inclusion of various disciplines and stakeholders raises issues about scientists and their research practices, as well as about the education of the next generation of scientists.

Conclusion: Agroecology is based on the concept that agricultural practices and food systems cannot be dissociated because they belong to the same natural and socio-economic context. Clearly, agroecology is not a silver-bullet, but its principles can serve as avenues for rethinking the current approaches towards achieving greater sustainability. Adapting research approaches in line with indicators that promote inter- and transdisciplinary research is essential if progress is to be made.

## Keywords

Alternative agriculture, Agrobiodiversity, Ecosystem services, Socioeconomic organization, Marketing channels, Interdisciplinary research, Participatory approaches, Innovation adoption


## 1. Introduction

Common practices in the food system, defined as 'conventional' (Altieri, 1999; Kremen et al., 2012), are coming under increasing criticism in western Europe. Historically, conventional agriculture has led to greatly increased yields and growth in agribusiness, flooding supermarkets with processed food products. Nevertheless, issues such as climate change, pollution, the decline in numbers of farmers and in food quality are being addressed, as reported in the International Assessment of Agricultural Knowledge (2009). Voices calling for a revision of the conventional food system in order to achieve greater sustainability have become louder. Agroecology (also sometimes written 'agro-ecology') is being promoted as a promising concept in answer to this call.

Stassart et al. (2012) retraced the historical broadening of the scope of agroecology, from a focus on ecological processes in agriculture to socio-ecological processes. Agroecology first emerged in 1928 and evolved during the 20$^{th}$ century as the application of ecological concepts to agricultural practices, with the primary aim of reducing the use of chemical inputs and the impact of agriculture on the environment (Altieri, 1999). Agriculture is responsible for environmental pollution through, for example, greenhouse gas emissions (25 % of the total emissions worldwide; and 9 % in Wallonia, Belgium; Guns, 2008) and the use of chemicals (e.g., pesticides, growth regulators, mineral fertilizers) that are toxic to the environment (Devine and Furlong, 2007) and human health (Baldi et al., 2013). Agroecological principles suggest that we should safeguard local ecological processes that underpin the delivery of ecosystem services (ES) crucial to agricultural activities (e.g., natural soil fertility, biological control), while maintaining the productive function of agriculture (Malézieux, 2012).

Since the start of the 21$^{st}$ century, agroecology has increasingly been seen as a concept dealing with both ecological and human dimensions, thus involving all stakeholders in the food chain, from production to consumption (Francis et al., 2003), with the aim of increasing the social responsibility and economic viability of farmers' activities. In the European Union (EU), the economic viability of farms is questionable because Common Agricultural Policy subsidies account for almost all of a farmer's net income (86 %, 97 % and 90 % on average in Wallonia in 2011, 2012 and 2013, respectively; Service public de Wallonie, 2014). In addition, the large number of suicides among farmers compared with the rest of the population (in France, 20-30 % higher; Bossard et al., 2013) can be seen as a worrying trend in society. There has also been a steady decline in the number of farms and farmers over recent decades (the EU lost 2.5 million farms between 2005 and 2010; Eurostat, 2015). These facts raise questions about both the social relevance and the economic viability of the conventional food system.

In the light of these sustainability challenges, attention has started to focus on agricultural research. The conventional agricultural system is based on the results of disciplinary and reductionist research that have been applied to a large variety of pedo-climatic conditions by changing and homogenizing these systems to meet our needs (Kremen et al., 2012). The complexity of the issues involved (i.e., environmental, economic, social and health concerns) shows that holistic and decentralized scientific approaches are needed if sustainable systems are to be developed (Louah et al., 2015; Méndez et al., 2013).

The term 'agroecology' is now increasingly being used in academic publications (Bellon and Guillaume, 2012). There is a large body of work on the ecological principles of agroecology (Duru et al., 2015; Malézieux, 2012) and the socio-economic dimensions of sustainable food systems (A. M. Dumont et al., 2016; e.g. Francis et al., 2003; Gliessman, 2011). So far as we know, however, only a few papers (e.g. Stassart et al., 2012) have brought the two dimensions of agroecology together and discussed how they could be adapted to support agroecological innovation.

Based on the literature, this paper looks at how agroecology can help in planning and supporting the transition of conventional food systems towards more sustainable ones. In particular, it seeks to answer the following questions: What are the propositions of agroecology in efforts aimed at improving (i) farming practices and designs to increase environmental sustainability of agriculture and (ii) the organization of the food system in order to enhance the social and economic sustainability of agricultural product processing, distribution and consumption? (iii) How the transition towards agroecological systems challenges current research practices? This last aspect is drawn on the authors' experience of the practical issues, constraints and successes while working within the multidisciplinary research platform 'AgricultureIsLife.be' (University of Liège).

## 2. Agroecological practices to increase environmental sustainability

Since the Green Revolution, conventional agriculture has focused mainly on the production service (i.e., food, feed, forage, fiber and fuel products), often using practices that are highly dependent on anthropogenic external inputs (e.g., chemical fertilizers, pesticides, irrigation based on non-renewable water sources). These practices, however, override the key ecological processes (i.e., biotic and abiotic interactions) that underpin the delivery of ES crucial to the long-term performance of agriculture (e.g., natural soil fertility, biological control, water-holding capacity, resilience to extreme events) and lead instead to serious agricultural disservices (e.g., agrochemical pollution, pesticide poisoning, greenhouse gas emissions) (Zhang et al., 2007).

