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Simulating potential growth in a relay-strip intercropping system: Model description, calibration and testing

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ABSTRACT

Intercropping tends to have a higher productivity than traditional sole crops, mainly due to complementary resource use in time and space among different species. Intercropping may become more important in a world that needs to produce 60–70% more food by 2050 with limited land and other agricultural resources. To assess the role of intercropping in agricultural systems and its contribution to future food security, an intercrop model is needed for growth and yield predictions of intercrops under different growing conditions. Strip intercropping is a prevalent intercropping system, but the existing intercrop models are generally built for full mixtures and are less suitable for strip intercrops. Here we describe a simple intercrop model which is developed based on a sole crop model using the radiation use efficiency (RUE) concept and a strip intercrop light partitioning module. The model allows simulating the growth and yield of each intercropped species in relay-strip intercropping under potential growing conditions (only competition for light; other resources are assumed to be non-limiting), and the intercrop could vary in species combination, planting configuration, sowing densities and sowing dates. The daily inputs of the model are temperature and radiation, and crop-specific parameters are required to simulate crop leaf area index (LAI), biomass and final yield. Data collected during two years (2013 and 2014) field experiments were used to calibrate and test the model. The experiments consisted of two sole crop treatments (sole wheat, SW and sole maize, SM) and three intercrop treatments (replacement intercrop, 6:2WM and add-row intercrops, 8:2WM and 6:3WM). The experiments were conducted in Wageningen, the Netherlands. Data of sole crops (SW and SM) and replacement intercrop (6:2WM) treatment were used to calibrate the model, and data of add-row intercrops (8:2WM and 6:3WM) were used to test the model. Bayesian analysis was applied to calibrate RUE of wheat and maize in sole crops and intercrop. This calibration procedure resulted in posterior distributions of RUE for sole crops and intercrop, on the basis of which distributions of biomass and land equivalent ratio (LER) were simulated. Biomass accumulation and yield of each species were simulated adequately but LAI was slightly overestimated compared to observations. The intercrop model allows simulating the contribution of border row effects to the productivity of intercrops. It combines a simple structure with easy calibration and enables growth and yield simulations for a wide range of relay-strip intercrops. The model thus can be of value in exploratory land use studies to assess the role of intercropping.

1. Introduction

Intercropping is defined as the cultivation of two or more crop species simultaneously in the same field (Vandermeer, 1989). Relay intercropping is the cultivation of different crop species with partial overlap in growing period, and strip intercropping is the cultivation of different crop species in alternating narrow strips. In strip intercropping, the crop strips usually are wide enough to permit independent cultivation but narrow enough for the crop species to interact with each other at the plant level (Vandermeer, 1989). A relay-strip intercrop is a relay intercrop which is arranged in strips. Examples are the wheat-maize intercrop and wheat-soybean intercrop in northwest China (Li et al., 2001; Knörzer et al., 2009), where wheat is sown in March and harvested in July, while maize and soybean are sown in April and harvested in September. A relay intercrop allows for a longer total growth duration compared to each sole crop, and the associated greater radiation capture over the whole season tends to increase yields compared to the sole

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crops (Fukai and Trenbath, 1993; Zhang et al., 2008; Yu et al., 2015). When relay intercrops are arranged as strips, the plants growing in border rows have more space and resources, especially during the time before or after the co-growth period. Those border row plants are likely to be more productive than those in inner rows or in a sole crop. For instance, in wheat-cotton intercrop, the co-growth of wheat and cotton is about seven weeks, resulting in significantly higher (61%) wheat grain yield in border rows than in inner rows (Zhang et al., 2007).

Relay-strip intercropping has been widely practiced by farmers in China (Li et al., 2001; Zhang et al., 2007), but a declining trend of intercropping is observed in the North China Plan due to the increasing labour price and a shift of rural labour into the construction and industrial sectors (Feike et al., 2012). This decline in the usage of intercropping could pose a risk to local food security as sole crops are generally less productive than intercrops. Land use studies can be helpful to reveal the role of intercrops in sustainable food systems in regions where intercrops have played or are playing an important role in food security. Crop models can integrate abiotic and biotic factors to assess the land productivity under different conditions and with different crop systems. Sole crop models are used to analyse yield potentials and yield gaps, for instance for rice, wheat and maize (Boling et al., 2010; Liang et al., 2011; Laborte et al., 2012; van Ittersum et al., 2013). They may also be used to study the resource allocation at farm or regional levels (Lu et al., 2004; van Oort et al., 2015).

Several intercrop models exist which simulate light competition between two intercropped species, but most of the models assume a horizontally homogeneous canopy (Kropff et al., 1984; Lantinga et al., 1999). For example, the crop-weed competition model INTERCOM (Kropff and van Laar, 1993) assumed a horizontally homogeneous canopy for crop and weed in a study on celery-leek intercropping (Baumann et al., 2002). A homogeneous mixing was also used to simulate pea-barley intercrop (Brisson et al., 2004; Corre-Hellou et al., 2009) and cereal-legume mixture (Tsubo et al., 2005). These models, however, are not well-suited to simulate the light competition in relay-strip intercrops, where the border row effect plays an important role (Zhu et al., 2015, 2016) and the strength of competition for light depends on the planting configuration (row spacing, sowing densities, and sowing dates).

