

Field-scale modeling of tree–crop interactions: Challenges and development needs



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ABSTRACT

Agroforestry has attracted considerable attention in recent years because of its potential to reduce poverty, improve food security, reduce land degradation and mitigate climate change. However, progress in promoting agroforestry is held back because decision-makers lack reliable tools to accurately predict yields from tree–crop mixtures. Amongst the key challenges faced in developing such tools are the complexity of agroforestry, including interactions between various system components, and the large spatial domains and timescales over which trees and crops interact. A model that is flexible enough to simulate any agroforestry system globally should be able to address competition and complementarity above and below ground between trees and crops for light, water and nutrients. Most agroforestry practices produce multiple products including food, fiber and fuel, as well as income, shade and other ecosystem services, all of which need to be simulated for a comprehensive understanding of the overall system to emerge.

Several agroforestry models and model families have been developed, including SCUAF, HyPAR, Hi-SAFE/Yield-SAFE and WaNuLCAS, but as of 2015 their use has remained limited for reasons including insufficient flexibility, restricted ability to simulate interactions, extensive parameterization needs or lack of model maintenance. An efficient approach to improving the flexibility and durability of agroforestry models is to integrate them into a well-established modular crop modeling framework like APSIM. This framework currently focuses on field-scale crops and pastures, but has the capability to reuse or interoperate with existing models including tree, livestock and landscape models, it uses parameters that are intuitive and relatively easy to measure, and it allows scenario analysis that can include farm-scale economics. Various types of agroforestry systems are currently being promoted in many contexts, and the impacts of these innovations are often unclear. Rapid progress in reliable modeling of tree and crop performance for such systems is needed to ensure that agroforestry fulfills its potential to contribute to reducing poverty, improving food security and fostering sustainability.

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1. Introduction

1.1. Agricultural models for systems analysis and decision-making

Agricultural models are often used to support decisions regarding the management of food production systems. They serve a wide range of purposes, including planning day-to-day management of cropping activities on farms (Hochman et al., 2009), informing development initiatives for rural poverty alleviation (Thornton et al., 1997), and projecting the impacts of climate change on food security (Webber et al., 2014). They are applied in making operational, tactical and strategic decisions (de Koeijer, 2002) and are capable of projecting field, farm and food system performance across a wide range of environmental and socioeconomic conditions (Holzworth et al., 2014). The primary objectives of these models are a) to synthesize experimental and conceptual information on how system components interact in agricultural systems; b) to identify and prioritize gaps in knowledge; c) to test through ‘virtual experiments’ the effect of a large number of interacting factors such as soil, climate, species, and management, that are too numerous to be studied empirically; d) to provide decision support to policy makers, researchers and extension staff (Aumann, 2007) and e) to share knowledge amongst researchers and practitioners about determinants of productivity.

Most agricultural production models contain a process-based sub-model at their core which simulates the growth of plants through their vegetative and generative stages on a particular unit of land (Steduto et al., 2009). This core model element is typically a crop model, which simulates production of a particular crop as a function of crop attributes interacting with environmental conditions, such as soil and weather, which are in turn influenced by climate, agricultural inputs and management. In most cases, the crop and soil components are the only ones that respond directly to changes in environmental or climatic conditions. A wide range of crop models have been developed, that simulate yields reasonably well for many crops. Examples of such

models include WOFOST (Van Diepen et al., 1989), DSSAT (Jones et al., 2003), APSIM (Holzworth et al., 2014), the ‘Wageningen crop models’ (Van Ittersum et al., 2003), Hybrid-Maize (for maize only; Yang et al., 2004), STICS (Brisson et al., 2003) and AquaCrop (Steduto et al., 2009). Researchers have sufficient confidence in many of these models to routinely use them for projections of crop performance in places where the crop of interest has never been grown (McLaughlin et al., 2006), or in projected future climates under which crop performance has never been observed (Parry et al., 2004).

The availability of reliable crop models is mostly restricted to monocultures, where interactions between plants are limited to resource partitioning between individuals of the same species (Steduto et al., 2009). Models typically simulate attainable yield, considering potential yield, which depends on crop genotype, radiation, temperature, and management, that is constrained by limiting factors such as water and nutrients. They do not normally simulate actual yields, which are generally below that attainable because of pests, diseases and weeds. Some models allow simulation of systems that are more complex than a monoculture. Amongst these are the inclusion of weeds in monocultures (Deen et al., 2003; Grenz et al., 2006) and intercropping systems (Carberry et al., 1996). There have been several attempts to model tree–crop interactions at various levels of detail, including HyPAR (Mobbs et al., 1998), WaNuLCAS (Van Noordwijk and Lusiana, 1998) and the SAFE family of models, which consists of Hi-SAFE (Talbot, 2011) and Yield-SAFE (van der Werf et al., 2007), themselves forming the basis for plot-SAFE and Farm-SAFE (Graves et al., 2011). There are also models for windbreaks and crops in the Sahel (Mayus et al., 1998) and coffee agroforestry (Van Oijen et al., 2010), and there is basic functionality to model trees within the APSIM crop modeling framework (Huth et al., 2002). These tree–crop interaction models, while capturing interactions to variable degrees, often fall short of accurately predicting attainable yields for both tree and crop components simultaneously, over a wide range of conditions (Walker et al., 2007; Bayala et al., 2008b).