The ES framework developed through the Millennium Ecosystem Assessment (Reid and Mooney, 2005) shows that a farming system not only provides 'output services' (provisioning and cultural ES), but also receives and depends on 'input services' (supporting and regulating ES), such as biological control, water purification and nutrient cycling. Through this framework, the development of environmentally sustainable agricultural practices focuses on optimizing the balance between input and output services (Zhang et al., 2007). Wezel, Casagrande et al. (2014) noted that agroecological practices are 'agricultural practices aiming to produce significant amounts of food, which valorize in the best way ecological processes and ES in integrating them as fundamental elements in the development of practices'.

Within the ES framework, biodiversity comes as a key concept when setting out agroecological practices (Altieri, 1999; Duru et al., 2015; Kremen and Miles, 2012; Wezel et al., 2014). Three levels of integration can be distinguished: planned, associated and landscape (bio)diversity. 'Planned biodiversity' refers to the biodiversity intentionally introduced by the farmer into the agroecosystem (Altieri, 1999). This biodiversity includes the productive (e.g., cash crop, forage, timber, livestock) and non-productive (e.g., flowers) biota introduced into the system and managed at varying temporal (e.g., rotation, cover crops), spatial (e.g., intercropping, agroforestry, wildflower strips) and ecological (e.g., genetic diversity at the population, variety and species level) scales (Kremen and Miles, 2012). 'Associated biodiversity' refers to the biodiversity unintentionally introduced into the agroecosystem (Altieri, 1999). This biodiversity relies on practices that provide favorable habitats for a diversity of above- and below-ground organisms, attracting them from the surrounding environment. It contributes indirectly to the productive function by enhancing ecological processes, which in turn can provide ES (Peeters et al., 2013; Tscharntke et al., 2005). 'Landscape diversity' level takes into account the integration of biodiversity through the structure and composition of the surrounding environment (Duru et al., 2015) and sees biodiversity as a function of its relationship with the surrounding landscape. Agroecological practices integrate these three levels of biodiversity in order to provide synergies between ecological processes and achieve multiple ES delivery within the system.

The link between the principles outlined above and the concrete implications in terms of management strategies at field, farm or landscape scale have been illustrated in detail in the literature with reference to a wide array of agroecological practices (Kremen et al., 2012; Power, 2010; Wezel et al., 2014a). For example, wildflower strips (planned biodiversity) can be sown along field margins in order to control insect pests. The flowers provide a refuge and food resources (nectar and pollen) that benefit insects (associated biodiversity) that can act as pest natural enemies (predators and parasitoids). The ecological process of biological pest control is therefore an input service benefiting farmers by enabling them to reduce their reliance on insecticides (Pfiffner et al., 2009). In terms of agricultural productivity, however, results with regard to final crop yields are still scarce (Tschumi et al., 2016), but product quality would benefit from the reduction in pesticide residues in the food supply for the consumers.

In order to ensure the delivery of these ES, the surrounding landscape needs to be taken into account. For example, the mere presence of wildflower strips might not be efficient enough for controlling pests (Pfiffner et al., 2009) because the delivery of this ES depends on the colonization of wildflower strips by insects coming from (semi-) natural habitats in the landscape (e.g., woodlots, perennial grasslands) (Jonsson et al., 2015). The interdependence between landscape and plot scale in order to maintain ES is specific to each practice. For instance, Tamburini et al. (2016) showed that conservation tillage (defined in this paper as the non-inversion of soil, often combined with permanent vegetation cover) could be efficient for maintaining biological pest control even in simplified landscapes.

Both examples illustrate that the efficiency of a practice in the delivery of one or multiple services depends on interactions at different scales. It is therefore necessary to take account of plot management and landscape composition and the processes relevant to the different scales when planning strategies to maximize services.

Furthermore, synergies may appear between practices. It is therefore important to implement multiple agroecological practices in order to optimize ES delivery. For example, in a recent meta-analysis, Pittelkow et al. (2014) revealed that implementing no-tillage alone led to a reduction in crop yield, whereas combining no-tillage with soil cover (by crop residues or cover crops) and crop rotation could increase yield.

Finally, ES resulting from the implementation of one or multiple agroecological practices do not necessarily occur at the same scale as the practice itself or within the same time frame. For example, the implementation of agroforestry (defined as a land-use system that integrates, in the same area, woody elements with crops and/or livestock production; Torquebiau, 2000) will deliver ES at the farm scale because the deep rooting system of the tree and litterfall participates to nutrient cycling and therefore maintains soil fertility (Tsonkova et al., 2012). Other benefits arise on a wider scale through various processes; for example, research has shown that the presence of trees helps with carbon sequestration and thus contributes indirectly to climate change mitigation on a global scale (Jose and Bardhan, 2012). Farmers can therefore expect an annual agricultural income from crops and/or livestock, as well as from fruits and/or nuts from the trees and, in the longer term, from the capitalization of the timber.

Despite the potential of agroecological practices in providing ES, there are still some uncertainties. As highlighted by Wezel, Casagrande, et al. (2014), who outlined the advantages and drawbacks of 15 agroecological practices, their effectiveness in providing ES depends greatly on the local context. Local pedoclimatic conditions affect the ecological processes and the economic and societal environments affect the final goods. Given this context-dependent efficiency, farmers' uncertainties lack of scientific knowledge about some ecological process, possible additional costs of equipment, increase in human labor, low commercialization rate of the product, new legislation and so on (Wezel et al., 2014). Thus, farmers need to develop tailor-made practices adapted to their local context, which often entails going through a lengthy process of trial and error.

