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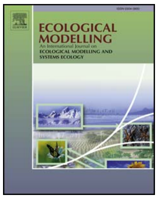

Exploring adaptation strategies of coffee production to climate change using a process-based model

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ABSTRACT

The response of coffee (*Coffea arabica* L.) agronomical performance to changes in climate and atmospheric carbon dioxide concentration ([CO_2]) is uncertain. Improving our understanding of potential responses of the coffee plant to these changes while taking into consideration agricultural management is required for identifying best-bet adaptation strategies. A mechanistic crop modelling approach enables the inclusion of a wide range of prior knowledge and an evaluation of assumptions. We adapt a model by connecting it to spatially variable soil and climate data, by which we are able to calculate yield of rain-fed coffee on a daily time-step. The model takes account of variation in microclimate and water use as influenced by shade trees. The approach is exemplified at two East African sites with distinctly different climates (Mt. Elgon, Uganda, and Mt. Kilimanjaro, Tanzania) using a global sensitivity analysis for evaluation of model behavior and prior parameter uncertainty assessment. We use the climate scenario driven by the Hadley Global Environment Model 2-Earth System representative for the year 2050 to discuss potential responses of the coffee plant to interactions of elevated [CO_2], temperature, and water availability. We subsequently explore the potential for adaptation to this scenario through shade management. The results indicate that under current climatic conditions optimal shade cover at low elevations (1000 m.a.s.l.) is 50%, provided soil water storage capacity is sufficient, enabling a 13.5% increase in coffee yield compared to unshaded systems. Coffee plants are expected to be severely impacted (ranging from 18% to 32% coffee yield reductions) at low elevations by increased temperature (+2.5 °C) and drought stress when no elevated [CO_2] is assumed. Water competition between coffee and shade trees are projected to be a severe limitation in the future, requiring careful selection of appropriate shade tree species or the adoption of other technologies like conservation measures or irrigation. The [CO_2]-fertilization effect could potentially mitigate the negative effect of temperature increase and drought stress up to 13–21% depending on site conditions and will increase yield at higher altitudes. High uncertainty remains regarding impacts of climate change on flowering. The presented model allows for estimating the optimal shade level along environmental gradients now and in the future. Overall, it shows that shade proves to be an important adaptation strategy, but this requires improved understanding regarding site-specific management and selection of tree species. Moreover, we do not yet include climate change uncertainty.

1. Introduction

Coffee is cultivated in over 70 countries throughout the tropics with approximately 60% of the production being *Coffea arabica* L. (Arabica coffee) and 40% being *Coffea canephora* Pierre ex Froehner, syn. *Coffea robusta* (Robusta coffee) (FAO, 2015). Over 70% of the world's coffee is produced by smallholders managing less than 10 ha of land (Fridell, 2014). Climate change is expected to have substantial impacts on suitable areas for coffee (*C. arabica*) cultivation (Bunn et al., 2015a; Ovalle-Rivera et al., 2015; Magrach and Ghazoul, 2015), pests and diseases pressure (Jaramillo et al., 2011; Magrach and Ghazoul, 2015) and genetic resources (Davis et al., 2012), thereby likely changing the

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agro-ecological zones most suitable for coffee production (Bunn et al., 2015b). Agroforestry systems can both contribute to climate change mitigation while potentially enabling adaptation to climatic changes (Matocha et al., 2012; Mbow et al., 2014; Vaast et al., 2016).

Due to the perennial nature of coffee with an economic lifespan typically up to 30 years (Wintgens, 2004) and the long time required for agroforestry trees to grow to maturity, decisions regarding adaptation to climate change are challenging. Therefore, there is an urgent need for decision support consisting of accurate estimates of climatic suitability for coffee production and the influence of modified microclimate by shade trees, including competition effects (Luedeling et al., 2014). Where long historical records of coffee performance, weather and soil conditions are available, this is a relatively easy task, but the majority of coffee growing areas lack such data (Luedeling et al., 2014). Statistical species distribution modelling approaches (Schroth et al., 2009; Bunn et al., 2015a; Magrach and Ghazoul, 2015) or agro-climatic indices (Lane and Jarvis, 2007) have instead been used. These methods are suitable for characterizing broad agro-ecological zones (Bunn et al., 2015b) and generating hypotheses on the suitable climatic conditions for coffee, but they lack a mechanistic process representation required to predict crop response outside the current growing domain, including the carbon fertilization effect (CFE) induced by rising atmospheric carbon dioxide concentration ([CO_2]). Furthermore, while the above studies have analyzed geographical shifts in coffee suitability, indicating a decrease of available area in the future, they did neither include phenotypic responses of the coffee plant (Nicotra et al., 2010) nor management practices allowing for adaptation to climate change, such as shade management, irrigation, or changes in coffee genotypes (Vaast et al., 2016).

Mechanistic crop models are believed to be more appropriate in generating realistic simulations of plant-soil-climate interactions. Moreover, they facilitate learning through hypothesis testing and identification of missing knowledge (Sinclair and Seligman, 1996; Boote et al., 2010), which enables guidance for management action (Harfoot et al., 2014). However, applying such models without sufficient data for calibration, results in large uncertainties of model predictions, next to existing uncertainties in model structure (Beven 2008; Luedeling et al., 2016). The latter is often not identifiable by comparing model outputs with observations alone, as many models can be fitted to the same data leading to the problem of equifinality (Beven and Freer, 2001). Model comparison and critical reflection of assumptions is considered more appropriate (De Kauwe et al., 2014).