1.2. The need for models of tree–crop interactions

In recent decades, integrating trees with crops for food and wood production has received considerable attention in both tropical (Garritty et al., 2010) and temperate regions (Palma et al., 2007). Agroforestry has shown potential to increase and sustain food production per unit area in systems like the parklands of the Sahel (Bayala et al., 2012), through the use of ‘fertilizer trees’ intercropped or in fallow rotations with crops throughout sub-Saharan Africa (Sileshi et al., 2008) and through integrating trees with crops on sloping land (Tiwari et al., 2009). It is increasingly seen as a promising approach to improving food security (Glover et al., 2012), largely because the trees are associated with enhancing and sustaining soil health and hence crop yield (Barrios et al., 2012). Trees also produce fodder, fuel and construction materials, which are in high demand in many rural areas and if produced on farm may reduce the costs of obtaining them off-farm. Through production of high value timber, farmers can often generate substantial additional revenue in both temperate (Dupraz et al., 1997) and tropical contexts (Dupraz et al., 1997; Bertomeu, 2006; Santos-Martin and van Noordwijk, 2009). Fruits obtained from trees can enhance both income (Mithöfer and Waibel, 2003; Luedeling and Buerkert, 2008) and human nutrition (Goenster et al., 2009; Kehlenbeck et al., 2013).

Agroforestry practices are often part of strategies to improve natural resource management (Ong and Kho, 2015), and they are often more effective than other land uses in providing regulating, supporting and cultural ecosystem services (Pagella and Sinclair, 2014), such as microclimatic buffering, amelioration of soil structure and water infiltration, reduction of overland flow, regulation of the water cycle and provision of habitat for wild species (Bayala et al., 2014). The potential of agroforestry practices to sequester carbon in wood and soil has been widely demonstrated (Luedeling et al., 2011; Kuyah et al., 2013). Agroforestry may also affect emissions of other greenhouse gases either positively or negatively (Verchot et al., 2008; Rosenstock et al., 2014) and is expected to help farmers adapt to climate change through the risk-mitigating effects of additional farm products derived from trees, positive microclimatic effects through shading and enhanced farm productivity through tighter nutrient and water cycles (Garritty et al., 2010).

Agroforestry interventions are envisaged in many places, including locations where they have never been tested. In a number of cases, substantial positive contributions of agroforestry to food security, natural resource management, and climate change mitigation and adaptation have been demonstrated, but it is clear that not all these successes can be replicated everywhere. The magnitude of all documented or assumed benefits of agroforestry depends on site-specific responses by trees, crops or other components of the system, with strong variation between locations and farming contexts (Coe et al., 2014). Benefits also vary over time, because many effects of trees on soils are slow to materialize (Barrios et al., 2012). For instance, the beneficial effects of *Faidherbia albida* on crop yields have been reported to start only after the trees reach 20 to 40 years of age (Ong and Kho, 2015).

The long life span of trees, and the large number of potential tree species means that it often takes a long time to establish the viability and relative merits of alternative agroforestry practices in new environments through empirical approaches. This makes recommendation domains for particular technologies difficult to delineate. Tools are needed for faster ex-ante assessment of performance potentials. Since planted trees can remain in place for decades, such tools need to consider the impacts of climate change (Luedeling et al., 2014). Process-based modeling has been identified as a viable approach to making such projections (Bayala et al., 2015a), but a number of obstacles must be overcome for agroforestry models to successfully meet this challenge.

The objective of the present analysis is to highlight key challenges in the process-based modeling of tree–crop interactions and to chart a path towards a modeling approach that can deliver reliable predictions of both tree and crop yields for a wide range of species and conditions.

We do this by (1) setting out the challenges of agroforestry modeling (2) defining model requirements, (3) examining currently available crop, tree and interaction models, and (4) recommending what is required to develop a modeling framework that can deliver reliable predictions of tree and crop yields when the two are grown together on the same land area.

1.3. Modeling tree–crop interactions

Many farming systems in developing countries are complex assemblages of several species, and they often include trees or other woody elements (Figs. 1 and 2) that exhibit competitive as well as complementary interactions with field crops (Bayala et al., 2015a). Trees can affect crop production in a number of ways, negatively through competition for light, nutrients and water, as well as positively through increased input of biomass from leaves and roots that often enhance nutrient cycling (Rao et al., 1998). Positive effects on crops may also arise through improved water relations (Bayala et al., 2008a) and microclimate (Muthuri et al., 2014). Modeling approaches for capture of water, nutrients and light that produce reliable predictions in monocultures may not suffice in more complex situations, because they do not consider critical competitive and facilitative interactions between trees and crops. In monocultures, accurate prediction of the timing and location of water uptake, nutrient uptake and light interception, is less critical than in mixtures, because all modeled plants are similar in their uptake and interception characteristics. Resource availability dynamics in different soil layers and over a sequence of days can thus be simulated relatively easily. In mixed cropping situations, this may be true for aggregated plant growth, but not for growth of competing components (van Noordwijk et al., 1998). The wide range of existing empirical and mechanistic tree models that operate from leaf to stand scales, while capable of modeling discrete trees and, in principle, their interaction with crops, have rarely been successfully coupled with crop models (Van Oijen et al., 2010). Similarly to monoculture crop models, most tree models are designed to simulate single trees or single-species forests or plantations. More complex arrangements, such as mixed-tree stands or seedling development in forests, have been modeled (López-Serrano et al., 2015), but such models remain limited to situations that are much simpler than most agroforestry settings (Porté and Bartelink, 2002).