## 3. Organizing the food system in order to increase social relevance and economic viability

A production system based on ecological processes instead of inputs, as described above, challenges the entire food system because it results in greater product diversity in space and time (Kremen et al., 2012). The challenge is particularly high given that the goods produced by agricultural systems are already numerous (i.e., feed, forage, fiber and fuel; Delcour et al. 2014).

With regard to food, the conventional food system, built on the model of supermarkets and controlled by a few transnational food companies, is based on logistic efficiency, product standardization and price competition (Raynolds, 2004). While product standardization became possible through the use of mechanization and external chemical inputs (Marsden and Murdoch, 2006), the need for logistic efficiency and price competitiveness led food companies – which drive the food system – to globalize their provisioning, creating competition between farmers and promoting short-term productivity (Kremen et al., 2012; Rosset and Martínez-Torres, 2012). The significant declines in the number of farmers, however, as well as the importance of EU subsidies in farmer income, are indicators of the limits of this economic model for EU agriculture.

It is in this context that the need to design sustainable food systems arose and this issue became an integral part of agroecology. Francis et al. (2003) proposed involving all stakeholders in building such systems: farmers, processors, retailers, consumers, scientists and politicians. As Gliessman (2011) states: "Farmers alone cannot transform the entire food system." The approach was clarified recently through a list of 13 principles on which sustainable food systems are based. These include: environmental equity, financial independence, partnership between producers and consumers and geographic proximity (A. M. Dumont et al., 2016).

Among the multiple stakeholders, particular attention has been given to consumers. Involving and educating consumers has been seen as essential for 'closing the loop' in the food system (Francis et al., 2003). In this context, Community Supported Agriculture (CSA) networks, which have existed for decades, are seen as an advanced model for sustainable food systems (Kremen et al., 2012). They are built on direct links between farmers and consumers through direct selling at the local scale. They are economically beneficial because they create jobs on farms and assure farm incomes over the longer term (compared with conventional food systems) (Wezel et al., 2014c). Farmer incomes can also increase because there are fewer intermediaries in short-supply chain marketing. In addition, consumers know more about how their food is produced and therefore request and choose food products based on sustainability criteria (Kremen et al., 2012). Finally, developing short food supply chains to reconnect producers and consumers is seen as an essential aspect of any agroecological transition (Guzmán et al., 2013) and is one of the 13 principles of sustainable food systems listed by Dumont et al. (2016). A recent criticism of the CSA model, however, is that it does not include the stakeholders in the entire food system (Lamine, 2015a). By definition, it bypasses the intermediaries, whereas the transformation process should involve them.

There are other innovative models based on multiple stakeholder involvement. One is the French food cooperative ‘Biocoop’, a network of 345 organic shops (Lamine, 2015b). Unlike traditional supermarkets, Biocoop brings producers, shop managers, employees and consumers together in an ‘ethical committee’. Its role is to establish common guidelines (e.g., prices at which products are bought to producers and processors, and sold to consumers) and to ensure that the common values are respected. Biocoop’s current governance has been strengthened by addressing the criticism it faced in the 1990s, when it grew considerably and developed logistical tools and management strategies that did not appear to differ much from those of the conventional food system. This illustrates the challenge facing sustainable food system initiatives of finding a balance between remaining in a highly competitive food market while conserving core values that differ significantly from those of food companies.

The challenge also lies in informing consumers of the originality of sustainable food systems, compared with the conventional system, especially because of the confusion that can arise when food companies imply, through labeling, that their products derive from sustainable systems. As Warner (2007) highlighted, labels are used in conventional food chains to persuade consumers of product quality, because food scares have become common and face-to-face relationships no longer exist. They are even seen as ‘initiatives to create ethical space within the marketplace’ (Barham, 2002) without transforming it. ‘Quality’ is an ambiguous term, however, its meaning changing over time (Warner, 2007). Whereas food companies try to meet the quality expectations of consumers, a sustainable food system that involves all stakeholders does not need quality labels. For example, information about synthetic pesticide use, animal welfare, production location and human working conditions (i.e., the most important quality criteria for consumers, according to Howard & Allen, 2010) can be made available through face-to-face relationships in short-supply chains; in systems such as Biocoop, these criteria are discussed by the ‘ethical committee’ and made available through a charter). Transparency in the production and processing steps, as well as democratic governance (two principles of sustainable food systems; (A. M. Dumont et al., 2016), allow these systems to be highly responsive to stakeholder expectations in terms of quality, which itself can vary from one location to another (Zepeda et al., 2013).

Unlike the conventional food system, these cases show that sustainable food systems can be diverse. Although they adhere to common principles, the way in which they are implemented can vary (A. M. Dumont et al., 2016) and thus attract criticism from unsatisfied stakeholders. This decentralized and therefore flexible approach, however, allows a diversity of projects to develop, each of them tailor-made to their local context.

