KEEPING A PARAMETER-SPARSE CONCEPT IN AGROFORESTRY MODELING WHILE INTEGRATING NEW PROCESSES AND DYNAMICS: NEW DEVELOPMENTS IN YIELD-SAFE

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Introduction

Yield-SAFE (van der Werf et al 2007), developed during the SAFE project (Dupraz et al.2005) is a parameter-sparse, process-based dynamic model for predicting resource capture, growth, and production in agroforestry systems that has been frequently used by various research organisations in recent years.
Within the AGFORWARD project (Burgess et al., 2015) the Yield-SAFE model has been enhanced to more accurately predict the delivery of ecosystem services provided by agroforestry systems relative to forestry and arable systems. This paper summarizes the new developments within the model.

The story so far…

The new developments to the model can be divided into:1) **Intrusive developments**, which improve existing state variables, 2) **Extrusive developments**, which use and change state variables, 3) **Complementary developments**, which use state variables to calculate new variables, 4) C**limate-drivers developments**, changing climate inputs and 5) **Interface developments**, facilitating the end user interaction and use of the model.
The **intrusive developments** have directly changed the existing equations to improve model performance. For example, crop water use is now linked to vapour pressure deficit to cope with water use efficiency in different environments (e.g. Mediterranean, Atlantic), and a new maintenance coefficient is used in crop biomass when it is not harvested.
The **extrusive developments** include implementation of new ecosystem dynamics that interact with the existing tree, crop, and soil state variables within the model. For example, the carbon in the tree leaf fall is now incorporated into soil, simultaneously reducing above ground biomass.
Complementary developments are those where existing state variables are used to estimate new indicators. For example, carrying capacity is calculated based on the energy supplied by crops and the energy required by livestock, considering or not a shadow effect to reduce the livestock energy requirements. Similarly, tree fruit productivity is based on tree leaf area, while the soil carbon module uses climate input and state variables, but not changing tree, crop or soil-water state variables.
Climate-driver developments influence the climate data used in the model, modifying a large number of state variables. For example the canopy effect of reducing thermal amplitude or reducing wind speed, will reduce vapour pressure deficit, reduce evapotranspiration, increasing water availability in soil, and can also reduce the number of heat stress days for livestock.
Interface developments do not change or add any equations to the model. For example, the model needs daily climate data and some of the new improvements require additional climate variables. Auxiliary tools have therefore been developed to facilitate this task, while programming new interfaces has helped the users to use the model in a more user-friendly way.
The following sections briefly describe the new developments of Yield-SAFE.

Intrusive developments:

Crop water use: This state variable is a simple relationship between the daily biomass growth (B_c, g m^2) and the water use efficiency parameter (γ_c, m^3 g^{-1}), i.e. $B_c * \gamma_c$. Formerly, for the same crop, there was a need to increase the water needed to produce the same amount of biomass for drier Mediterranean climates relative to more humid Atlantic climates. This dual calibration carried out within the yield safe model was required mainly due to a higher vapour pressure deficit (VPD) in drier regions. The water use efficiency of the crop is now a reference for a VPD of 1 kPa while the water use responds to the daily VPD calculations. The decision to link the water uptake to VPD led to the increase of climate inputs (minimum temperature, maximum temperature, and relative humidity), but the use of these climate variables also increased the potential to assess other aspects of the ecosystem services provided by agroforestry systems.

Perennial understory biomass cycle: Contrary to conventional annual crops, grasses are usual perennial crops. As Yield-SAFE did not previously account for crop respiration, the result was an unrealistic yearly annual accumulation of biomass in the system. Therefore a crop respiration rate was added for the modelling of perennial crop species, enabling the reduction of biomass when the daily growth is lower than the carbon used for biomass maintenance. The addition of this parameter not only improves modelling of the typical biomass cycle for grass, but also analysis of carrying capacity, which is related to the water resource use of the system.

Extrusive developments

Tree leaf fall and root mortality: Leaf fall and therefore leaf biomass has been incorporated in the soil as plant input material in the soil carbon dynamics module. This is achieved using the specific leaf area (in cm^2 g^{-1}) which is multiplied by the tree leaf area and, given a carbon content ratio, provides the amount of carbon added to the soil during tree leaf fall. In the case of perennial trees, leaf fall is considered to be a proportion of the current leaf area. The fallen leaf biomass is removed from the total biomass. Fine root mortality with a carbon content ratio, also adds plant material to the soil carbon module. To achieve this input of carbon by fine roots, the total root biomass is estimated in a first step with a root-to-shoot ratio from above ground biomass using a root-to-shoot ratio (RSR) of 0.2 and 0.25 for conifers and broadleaf respectively (IPCC, 2006). Literature suggests that fine root mortality can be taken as a proportion of root biomass in the same proportion as leaves in the aboveground biomass. Alternatively, a user can define the root-to-shoot ratios and proportion of fine roots in the belowground biomass.

Complementary developments

Carrying capacity: The need to study silvopastoral systems in AGFORWARD led to the need to estimate livestock carrying capacity. The model now uses the Farm Accountancy Data Network (FADN, 2016) reference for a livestock unit (LU) that, together with 1) livestock metabolizable energy requirements (LMER), 2) the energy provided by the crop, and 3) the tree fruit (see section *Tree fruit productivity*), provides an estimate of the carrying capacity of each land system modelled.