Although the level of details in simulation models has increased along with advances in computer hardware, complex models have generally not fulfilled their potential for advancing ecological understanding of species interactions in complex systems (Aumann, 2007). Better performance predictions for multispecies systems require renewed research efforts, combining both agronomic and ecological concepts and tools (Malézieux et al., 2009).

2. Key challenges in predicting agroforestry performance

2.1. Complex spatial and temporal domains

Agroforestry has been simply defined as where trees and agriculture interact (Sinclair, 2004). This is a scale neutral concept, so that interactions may occur within a field or farm, across a landscape or globally. Agroforestry practices at field or farm scales are highly variable in the number of crop, tree and animal species involved, the management of these species, their spatial and temporal configuration, and spatial and temporal variation in the availability of light, water and nutrients. Tree densities vary between single trees in large fields and densely planted woodlots; trees can be pruned heavily, coppiced, pollarded or left undisturbed; farmers can actively plant trees or rely on natural regeneration. Trees can be configured in many ways in agroforestry practices, and species diversity, composition, differences in provenances and variability in planting materials are also important (Sinclair, 1999). The wide

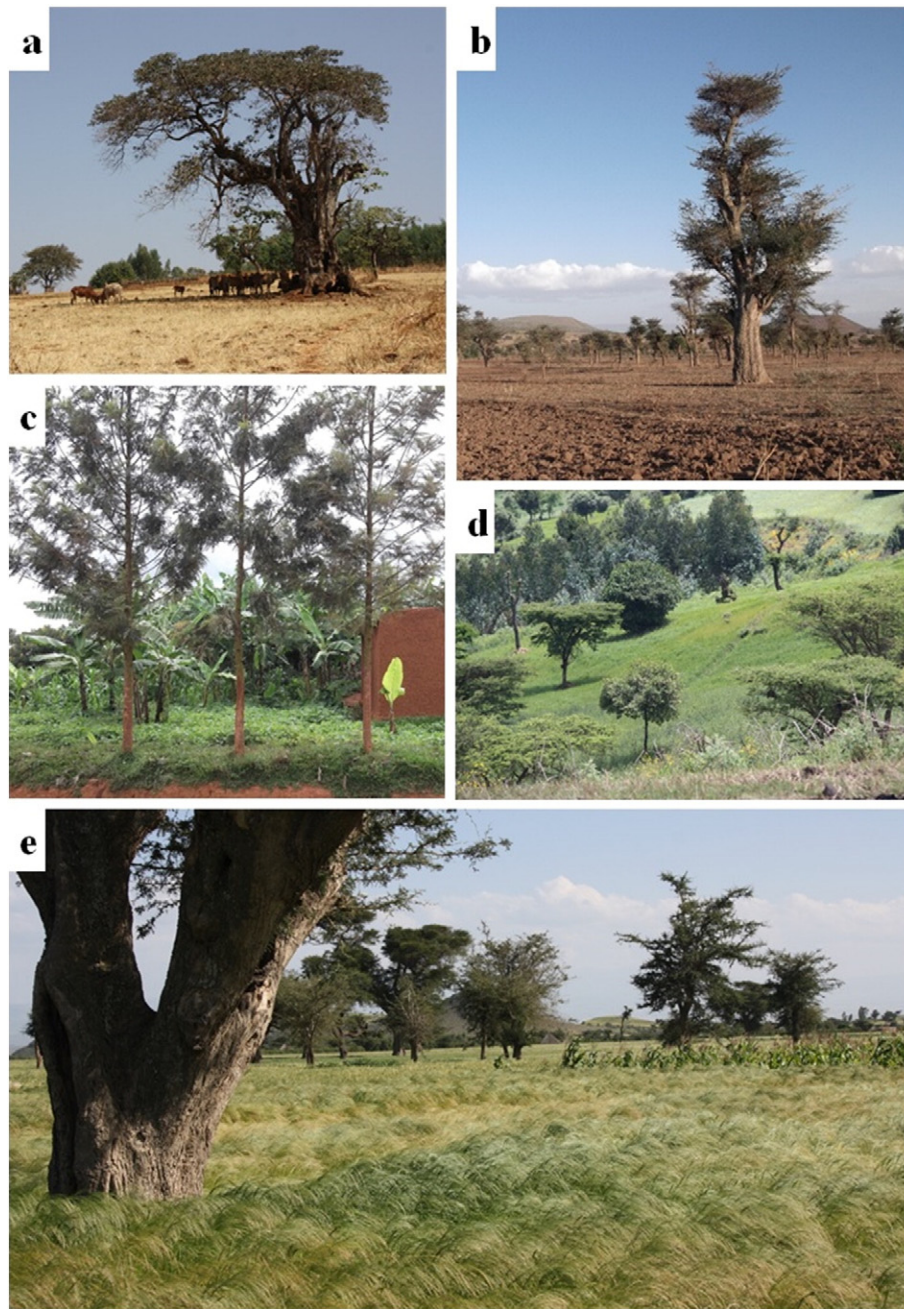


Fig. 1. African agroforestry systems: a) cattle in a harvested maize field under a tree: all three components are productive and interactions are important; b) *Acacia tortilis* trees in a plowed cereal field in Ethiopia; c) multi-story homegarden in Rwanda; d) mixed stand of trees in an Ethiopian cereal field; e) mature acacia tree in a teff field in Ethiopia.

range of practices makes it difficult to generate models that capture even a small fraction of the existing variability in a generalized manner.

Possible temporal arrangements in agroforestry are sequential presence of system components as in shifting cultivation, or simultaneous presence, as found in alley cropping or multi-story homegardens (Sanchez, 1995). Inclusion of temporal aspects in an agroforestry model is required to capture long-term impacts on environmental variables. Spatial configuration refers to the positions of trees in relation to crops within a plot, which can be mixed with various levels of intimacy and patterns, or separated (Sinclair, 1999). Where trees and crops are intimately mixed, the spatial configuration both horizontally and vertically and above- and below-ground will influence resource capture and competition for resources amongst components (Fig. 3). Above-ground, both vertical and horizontal aspects of species arrangements determine light distribution in the system. Below-ground, the spatial

characteristics of soil and the distributions of roots of the different species determine how water and nutrients are partitioned between components.

The wide range of possible arrangements of trees and crops encountered in agroforestry systems requires a flexible approach to modeling, and a more disaggregated spatial domain than needed for most annual crops. Depending on the particular system, the domain may need to extend in both vertical and horizontal dimensions. The roots of trees and shrubs can reach a depth of more than 10 m, and those of some trees have been found more than 30 m below ground (Canadell et al., 1996). However, in the absence of management many trees will predominantly root in surface soil and outcompete crops (Jones et al., 1998). The depth to which trees root depends on availability of water and nutrients in the soil profile, which itself is affected by crop uptake in agroforestry systems (Sinclair et al., 2000). The horizontal dimension