# 4. Scientific practices and agricultural innovations

As is clear from the discussion above, natural, social and agricultural sciences are intrinsically intertwined in food production systems and among the stakeholders in those systems. Accompanying agroecological transition therefore throws up new challenges and opportunities for research. Agroecology questions scientists about their research topics, the methods they use and develop, and the results they produce. Rather than saying that research in conventional agriculture using a biotechnological approach is no longer relevant, this section explores more holistic approaches that scientists could use to integrate complexity and uncertainty into their research practices. Not facing these challenges would lock scientific research into a limited range of thought and action, which in turn would hamper agroecological innovation (Vanloqueren and Baret, 2009).

First, in order to foster innovation, research should draw on several disciplines, in line with the holistic and complex approach of agroecology. This movement is known as 'interdisciplinary research', which is research practice that involves several unrelated academic disciplines, each with its own contrasting research paradigm (Baveye et al., 2014). Linking together agricultural, ecological and many other disciplines leads to innovative practices that restore ecological regulating processes, which increase the flow of ES and, consequently, reduce farmers' reliance on external inputs. Adding social disciplines provides the opportunity to study the conditions and processes of learning and change, as well as the interdependencies between the diversity of stakeholders in the food system (Lamine, 2015a). Such research highlights, *inter alia*, the long-term processes of change in farming practices (e.g., Chantre & Cardona, 2014) or the main reasons for a system's irreversibility, also known as the 'lock-in effect' (e.g., (Stassart and Jamar, 2008) on the Belgian Blue commodity system and (Vanloqueren and Baret, 2009) on genetic engineering). These examples illustrate how this level of understanding facilitates the development of innovative food systems.

Second, the ambition of agroecology to include all stakeholders in the whole food system leads to their iterative involvement in the research process. This research movement is known as 'transdisciplinary', defined as participatory research focused on developing practical knowledge in pursuit of worthwhile human objectives (Baveye et al., 2014), whatever the origin of the science involved and the source of knowledge implied. This approach is sometimes also referred to as 'action-oriented' or 'participatory' research, although there are distinctions between the terms and their interpretation varies among authors (Baveye et al., 2014; Méndez et al., 2013; Scholz and Steiner, 2015).

Such research practices are increasingly being acknowledged as beneficial in many ways. They create research that is relevant to a local context, which is necessary with the agroecological approach as the studied systems are highly context-dependent (Altieri, 1999; Lyon et al., 2011). They also create opportunities for collective social learning by facilitating an exchange of information among stakeholders with differing values, views and mental frameworks (Duru et al., 2015; Vilsmaier et al., 2015). Above all, they address the gap between theoretical scientific questions and everyday problems faced by local stakeholders (Duru et al., 2015), which facilitates the adoption of research outcomes. This enhances the likelihood of innovations being taken up (Biggs et al., 2011; Duru et al., 2011) and empowers participants (Méndez et al., 2013). This type of research has been successful in many transitions to agroecological-based systems, including the transition from a conventional to an organic beef production chain in Wallonia that required overcoming several cognitive, logistical and commercial 'lock-ins' (Stassart et al., 2008). Another example is illustrated by Cuéllar-Padilla & Calle-Collado (2011), who empowered farmers and supported them in the transition towards organic farming at a time when they had lost control over their marketing processes to transnational intermediaries. Transdisciplinary research is also useful in improving current management, as shown by Duru et al. (2011), who developed an assessment tool with – and for – farmers for the management of permanent grasslands that took account of the wide range of ES provided by such ecosystems. In essence, integrating various knowledge systems (i.e., scientific and practical) enables the contextual socio-ecological complexity to be taken into account while accompanying agroecological transition and developing appropriate tailor-made innovations (Cuéllar-Padilla and Calle-Collado, 2011)

It should be noted that, currently, there is still a debate about the organization of agroecology as a discipline *per se* or as an inter- or transdisciplinary practice. This debate is similar to the one about sustainability sciences: Do we need to build one overarching scientific discipline that will address the whole spectrum of sustainability issues – or agroecological issues – or is a dynamic contribution through the expression of various knowledge outputs preferable (Dalgaard et al., 2003)? Beyond this epistemological issue, it is argued that, in practice, agroecology requires a variety of sources of information and therefore that inter- and transdisciplinarity practices are complementary ways of learning (Chantre and Cardona, 2014). Indeed, the meta-level of analysis promoted by inter- and transdisciplinarity requires a certain level of disciplinary expertise to build upon.

Despite much evidence of the opportunities for research to adopt an inter- and transdisciplinary approach, challenges remain for scientists when applying these principles in practice. In order to ensure socially robust innovations, time needs to be invested from the outset of the research in setting common research objectives to address a commonly defined problem (Méndez et al., 2013). This time investment can differ between social and natural sciences, because they produce knowledge at different rates. True co-leadership between science and practice is required, where both knowledge systems are rendered visible and integrated in order to achieve greater symmetry between the two (Scholz and Steiner, 2015). Throughout the whole project, regular feedback and discussions need to take place among all stakeholders in order to redirect research or its methodology, if necessary, so as to achieve the objectives of both scientists and practitioners (Cuéllar-Padilla and Calle-Collado, 2011). In essence, communication is essential in order to learn from each other, build a climate of trust and ensure socially robust outcomes (Méndez et al., 2013).