Crop radiation use efficiency (RUE) is defined as the ratio between dry matter production and cumulative intercepted photosynthetically active radiation (PAR) (Monteith, 1977; Gallagher and Biscoe, 1978; Haverkort and Bicamumpaka, 1986). The RUE concept laid the foundation for crop models to simplify crop biomass accumulation from parameter-rich photosynthesis process-based models, e.g., SUCROS (Bouman et al., 1996; van Ittersum et al., 2003) to more parameter-sparse models based on light interception and utilization, e.g., LINTUL (Spitters and Schapendonk, 1990; Bouman et al., 1996) and APSIM (Keating et al., 2003). The RUE of a crop in an intercrop may differ, however, from its value in a sole crop. For example, when intercropped with millet, groundnut has a higher RUE than when it is grown as a sole crop (Marshall and Willey, 1983; Harris et al., 1987). Intercropping of wheat and maize increases wheat RUE but lowers maize RUE (Gou et al., submitted). These different RUEs are not captured in crop growth models. Often, intercrop models are parameterised based on characteristics of sole crops and then used for intercrops, e.g., celery-leek intercrop (Baumann et al., 2002) and pea-barley intercrop (Corre-Hellou et al., 2009). While similarity of RUE in sole crops and intercrops is a useful null hypothesis and starting point for intercrop modelling, it may not be realistic for asymmetric competitive relationships in intercrops that affect radiation use efficiencies. All in all, the existing intercrop models could neither be well suited to simulate light competition in relay-strip intercropping arrangement, nor be properly calibrated for intercropping growing conditions.

The objectives of this paper are: 1) to develop an intercrop model based on the radiation use efficiency approach for a strip intercrop, and 2) to calibrate this crop model based on literature data and experimental data for sole crops and replacement intercrop with wheat and maize, taking into account possible differences in radiation use efficiency between crops grown as sole crops or as intercrops; 3) to test the model by comparing simulated leaf area index, and biomass accumulation in augmentative intercrops with field data; 4) to show in a simulation study how accounting for strip structure affects calculated light interception and biomass growth of each species, and 5) to illustrate by sensitivity analysis how the key parameters influence the leaf area index and biomass growth of each intercropped species.

2. Materials and methods

2.1. Model description

The model considers two crop species planted as a relay-strip intercrop, with strip width (Strip 1) and path width (Path 1) for the early sown crop, and strip width (Strip 2) and path width (Path 2) for the late sown crop (Fig. 1). The two crops are assumed to only compete for light. For each crop, phenological development and biomass growth are simulated and related to a temperature sum (T_{sum}). Fig. 2 shows the general structure of the model; feedbacks of light interception, biomass accumulation and leaf area dynamics are simulated for each crop. The strength of light competition of two crops is determined by their height, leaf area indices and planting configuration (strip and path width of each species).

2.1.1. Phenological development

Crop phenological development is determined by temperature sum (or thermal time, T_{sum}, °C d) from sowing date to crop maturity. The T_{sum} is calculated on the basis of daily mean temperature (T_{ave}) and crop base temperature (T_{b}); and T_{sum} is also an indicator for simulation of leaf area dynamics (leaf growth and senescence) and biomass partitioning.

$$T_{\mathrm{sum}} = \sum \max(0, (T_{\mathrm{ave}} - T_{\mathrm{b}})) \tag{1}$$

where the "max" function means zero degrees will be added to T_{sum} when the daily average temperature is lower than T_{b}.

2.1.2. Leaf area expansion

Simulation of light interception and crop growth requires simulation of leaf area index (Monteith, 1977; Jamieson et al., 1998). Under potential growing conditions, when crops are supplied sufficiently with water and nutrients and their growth is not reduced by pests and diseases (van Ittersum and Rabbinge, 1997), the main factors affecting the rate of LAI increase are temperature (Horie et al., 1979), radiation and dry matter accumulation (Dale, 1988). In this model, two phases of LAI expansion (LAIa and LAIb) are recognized for each intercropped species: temperature-dependent and radiation-limited expansion. The critical point of transition occurs when LAI ≈ 1.5 (under sole crop condition) for wheat when self-shading or self-competition begins to be important (van Delden et al., 2001). For temperature-dependent growth, an exponential growth of LAI is assumed, and the relative growth rate of the leaves (RGRL) is a function of daily active temperature (Eq. (2)).

$$\Delta LAIa = LAI_{\mathrm{t-1}} \times RGRL \times \max(0, (T_{\mathrm{ave}} - T_{\mathrm{b}})) \tag{2}$$

where $LAI_{\mathrm{t-1}}$ is the leaf area index at the previous day, $\Delta LAIa$ represents daily LAI increase during temperature-dependent growth, and $RGRL$ is the relative growth rate of LAI ((°C d)$^{-1}$).

During radiation-limited growth, leaf area expansion is proportional to leaf weight increase, where the daily leaf area expansion