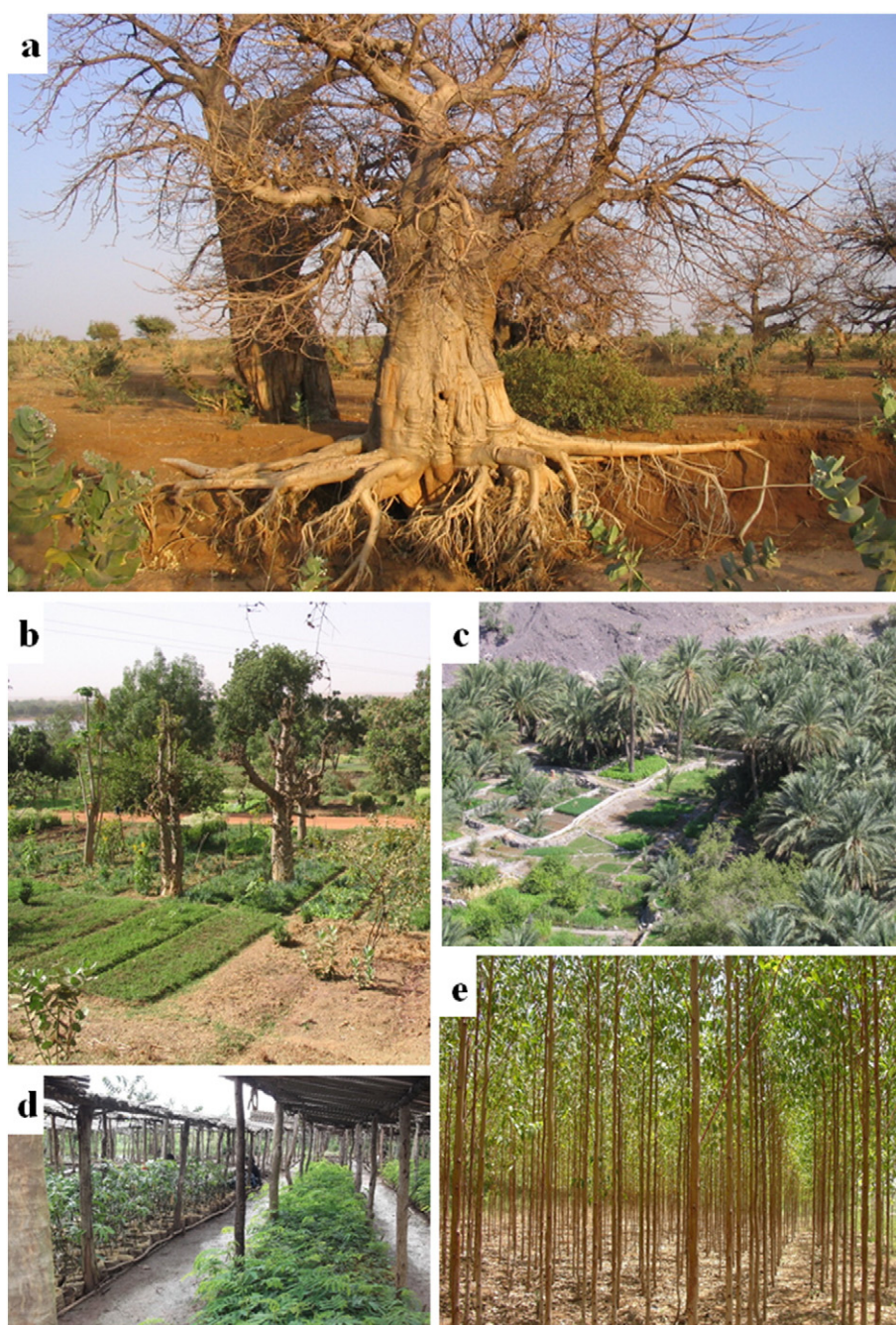


Fig. 2. Agroforestry impressions: a) exposed root system of a baobab tree in Sudan; b) baobabs and other trees in commercial vegetable production in Niamey, Niger; c) date palm/fodder oasis system in Oman; d) agroforestry tree nursery in Rwanda; e) eucalypt woodlot in Western Kenya.

of species distribution can be equally critical. Resource use patterns of agroforestry components differ greatly with arrangement, in particular with the spacing of trees and crops (Fig. 3) and their subsequent management, particularly shoot pruning, which affects both above and below ground plant structure and resource capture (Jones et al., 1998). An agroforestry modeling framework capable of reliable yield prediction has to represent both horizontal and vertical stratification sufficiently to predict resource uptake of different components when interacting with each other (Muetzelfeldt and Sinclair, 1993).

2.2. Long life cycles

A major challenge to agroforestry modeling is the long life span of the tree component. In contrast to virtually all field crops, many trees

live for decades, undergoing different stages of their life cycle, from seeds, seedlings or cuttings to mature trees. The impact of trees on other components varies with their age. To gain comprehensive insights about agroforestry innovations, all life cycle stages