This communication can, however, be hampered because of the variety of stakeholders involved, and hence the variety of (sometimes confronting) worldviews and knowledge systems. Each stakeholder sees a farming system from a different angle, depending on the plurality of the system's elements and context. With regard to scientists' worldviews, Bawden (1997) defined three research positions: technocentric, ecocentric and holocentric. Whereas the technocentric position promotes technical solutions, the ecocentric one seeks to manage ecological processes and the holocentric one integrates human processes and their interactions within the natural environment. Disciplines and knowledge systems also have their own traditions, methods, language and frameworks, which can prove difficult to coordinate and hamper discussions (Dalgaard et al., 2003; Vilsmaier et al., 2015). In addition, knowledge is influenced by one's experiences (referred as 'grounded knowledge', Ashwood et al., 2014), which further challenges coordination.

Given the challenges of implementing inter- and trans-disciplinary research, we argue that such shift in a researcher's position needs to be supported. A more fundamental and methodological type of research is needed, one that develops methodologies that are readily applicable in inter- and transdisciplinary research, such as 'World Café', 'Delphi surveys' and 'Citizen juries' (Elliott et al., 2005). More importantly, educational programs have a role to play in fostering and conveying these new methods and training scientists in these new approaches. Some academic agroecological programs are based on learning-by-doing pedagogy (Francis et al., 2013; Lieblein et al., 2007), with the students' learning taking place *in situ* (e.g., farm, rural development organization) and being open-ended (i.e., searching for solutions not already known by professors). Theoretical and methodological approaches from natural and social sciences are progressively introduced to the students, who have to integrate demands from the stakeholders. In this way, students are trained in inter- and transdisciplinary practices to give them the ability to coordinate distinct grounded knowledge through a reflexive process. The contrast with conventional agricultural education systems is obvious: agroecological programs enable students to reconnect with actual conditions in the field, something that has been lost in agricultural academic institutions. They also focus on the system as a whole with a holistic perspective, rather than focusing on narrow segments of the food system (Louah et al., 2015). We believe that there is a need for a thorough reform in agricultural academic institutions where, currently, agroecological approaches play a minor role (DeLonge et al., 2016).

Repositioning the researcher raises further questions about current academic mindsets and institutions. The process of including stakeholders within the definition of the research issue, reflection and action, and of integrating various disciplines, is time-consuming, produces practical knowledge relevant to a specific local area (Cerf, 2011) and leads to multiple research leaders, multiple data owners and multiple author articles. All this ill suits the classical scientific working climate, with its academic performance benchmarks of personal fast accumulation of publication (Cowling et al., 2008; Daily and Ehrlich, 1999; Dalgaard et al., 2003). Adapting current research context in order to integrate inter- and transdisciplinary research approaches into the development of agroecological innovations is a major challenge, but one that urgently needs to be addressed.

## 5. Towards tailor-made solutions rather than recipes

The term 'agroecology' is now widely used, but its meaning differs depending on who is using it. Too often, agroecology is presented with only one of its two major components considered: agricultural practices and food system organization. In addition, some research projects claim to use the concept of agroecology, and yet ignore the holistic approach. In this paper we argue that, within agroecology, agricultural practices and food system organization cannot be dissociated from each other because they are both needed in order to achieve sustainability from field to fork. We also argue that inter- and transdisciplinary approaches are needed in order to address the issues of sustainability.

We have shown, first, that there are practices based on ecological processes that allow the use of external inputs to be reduced and thus increase the environmental sustainability of farming. Second, we have shown that stakeholders in the food system are able to organize themselves in order to safeguard their activities and guarantee the social relevance and economic viability of the practices. It is clear, however, that challenges remain and therefore none of the existing examples should be taken as copy-paste solutions. Agroecology is not about 'one-size-fits-all' solutions or clear-cut recipes (Lyon et al., 2011). Rather, it suggests taking into account the natural and socio-economic environment where the food is produced and calls for the development of innovations within this precise context. We have shown that contextualizing innovation processes can require working across different scales, combining a variety of methods and drawing on various kinds of knowledge because the challenges are often complex. Agroecology therefore requires the involvement of multiple disciplines and stakeholders within the research process. With this research approach, researchers need to adapt the way in which they address the problem: the choice of the methods to use and the scales to work at will depend on the problem they need to address. Similarly, farmers facing problems with crops or livestock need to adapt their practices according to the specific conditions of their farming context (Lyon et al., 2011).

Overall, in order to re-organize the food system and develop innovations through research, agroecology proposes that is necessary first to step back and observe the complexity of local conditions before applying general solutions. Contextualization means there can be no silver-bullet; every problem requires a tailor-made solution adapted to its specific socio-ecological context. This is why there are numerous examples of agroecological innovations, as well as their shortcomings. These tailor-made solutions, however, are an appropriate way of achieving sustainability in agriculture and in the organization of the food system.

