Field Crops Research 215 (2018) 83–93

Contents lists available at ScienceDirect

Field Crops Research

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

How does STICS crop model simulate crop growth and productivity under shade conditions?

S. Artru[a,*,1], B. Dumont[a,1], F. Ruget[b], M. Launay[c], D. Ripoche[c], L. Lassois[a], S. Garré[a]

[a] Université de Liège, Gembloux Agro-Bio Tech, Terra Research Center, AgricultureIsLife, Passage des deportés 2, 5030 Gembloux, Belgium
[b] UMR1114 EMMAH, INRA, centre de recherche PACA, 228 route de l'Aérodrome, Domaine Saint Paul, Site Agroparc, 84914 Avignon, France
[c] US1116 AGROCLIM, INRA, centre de recherche PACA, 228 route de l'Aérodrome, Domaine Saint Paul, Site Agroparc, 84914 Avignon, France

ARTICLE INFO

Keywords:
STICS model
Agroforestry
Shade
Winter wheat
Grain yield
Grain number

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.

1. Introduction

Within silvoarable agroforestry systems, defined here has the integration of tree rows within cropped area, 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 growing season time scale, 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 path, an appropriate tree density and an adapted 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

* Corresponding author.
E-mail address: artru.sidonie@gmail.com (S. Artru).
[1] These authors contributed mainly to this work.

http://dx.doi.org/10.1016/j.fcr.2017.10.005
Received 30 January 2017; Received in revised form 31 August 2017; Accepted 5 October 2017
0378-4290/

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 important 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 the computation time (Leroy et al., 2009; Malézieux et al., 2009; Roupsard et al., 2008) and therefore the discretization level should be adapted to the modelling objectives.

In a review comparing representative multi-species system models, Malézieux et al. (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, in such models the radiation received by the crop is summarized by the daily cumulated global radiation. Nevertheless, several studies highlighted that a decrease in vegetative growth is observed under a fluctuating and heterogeneous light environment, the decrease in biomass being however not proportional to the light reduction (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.

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 range of validity (e.g. a reduced light environment), which can lead to an over- or underestimation of crop growth.

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. STICS has already been validated under full light conditions (Coucheney et al., 2015) but never under shaded conditions while within silvoarable agroforestry system, implementing an east-west tree line orientation induces a high degree of light heterogeneity for the crop. In fact, 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. In this context, this paper deals with two specific research questions: Using STICS crop model (i) Is it possible to predict the response of winter wheat to these different light conditions, using a single and common plant parameter set? (ii) Is the daily cumulated global radiation sufficient as the main driver to simulate the development of winter wheat subjected to periodic shade?

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.

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 location 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 the last 30 year (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) (Fig. 1c & d).

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 × 5 m) 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