should be considered, not only for the crop, but also for the tree. For many systems, this requires considering time horizons of several decades, in contrast to the single growing season that is sufficient for most field crops. It also means that many data are required for parameterization.

A specific challenge arising from the long life cycles of trees is that there is more time for farmers to intervene and change what crops are grown where, and how and when trees are pruned or thinned. Since such decisions are based on observation of tree performance and state, as well as other biological or economic considerations, agroforestry models may need to include decision rules to simulate farm

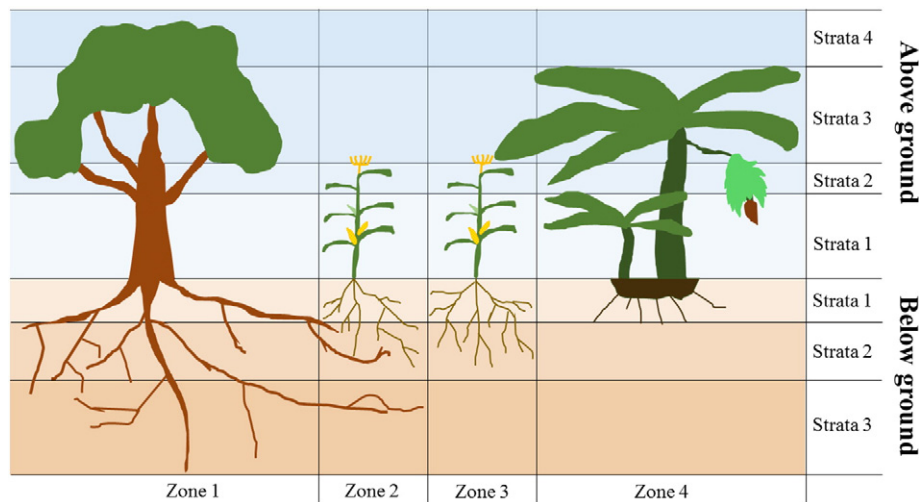


Fig. 3. Diagrammatic representation of spatial arrangements in a hypothetical agroforestry system, displaying horizontal zones and vertical strata.

management. Crop models do not generally include such decisions, and information flow in bioeconomic models tends to be directed from biological to economic model components, with little feedback going in the opposite direction. New algorithms are needed for strengthening two-way communications within bioeconomic models. Only a few frameworks currently allow for the inclusion of true feedback between economic and biological systems (Graves et al., 2011; Holzworth et al., 2014).