# Conclusions, discussions, perspectives

# Overview of the results

- For both crops, the magnitude of final yield repercussion varies with the length and severity of light reduction, as well as the stage of crop development at which the light reduction occurs.
- The artificial shade simulated shading from a canopy of late-flushing trees. At the scale of the crop growing season, the shade treatments were applied over a period of 67 days on average (out of 290 days) for the winter wheat, and 136 days (out of 190 days) for the sugar beet.
- Under the artificial shade treatment, the maximal decrease in global radiation reaching the crops ranged from - 64 % under the continuous shade treatment, to - 43 % under the periodic shade treatment. According to the sAFe-Light model, crops growing under a north-south tree line orientation never experience a reduction in light greater than 60 %, even under 50-year-old agroforestry systems. The value recorded under the continuous shade treatment would be achieved only under east-west orientation from 40-year-old systems, and only on 10 % of the cropped area.
- For the winter wheat, the artificial shade treatments significantly affected final yield, through a reduction in the average grain weight and the number of grains per $m^2$. The maximal reduction was observed during the growing season 2014-15, with a decrease of final grain yield by 45 % and 25 % for the continuous and periodic shade treatments respectively, as compared to the treatment without shade.
- For the sugar beet, the artificial shade treatments induce morphological changes in the aboveground part of the crop, in addition to a reduction of the final root dry matter and sugar yield. Whatever the shade treatment, the final sugar yield reduction was proportional to the amount of global radiation received during the growing season. The continuous shade treatment induced a maximum yield reduction of 74 % in 2015, while the periodic shade treatments led to intermediate productivity, with a decrease ranging from 38 % in 2015, to 22 % and 40 % for the periodic shade treatments $PS_{am}$ and $PS_{pm}$ in 2016, respectively. Sugar beet quality was also affected by shading, but to a lesser extent than the final root dry matter and sugar yield.
- Under the tree-bordered field, the presence of the poplar trees significantly reduced final grain yield, with spike number per $m^2$ and grain number per spike following a gradient from tree to the centre of the field. Even when subjected to other biotic and abiotic interactions, the maximum yield reduction observed in this field never reach the level of

decrease observed under the artificial continuous shade treatment. In fact, at 3 m from the trees, final yield was decreased by - 41 %, as compared to the data at 30 m.

› The STICS model allows us to correctly simulate aboveground biomass dynamics under constant shade treatment, but not under the periodic shade treatment. Further adjustments are required in biomass partitioning formalism in order to accurately predict the final yield of winter wheat under shade environments.

› Finally, we present agroecology as a conceptual framework to develop sustainable and profitable agroforestry systems in Europe, reflecting on agricultural practices, food systems, and research methodologies. We argue that there is no silver bullet solution, and the implementation of an agroforestry system requires tailor-made solutions adapted to its specific socio-ecological context.

# General discussion and perspectives

Despite the increasing number of studies dealing with agroforestry systems, knowledge is still lagging behind on monocrop systems due to the complexities of the interspecies interaction. Moreover, the numerous possible combinations between tree and crop species, pedo-climatic environments and practices as well the long time scale needed for such research are limiting factors. Faced with this diversity it remains difficult to obtain a clear overview of the overall system functioning which challenges our research practices. In this thesis, we addressed only the question of competition for the resource “light”, which simplifies the complexity of the system under study. Experimental and modelling approaches were combined to get insights into how the growth mechanisms of crops and final yield respond when subjected to a heterogeneous spatio-temporal shade environment.

## 1. Artificial shade: a good proxy for the light environment of an agroforestry system?

In our experiments, the experimental set-up of the artificial shade was developed in order to isolate the competition for light from other possible abiotic and biotic interactions occurring in agroforestry systems. The shade structure was designed to recreate, as far as possible, the inherent physical characteristics of the radiation environment observed in an agroforestry system.

In view of the large diversity of agroforestry systems, it is difficult to associate the current experiment with a specific agroforestry system light environment. Firstly, the military cloth does not entirely reproduce shade under tree leaves, since the gradual intensification of shade during the growing season cannot simply be reproduced by adding a single additional layer of cloth. The artificial shade set-up induced a sharp reduction in light availability from one day to the next, while the data under the poplar trees in Herzele shows that, in reality, there is a more progressive intensification of shade. Furthermore, as highlighted by Talbot et al. (2012), in agroforestry systems, a permanent presence of shade can be expected due to the trunk and branches of the leafless trees in winter, which was not reproduced by our artificial shade structure. In addition to differences in quantity and timing, we also can expect differences with respect to light quality. In this thesis, we did not evaluate whether the shade material absorbs or blocks PAR wave bands. Varella et al. (2010) has shown that using a slatted wood structure above lucerne can allow us to reproduce the same spectral change in the R/FR ratio as is produced by coniferous and deciduous tree shade, as compared to full light conditions. Under trees, red light is absorbed by the leaves, while far red light penetrates through the canopy. Under the slat material, the authors hypothesize that some of the red and far red wave bands are blocked by the opaque wooden slat, while the rest coming through the gaps are reflected upwards by the crop canopy and then re-reflected by the wooden slat—increasing the proportion of far red wave bands under the shade structure. In our studies, a similar behaviour can be expected under the camouflage net material, because it consists of an opaque cloth with a certain proportion of holes.

Secondly, the combination of tree age and field layout may result in a range of possible situations, all corresponding to our shade treatments. The artificial shade set-up creates an extreme range of shade environments. In Chapter I and Chapter II, we showed that the CS treatment is an extreme case, corresponding to old trees and high plantation densities, or to tree rows with an east-west orientation, and will most probably not occur in the field, given current agricultural practices and machinery. Even the measurements conducted under 35-year-old poplar trees in Herzele did not result in shade levels comparable to the CS treatments. The PS treatment is more realistic, simulating lower shade environments, corresponding to younger trees and/or more open plantation densities.