Most of the parameters in a crop model are considered “genetic coefficients”, and do not have to be adjusted when applied at different sites (Yin et al., 2004). Yet, some parameters encompass limited process understanding and require calibration when the model is applied to different sites. These include parameters related to the induction of flowering in coffee (Van Oijen et al., 2010b; Rodriguez et al., 2011). Another aspect related to parameter values is phenotypic plasticity, i.e. changes in morphological, chemical, and physical characteristics of a plant in response to the environment. If phenotypic plasticity is explicitly accounted for, there is no need to adapt parameters in different environmental conditions (Yin, 2013). Obviously, this is only possible when the required knowledge is available to adequately represent these processes. Considerable understanding is available on phenotypic responses of coffee to water (Poorter and Nagel, 2000; Carr, 2012; Cavatte et al., 2012; Cannavo et al., 2011) and light availabilities (Matos et al., 2009; Charbonnier et al., 2013; Martins et al., 2014a), but uncertainty is much greater with regard to phenotypic plasticity to atmospheric [CO_2] variation (Yin, 2013), with only few experimental studies regarding coffee so far (Martins et al., 2014c; Ghini et al., 2015; DaMatta et al., 2016).

Other difficulties in exploring possible impacts of climate change on crop production are related to modelling climate extremes and its impacts (Thornton et al., 2014). Depending on the used Global Climate Model (GCM) and the methods for downscaling the output to scales relevant for agriculture, the projected changes in climate may only represent mean changes in temperature and precipitation and not adequately represent changing climate variability, notably temperature and precipitation extremes (Müller et al., 2011; Ramirez-Villegas et al., 2013). In addition to uncertainty in boundary conditions, there is also uncertainty in the actual effects of such extremes on the plant (Reyer et al., 2013).

The goal of this study is to use a mechanistic coffee model, which integrates current knowledge on coffee ecophysiology, to evaluate potential impacts of climate change in various agro-ecological settings and agricultural managements. By making use of statistical approaches to explore the plausible parameter space, we identify optimal current and future management practices of a wide range of potential genotypes. The objectives of this paper are to 1) present the proposed coffee model, 2) assess model outcome in time and space using mean literature derived parameter values, 3) identify model behavior through global sensitivity analysis and 4) evaluate how robust the predicted change is despite parameter uncertainty conditioned by different climate scenarios. We used two contrasting sites of East Africa as case study areas, namely the wet slopes of Mount Elgon, Uganda *vs* the drier slopes of Mount Kilimanjaro, Tanzania.

2. Material and methods

2.1. Coffee model

The original version of the coffee agroforestry model (CAF2007) was described by Van Oijen et al. (2010b) and extended by Ovalle-Rivera (2014). This study adapts the CAF2014 model for use as a spatially contextualized decision support tool (SpCAF). This model was chosen as it is specifically designed to deal with coffee agroforestry systems and includes a mechanistic light use efficiency approach that deals with the interaction between temperature and [CO_2]. In comparison to CAF2014, we assume no nutrient limitations as we intend to isolate the impact of climate on coffee and therefore focus on yield response to water (i.e. water limited yield according to Van Ittersum et al., 2013), temperature and atmospheric [CO_2] levels. Consequently, coffee yield is expressed exclusively as a function of climate and soil water availability, excluding nutrient competition, pest and disease alterations, or allelopathic properties of shade trees on understory coffee. Tree shading is simplified to a canopy that provides shade and competes for water through evapotranspiration. Thus, the objective is not to explicitly model a specific shade tree species, but rather allow for exploration of the continuity between no shade and heavy shade and its effects on microclimate and water competition. The model calculates water-limited coffee yield at a daily time-step and is implemented in R statistics (R Core Team, 2014). In the following sections, all key processes and model assumptions are presented. An overview of the model is illustrated in Fig. 1.

2.1.1. Coffee growth under optimal water supply

Canopy photosynthesis is modelled using a mechanistic light-use efficiency (LUE) approach based on the leaf photosynthesis model of Farquhar et al. (1980) and scaled up to canopy photosynthesis (Charles-Edwards, 1982), as described in detail by Van Oijen et al. (2004). This formula for LUE is calculated on a daily basis and depends on temperature, atmospheric [CO_2] concentration, light intensity and the Rubisco content of upper leaves. Instead of modelling photosynthesis and respiration separately, the LUE approach assumes a constant ratio of daily rates of respiration and photosynthesis, which has been explained experimentally (e.g. Gifford, 1995, 2003) and theoretically (Van Oijen et al., 2010c). The parameters have been adjusted to very low and high light intensity, yielding highest values for LUE at low intensity (Van Oijen et al., 2010b). This allows consistency with observations as reported by Franck and Vaast (2009), Cavatte et al. (2012) and Charbonnier et al. (2017) for Arabica coffee. Moreover, by