The cumulative impact of climatic and environmental factors on tree growth and development may also have to be considered in simulating systems with long-lived trees. Many trees display complex phenological responses, often to environmental cues (sometimes coupled with endogenous cues) that are not well understood (Broadhead, 2015). For example, *F. albida* sheds its leaves during the rainy season in many locations, but this reverse phenology does not appear everywhere and the reasons for this variation are not clear (Ong et al., 1992). Many trees, such as avocados and pistachios, display alternate bearing behavior, in which fruit yields vary strongly with an apparent biennial pattern of 'on' and 'off' years (Rosenstock et al., 2010). Also here, the underlying factors are not well understood (Krasniqi et al., 2013). Many tree species have particular climatic requirements regardless of season, with low growth or yield when these are not fulfilled. For instance, when temperate species like peaches or apples are grown in locations where their winter chilling requirements are not met, physiological development can become irregular, fruit yields can be depressed and, if such conditions persist over several years, trees can senesce prematurely (Luedeling, 2012). Drought periods can also impact tree growth for many years (Cavin et al., 2013).

Management practices can have long-lasting effects on tree growth. Protection, weed control, irrigation and fertilization in early development stages may lead to greater vigor throughout the tree's life, while pruning of branches or roots or browsing can reduce growth and change carbon allocation amongst shoot and root. Many interventions have immediate effects – such as crown pruning affecting competition for light – but they may also have long-term impacts that only manifest themselves after several years, sometimes affecting the remaining life span of the tree. Incorporating such cumulative effects in a model is difficult and experiments to adequately calibrate or validate such model components would be costly.

2.3. Competition and complementarity of resource capture

Potential advantages of well-chosen mixtures of plants in cultivation are (1) higher overall productivity through enhanced resource capture because of niche differentiation (Anderson and Sinclair, 1993),

(2) better control of pests and diseases (Malézieux et al., 2009), (3) enhanced regulating, supporting and cultural ecosystem services and (4) greater economic profitability and stability (Palma et al., 2007). Net complementarity or competition amongst different species in a plant mixture arises from the balance of many individual interactive processes such as competition for light and nutrient re-cycling from deep soil layers to the surface (Anderson and Sinclair, 1993). Even though annual crops are typically relatively shallow-rooted while tree roots can extend deep below the soil surface, trees may also extend lateral roots well beyond the edge of the tree canopy (Van Noordwijk et al., 2015). Deep tree roots can tap into ground water, but evidence from sap flow studies (Brooksbank et al., 2011) indicates that trees preferentially access water from surface zones when this is available. This is because fine roots, which are most active in water and nutrient extraction, are concentrated in the upper soil layer (Jones et al., 1998). Preferential use of shallow water by trees may be related to the high energy demand of lifting groundwater to transpiring plant parts. Trees and crops in such situations compete for nutrients and water (Bayala et al., 2015b), but the overall impact on crop yield varies according to rainfall distribution (Bazié et al., 2012) and nutrient availability (Buresh et al., 2004).

Complementarity may be either spatial or temporal. Spatial complementarity occurs, for example, when trees exploit deep reserves of water and nutrients outside the reach of annual crops (Smith et al., 1997). By contrast, temporal complementarity occurs when trees primarily demand resources at different times than crops, as reported for pruned *Leucaena leucocephala* (Black et al., 2015). One way of achieving such temporal complementarity is to use trees that are leafless during the cropping season (Broadhead, 2015). Muthuri et al. (2005, 2009) reported positive effects on maize of *Alnus acuminata* that fixes nitrogen, no effect of the deciduous tree *Paulownia fortunei* and substantial reductions in maize yield (by 36% close to the tree rows) of the evergreen tree *Grevillea robusta*. Despite *P. fortunei* being deciduous (3 months without leaves), its faster growth rates and water uptake when leaves were present may have counterbalanced any positive effects expected from its phenology. *F. albida*, also a nitrogen fixer, sheds its leaves during the cropping season in many locations and is, therefore, retained in crop fields (Garrity et al., 2010). But, since most trees do have leaves during the cropping season, farmers have developed management practices such as reducing tree density, combining contrasting species, and root and shoot pruning that help control both above and below-ground competition (Namirembe et al., 2009). However, these options are not always effective or economic (Sudmeyer and Flugge, 2006; Huth et al., 2010).

Trees, through their litter layer and its impact on soil biota and reduced exposure of the soil surface, can improve water infiltration into

the soil (Hairiah et al., 2006) and hence reduce surface runoff (Ilstedt et al., 2007), a process of particular significance in erosion control with contour hedgerows and in flood risk management (Carroll et al., 2004). In many situations, however, higher canopy interception of water and the transpiration demand of trees will reduce groundwater recharge and dry season flow (Ghimire et al., 2014). Predicting the conditions where the net balance on water flow is positive requires an evaluation of complex interactions, including the reduced evaporative demand of crops per unit of photosynthesis because of lower windspeeds and higher humidity under trees, which partially compensates for the increased water use by the tree (Wallace and Batchelor, 1997). In some situations, such as where rising water tables would lead to salinity, high water use can be the prime objective of introducing trees into crop fields (Luedeling and Wichern, 2007).