Finally, in this experiment, we assume that no climatic variables other than light are significantly modified by the shade structure. As a consequence, we relate crop adaptation to shading effects only. Former work on agroforestry systems suggests that air temperature at crop canopy level may be reduced by shade. In mature agroforestry systems (15–20-year-old hybrid walnut plots), Gosme et al. (2016) found that, on clear days in spring, when temperatures are high and the trees have leaves, the daily average air temperature 1 m above the soil can decrease by, on average, 1.2°C in the agroforestry plot, as compared to the control plot. Likewise, Karki and Goodman (2015) recorded a maximum decrease of 3.8°C in August under 15-20-year-old loblolly pines. At a daily timescale, air temperature is higher under trees at night and lower during the day than in open air (Gosme et al., 2016). The same daily patterns have been observed under a wooden slat artificial shade structure installed 0.3 m above lucerne (Varella et al., 2010). In contrast, Marrou et al. (2013) showed that under agrivoltaic systems, air temperature and vapour pressure deficit at 2 m above the soil were not significantly affected, due to sufficient air circulation. The differences observed between the studies can be explained by the fact that air temperatures recorded at 2 m may differ strongly from near canopy temperatures, because crop transpiration rates affect microclimatic conditions and thus might either mitigate or amplify the impact of air temperature on crop development. In our work, the height of the artificial shade structure and the presence of holes in the shade layers allowed the air to circulate. Nevertheless, under the constant shade treatment, as well as at 3 m and 5 m from the poplar tree in Herzele, we noticed a delay in winter wheat maturity of around 10 days. In addition to light availability, this delay might have been caused by differences in air temperature. We therefore recommend this aspect be tested in further research.

## 2. Impact of a reduced light environment on winter wheat and sugar beet in the Belgian soil and climatic context: what did we learn?

The combination of data acquired in this study, on winter and spring crops, and on the comparison of simulated hybrid walnut trees and poplar trees, has allowed us to test contrasted situations for Belgium's soil and climatic context, in terms of shade duration at the diurnal and growing season scales.

Regardless of the combination, winter wheat and sugar beet responded to the light decrease with decreases in growth and yield. These results are no exception to what can be found in the literature (Chirko et al., 1996; Dufour et al., 2016; Li et al., 2010; Mu et al., 2010; Pidgeon et al., 2001; Watson et al., 1972; Werker and Jaggard, 1998). Nevertheless, we propose that the magnitude of the impact of shade depends greatly on the crop species and the phenological stage during which shade is applied.

For the sugar beet, the shade treatments were applied during the major part of the vegetative period, influencing both aboveground and belowground development. The sugar beet responded by adjusting a set of morphological traits in order to optimise light capture and use. This shade-avoidance strategy resulted in a redirection of more biomass into the petiole than into the leaves, energy because the plant is not allowed to escape the shade of trees. The storage of biomass in the roots, and the final sugar yield, were drastically reduced, and this reduction was proportional to the amount of global radiation received throughout the growing season.

The reduced light environment also had a negative impact on the final grain elaboration and filling periods of winter wheat. Under poplar trees, we additionally observed a reduction in the accumulation of vegetative biomass. However, here we did not observe clear morphological changes due to shade. The final grain yield reduction of wheat is caused by a decrease in the number of grains per $m^2$. In the artificial shade experiment, the number of grains per spike was reduced, whereas under the poplars it was rather the number of spikes that reduced. We also noticed differences regarding the grain filling process in the two systems. Under the artificial shade system, thousand grain weight decreases with increasing shade, while the inverse pattern was observed under the trees, with well-filled grains near the trees as compared to the reference. This difference can be explained by the significant decrease in the number of grains per spike near the tree, allowing them to be fully filled even if the pool of assimilate accumulated before flowering had been reduced by the shade. Thus, the final grain yield reduction observed, even very near to the poplar trees in Herzele, did not reach the decrease recorded under the CS treatment. Under this treatment, the level of shade was higher than under the trees, but light competition was the only abiotic interaction. Under the trees, potential competition for water or nutrients also has to be taken into account together with the light reduction. Microclimate change, soil moisture, nutrients, or simply plot heterogeneity may explain some of the differences observed in the real tree-bordered plot.

The artificial shade levels created by the artificial shade set-up allowed us to gain an insight in crop response to continuous and fluctuating shade environments. We observed that the magnitude of the response of both crops varies with the level of shade application, leading to intermediary repercussions for crop growth and productivity if periodic shade is applied. Final root dry matter and sugar yield of sugar beet are correlated to the cumulated incident global radiation, whatever the light periodicity. Final winter wheat grain yield is non-linearly related to the cumulative global radiation from sowing date to harvest, with a complex response pattern under the periodic shade treatment. From a physiological point of view, a fluctuating light environment has a major impact on a plant's photosynthetic rate. The response of the plant to this particular light encompasses complex feedback mechanisms between stomatal conductance, the activity of photosynthetic enzymes, and combined environmental factors (ie. solar radiation, air temperature, humidity, and soil water potential CO2 concentration) (Pearcy et al., 1996; Peri et al., 2002). Nevertheless, the relative role of each of these factors is not yet well understood. Our observations should therefore be interpreted with care, and extrapolation to other situations remains difficult at the present time.

Furthermore, it must be emphasised that the crop varieties sown in our experiments have been selected to perform under full light growth conditions. Several authors highlight the necessity of selecting varieties with strong capacities to adapt and remain resilient to a heterogeneous growing environment (Desclaux et al., 2016; Smith et al., 2012). In this context, the use of a composite cross population (CCP) created by a recombination of diverse seed stocks through hybridisation may be an alternative to the classical idea of a homogeneously sown field, especially in the highly heterogeneous environment created in agroforestry systems.