Tree shadow influence on carrying capacity: Trees have a positive effect on animal welfare, especially in extreme hot or cold climates. Several studies have shown that livestock start to suffer from heat stress above certain temperature and humidity levels. Based on studies of McDaniel and Roark (1956) and McIlvain and Shoop (1977), this is expressed using the temperature and humidity index (THI) which combines temperature and humidity and relates it to stress in animals. A stress day is defined as day when temperature + humidity are above 130 (temperature in Fahrenheit, humidity in %). Stress in hot climate means that animals use energy to reduce their body temperature, instead of using it to gain weight. Based on the results from the same authors, the model has been improved to calculate a reduction of 11% in LMER when trees have a minimum height of 4 meters and when the THI is above 130. Calculation of this effect on carrying capacity requires calculation of relative humidity which was introduced during the improvements in crop water use (see section *Crop water use*).

Tree fruit productivity: Tree fruit products are an important economic product of tree based land use systems. They also provide an important energetic food resource input for the calculation of the utilizable metabolizable energy (UME) available for livestock, and production data is therefore required to calculate the global carrying capacity of the land systems. Literature often considers fruit productivity to be a linear relationship to leaf area, therefore a parameter defining the fruit productivity (in g m^{-2} of canopy) is now linked to the existing leaf area state variable of the model. However, fruit productivity is strongly dependent on climate events (e.g. late frosts, heat waves) or even climate conditions when reserve accumulation occurs before winter. Furthermore, fruit production also depends on tree age and therefore further developments are needed to improve fruit productivity (see section *Further improvements*).

Soil carbon dynamics: RothC (Coleman and Jenkinson, 2014) has been integrated within Yield-SAFE. RothC is a monthly time step model and therefore some adaptations were made to fit it to the daily time-step use in Yield-SAFE. The link between the models was made with climate, crop, and water state variables (crop cover, evapotranspiration) in Yield-SAFE, being used as inputs to RothC, and has required in Yield-SAFE, new estimations of tree leaf fall biomass and trees/crop root mortality (see section *Tree leaf fall and root* mortality). The model can also include the application of manure and emission of livestock faeces as carbon inputs to the soil. However, it should be noted that neither of these actions provides feedback to modify crop or tree yields within the model.

Non-timber forest products (cork): Due to the importance of some tree species where neither the fruit or wood are the main valued product, for example cork oak (*Quercus suber* L.), modules with specific equations have been added. In the case of cork oak, a module was added hybridizing Yield-SAFE state variables to cork productivity (Paulo and Tomé 2010). In future other non-wood products may be added that could link the production to the tree or crop state variables. The implementation of non-timber forest products is typically a complementary or extrusive implementation.

Climate-driver developments

Canopy effect on microclimate (temperature): This effect is linked to the shadow effect on livestock (see section *Tree shadow influence on carrying capacity*). However, in this section there is a focus on the fact that tree canopies not only reduce temperature in summer but also increase temperature in winter (Gill and Abrol, 1993). Modifying the temperature when tree height reaches a certain threshold (in this case 4 m, same threshold for shadow effects on livestock) also modifies a number of related state variables. For example, VPD is affected altering crop water use and soil evaporation which in turn, affects the water balance of the soil. Also, new features of Yield-SAFE such as carrying capacity are modified, because by reducing temperature in summer, there are fewer stress days for livestock, and the canopy therefore helps to promote weight gain in livestock relative to a no shade scenario, counteracting the negative impact on grass yield caused by reduced light penetration and favouring a mechanism of adaptation to climate change. Additionally, increasing temperature in winter may increase number of growing days for the crop.

Canopy effect on microclimate (wind): Trees on landscapes are known to reduce wind speeds. The efficacy of this depends on tree disposition and wind direction and, in some cases, trees may also increase wind speed, for example, if the crop alleys and wind are oriented in the same direction, providing conditions for the Venturi effect (Geiger et al. 2012). Nevertheless, literature related to windbreaks shows consistent relationships between distance and height in reducing wind speeds. From recent research in alley cropping systems, relationships between wind speed and alley width can be found to build a function to reduce wind speed (Böhm et al 2014). Yield-SAFE now includes this effect, in terms of the effect on evapotranspiration but wind direction is excluded and therefore this feature of the model should be used carefully.

Interface developments

Activation and deactivation of improvements: The implementation of the new improvements in Yield-SAFE takes into consideration that the user may choose not to activate the new processes described earlier, either due to lack of interest in certain process, or because they want to compare results “with” and “without” the new process to gain better understanding of the interactions and implications of the modelled land use system. The ability to switch these processes “on” and “off” has therefore been provided. In addition, the new developments take into consideration the simplicity objective of Yield-SAFE, maintaining ease of calibration and parameterization by trying to 1) add as few parameters as possible and 2) use commonly used parameters.

Daily Climate: As the model runs in a daily time step, daily climate data is needed. However, obtaining such data is often challenging. Under the AGFORWARD project, a tool called “Clipick” was developed to help in the provision of artificial daily climate data in order to run the Yield-SAFE model (Palma 2015). The tool can also provide data on future climate scenarios based on data reported to the International Panel on Climate Change.

New interface on the way: As new developments are integrated, the original MS Excel interface developed during the SAFE project has become a very large file that is difficult for standard computers to load. Therefore a new interface is being developed which can be accessed via internet to ease the usage of the model. The new interface has “Clipick” integrated into it to facilitate the input of climate data, whilst the model can be accessed through any programming language that can retrieve http requests, including MS Excel. In fact, this characteristic recently enabled the integration of Yield-SAFE into FarmSAFE(Graves et al., 2007; 2011), allowing a dynamic link between the biophysical and the economic models.

Further improvements

The requirements of the AGFORWARD project have raised needs in terms of modelling agroforestry from an ecosystem perspective. Some of these needs are identified but have not yet been implemented. These include for example: 1) accounting for energy provided by tree pruning for feeding to livestock and also consideration of pollarding management; 2) consideration of canopy effects on livestock energy needs under cold climates, and;3) estimation of the number of flowers (based on fruit production) as an indicator of pollinator feedstock (biodiversity indicator).

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