Calliandra calothyrsus and *Sesbania sesban* planted on terraces have been reported to improve soil structure and fertility (Siriri et al., 2013). Trees can act as a safety net by capturing nutrients leached from the topsoil, and they can return these to the soil surface as litter (Rowe et al., 1998). The main structural roots of trees are long-lived, while fine roots have shorter life spans. Fine roots have a high turnover rate that contributes considerably to soil carbon accumulation. Fine root turnover may in fact be the major source of soil organic matter in situations where aboveground organic inputs decompose in a surface litter layer (van Noordwijk et al., 2004). Some trees fix nitrogen and produce leafy biomass that can return fixed nitrogen to crops (Okogun et al., 2000).

Crop responses to the presence of trees depend on agro-ecological conditions (Coe et al., 2014). Results of recent meta-analyses have shown 1) that in areas with rainfall $>800 \text{ mm year}^{-1}$, certain parkland systems and coppicing technologies exert more severe negative impact on cereal grain yield than in drier areas, 2) that with lower rainfall, these practices improve cereal yield on poor soils as opposed to the fertile ones (Ong and Kho, 2015), and 3) that the yield response of maize associated with fertilizer trees in fields varies across sub-Saharan Africa with soil type, elevation and rainfall.

2.3.1. Nutrient capture

Nutrient capture can be an important consideration in intercropping systems. When and where roots of different plants occupy the same soil zone (laterally or vertically), they potentially compete for nutrients. In some instances, however, complementary relationships have also been documented. There is a general pattern of higher fertility under tree crowns that is usually characterized by a gradual decline with increasing distance from the trunk and increasing soil depth and appears to respond to several factors including land form, soil type, tree density, tree size/age and management practices, as well as tree species (Bayala et al., 2015a).

Woody nitrogen fixing plants can substantially improve the balance and availability of N in agro-ecosystems. Danso et al. (1992) reported rates of N accumulation of $43\text{--}581 \text{ kg N ha}^{-1} \text{ year}^{-1}$ by several tropical plantation trees, even though not all N originated directly from the atmosphere. However, several important tree species, including some acacias, have been shown to accumulate N at very low rates ($<50 \text{ kg N ha}^{-1} \text{ year}^{-1}$). The highest rates of N fixation in acacia plantations have been reported for *Acacia mangium*, at $66 \text{ kg N ha}^{-1} \text{ year}^{-1}$ in Brazil (Bouillet et al., 2008) and up to $121 \text{ kg N ha}^{-1} \text{ year}^{-1}$ in Indonesia (Wibisono et al., 2015). Application of $10 \text{ t ha}^{-1} \text{ year}^{-1}$ fresh leaves of N-fixing tree species to a lowland rice system resulted after 3 years in improved soil fertility and crop yields that equated or surpassed those achieved with conventional use of an NPK fertilizer including $80 \text{ kg N ha}^{-1} \text{ year}^{-1}$ (Tomar et al., 2013).

Evidence has also been provided for increased availability of nutrients other than N, including P, K, Ca and Mg, which are supplied by applying leaves to the soil (Tomar et al., 2013). By the same mechanism, non-N-fixing tree species, such as *Senna* spp., increase nutrient

availability to crops (Duarte et al., 2013). Particular species, such as *G. robusta*, mobilize P through exudation of organic acids by roots or mycorrhizal hyphae, thereby making P available to crops (Watt and Evans, 1999), but it is unclear whether the magnitude of P mobilization by exudates has practical significance in agroforestry (Jones, 2003). Trees can access nutrients from subsoils that are not accessible to shallower-rooted plants, including nutrients leached through surface soil (Rowe et al., 1998). These nutrients can subsequently become available to annual plants through above- and below-ground litter production, and by stem- and through-flow. This nutritional benefit to crops is delivered slowly, depending on the speed of litter decomposition, and so nutrient supply may not match nutrient demand by the crop. Trees can also trap dust and sediment as well as being sites for nutrient accumulation from animals (including birds) that perch on them or seek shelter in their shade, where they urinate or defecate (Mills et al., 2012).

Rates of mass flow and diffusion, two major nutrient uptake mechanisms for crops (Tinker and Nye, 2000; Olander and Vitousek, 2004), are positively related to soil water content. Hence, any process that reduces soil water content below field capacity is likely to lead to a reduction in nutrient supply. This effect is commonly strongest for phosphate, as its transport rate is low even in wet soil, and it tends to occur in surface layers that dry out earliest (Radersma et al., 2005). Experimental separation of the water and nutrient components of competition is difficult, as one has to reduce the availability of one factor while maintaining the other at a non-limiting level. Fertilizer or irrigation treatments are needed in conjunction with measurement of water and nutrient stress indicators, such as calibrated xylem water potential and foliar nutrient concentrations. Such experiments have shown that nutrient competition can be very important, especially in dry environments (Smethurst and Nambiar, 1989). It is only through this level of understanding, and the use of models, that we can expect to quantitatively predict the outcomes of nutrient competition in agroforestry (Ong et al., 2004).