In future work, research activities are needed on other tree-crop-environment interactions, in order to gain an overall view of system functioning. In addition to a wider set of processes which need to be monitored, a broader range of agroforestry systems and farms should also be targeted, in order to come to a real understanding of system functioning within a specific local context. We have argued that it also remains necessary to include tree productivity in the research reflections, in order to evaluate the rate of compensation of crop yield decrease. Finally, not only crop productivity but also tree growth should be assessed, in order to evaluate whatever yield loss can be compensated for by wood production.

## 3. Can current crop models deal with dynamic shade?

In general, crops models do not account for diurnal variations in environmental conditions, and use mean daily data as input variables. Based on our observations of different crops' growth under constant or dynamic shade, we have evaluated whether this simplified modelling approach would give satisfactory results under dynamic shade.

We have shown that the overall aboveground biomass of winter wheat was predicted well under the constant shade treatment, while biomass was underestimated when the winter wheat was subjected to a periodic fluctuating shade environment. Furthermore, in order to accurately simulate the timing of the phenological stages, we had to impose a reduction in the mean daily air temperature under the CS treatment, in addition to the reduction of the incident global radiation. For the periodic shade treatment this was not necessary. This again shows that additional micro-climatic change might have occurred, and needs to be taken into account in our experiment. Consequently, this also challenges the modelling of a crop as part of an agroforestry system within which a gradient of microclimatic conditions occurs.

Regarding final yield, grain number was predicted well under the three light conditions. Nevertheless, the STICS formalism did not allow us to adequately reflect the complexity of reserve partitioning occurring for plants growing under shade conditions. To accurately address this complexity, the use of an explicit remobilisation process in our modelling approach appears necessary. It would have been interesting to evaluate the ability of the STICS crop model to simulate sugar beet growth and productivity under shaded conditions, because the dynamics of biomass accumulation within the vegetative and root compartments remain linearly correlated with light, and present one of the simplest remobilisation formalisms. The late shade simulated by the artificial shade treatment in this PhD thesis only gave us the opportunity to focus on grain elaboration formalism. It would be interesting to use the artificial shade set-up with shade applied earlier in the season, in order to evaluate the ability of the STICS model to simulate aboveground biomass accumulation before flowering with potential morphological modifications under shade.

## 4. How to include stakeholders to co-construct research questions?

In this thesis, we assess one single aspect of agroforestry systems by focusing on light resource interaction through an experimental and modelling approach. Nevertheless, the adoption of agroforestry practices will depend greatly on local agricultural practices and economic opportunities (Graves et al., 2009). As mentioned in the last chapter of this thesis, addressing the issues of sustainability from field to fork requires changes in current research and educational systems. In fact, the complexity and multifunctional nature of agroforestry calls for a multidisciplinary research approach. According to Doré et al. (2011), multiple-objective practices—such as agroforestry systems—and context-dependent agriculture challenge agronomic research, and call for the diversification of knowledge sources. These authors propose combining the agronomic approach, based on recent progression in plant sciences, with natural ecosystem functioning analysis, and farmers' knowledge. The inclusion of various disciplines and stakeholders challenges current research practices, demanding the adoption of real interdisciplinary and transdisciplinary research. According to Mackenzie et al. (2012), in a transdisciplinary approach, 'participants, those with a stake in the outcomes of the research, take on an active co-researcher role'. Thus, 'researchers enter into a collaborative partnership with participants to facilitate improved practice through the direct application of research findings in a practical context'.

With this in mind, we initiated such a participatory approach in order to generate the relevant scientific questions to be developed on the agroforestry plot of the experimental farm of Gembloux Agro-Bio Tech. Fifteen persons, including four farmers, seven researchers, and a broad panel of members of associations met to discuss system management and prioritise future research questions. All the farmers are landowners, with agroforestry projects ranging from poplar short-rotation coppice, to silvoarable systems with high value trees, and hedgerows, with periods of implementation from four to ten years. During the discussion, the four farmers emphasised that improvements in environmental services, such as soil conservation and biodiversity, contributed to their choices to implement agroforestry systems on their own farms. They also mentioned diversification of products and income, and these varied according to the farmers' projects or profession. Furthermore, the user group highlighted some obstacles to and concerns with the development and adoption of agroforestry systems. Aside from difficulties related to legislation, the complexity in managing such diversified systems was highlighted. Many questions emerged, regarding the management of strips under trees, and whether they act as a reservoir for weeds, on the ideal width of a strip to minimise competition and optimise beneficial interactions between tree and crops, on pruning strategies for trees and hedgerows, and so on. The discussion indicated that there is a strong need for reference material and technical advice regarding agroforestry management. At the conclusion of the meeting, research priorities raised by the stakeholders included: quantification of soil biodiversity (micro and macro fauna); quantification of the presence of pests and pollinators; studying weed diversity and dispersion; evaluating the influence of shade and windbreaks on crop productivity; characterising tree rooting systems for better management; and tracking the evolution of soil organic matter. Overall, participants argued for optimising ecological processes by combining agroforestry with other practices, in order to minimise the need for external inputs, and they highlighted a lack of knowledge, and the complexity of this question. Thus, they emphasise the importance of sharing experiences and mistakes in order to transform agroforestry into a safe and sustainable investment. This meeting was an encouraging first step in the participatory process. Future meetings will be held twice a year, each time hosted by one member of the user group, and will discuss new research results, co-construct questions and solutions, and explore different agroforestry systems through field visits organised by the hosting partner.

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