2.3.2. Water capture

Competition for water between crops and trees in agroforestry systems is one of the main challenges encountered in arid and semi-arid regions (Ong and Kho, 2015). However, this competition varies in all three spatial dimensions, as well as with time, depending on tree phenology and age (Teixera et al., 2003). Many tree root systems can access water from deeper soil horizons than herbaceous or annual plants. A review of older literature by van Noordwijk et al. (2015) concluded that generalization of tree root architecture was not possible because of the variety of tree root system geometries that exist without clear relationships between width and depth of root systems and those of crowns. Other data from Australia, North America and Africa show a common basic geometry of root systems of tall single stemmed trees, resulting in a root influence zone that extends out to approximately 3 to 3.5 times the tree height. Competitive pressure from trees is especially high close to the trees (1.5 to 2 tree heights), where high root density enables high rates of soil moisture extraction (Huth et al., 2010).

Much of the competitive pressure from trees on soil water comes during the crop growing season, when trees and crops compete for water. However, in some farming systems where stored moisture is important for crop yield, water use by trees prior to crop sowing is a major cause of yield loss. Extraction of soil water prior to sowing can also cause extensive crop germination failure. Studies in northern Australia (Huth et al., 2010) have shown that while the spatial extent of competition is comparable with other regions, local agronomic practices developed for variable climatic conditions and deep clay soils, allow trees to extract soil water stored during fallow periods, resulting in higher production losses, as crops are often grown on stored soil moisture in these farming systems. Furthermore, farm machinery has been adapted to allow deeper sowing of seeds so that rainfall is not always required for germination. Here, trees can dry the soil during fallow periods resulting in less

stored moisture for crop growth and sometimes insufficient soil moisture for seeds to germinate.

Agroforestry may improve water use efficiency by reducing the unproductive components of the water balance, such as run-off, soil evaporation and drainage (Bayala and Wallace, 2015). Approximately 40% of the rainfall received by a watershed in Niger was lost to soil evaporation and 33–40% to deep drainage, with the smallest proportion of 6–16% being used for transpiration by pearl millet (Rockström, 1997). Such studies indicate that high proportions of potentially available water, which are lost to biological production, might be captured by incorporating trees into land use systems, although effects on groundwater recharge may also need to be considered (Ong et al., 2006). In addition, many trees in agroforestry systems capture water resources that would not be put to productive use in the absence of trees, mainly from deep soil layers beyond the reach of annual crops. Crop roots in drier surface soil may benefit from hydraulic lift of water by trees from wetter soil at depth (Burgess et al., 1998), either at night when transpiration is low (Hultine et al., 2003) or during the day along water potential gradients driven by variation in soil salinity (Hao et al., 2009). This process, generally found in trees with dimorphic root systems, redistributes water to upper soil layers where it can be taken up by plants. The process of hydraulic lift has been demonstrated in more than 50 plant species from a variety of climates, including Mediterranean, cool, temperate, and seasonally dry tropical and subtropical climates (Jackson et al., 2000).

Published estimates of the volume of water lifted vary from 5% to 30% of daily evapotranspiration, indicating that hydraulic redistribution can postpone water stress (Bayala et al., 2008a). Its most immediate effects, however, can be through increased nutrient availability in dry soil layers. Based on the same physical principle, tree roots may also redistribute water from shallow to deeper soil horizons at the start of the rainy season, speeding up recharge of the soil profile but reducing water availability to field crops in early stages (Burgess et al., 1998).

2.3.3. Light capture

Competition for light is one of the key interactions between trees and crops. Trees reduce the amount of sunlight reaching soils and crops through shading. Light capture is influenced by both environmental and plant factors such as tree leaf area, leafing phenology, crown structure and crown management. Unless trees are leafless during the cropping season or heavily pruned, competition can be substantial. Field measurements in parkland systems revealed a reduction of photosynthetically active radiation (PAR) under *Vitellaria paradoxa* and *Parkia biglobosa* trees to 47–51% and 30–38%, respectively, of its value in an open field (Bayala, 2002). Kessler (1992) found a reduction of PAR to only 20% of the open-field value near the stem of *P. biglobosa* and 40–50% for *V. paradoxa*. This was associated with a reduction of cereal yield of 44% to 70%, while cotton yield was only reduced by 2% (Kater et al., 1992; Kessler, 1992). However, under *F. albida*, which sometimes exhibits ‘reverse phenology’ by shedding leaves at the beginning of the rainy season and foliating in the dry season, light interception is generally considered to be low and not to affect crop production significantly (Boffa, 1999). For Sahelian parklands dominated by *P. biglobosa* and *V. paradoxa*, however, Bazié et al. (2012) experimentally demonstrated that light was a major limiting factor for crop growth. Light competition, of course, is of little importance in rotational or segregated agroforestry systems, where trees and crops do not occur in the same space at the same time.

Competition for light has been comprehensively studied in a wide range of tropical and temperate agroforestry systems and general models developed at various levels of spatial and temporal disaggregation (Charbonnier et al., 2013). The most ubiquitous and basic approach treats the tree canopy as homogenous with light extinction as an exponential function of the leaf area index modified by an empirical extinction co-efficient that takes leaf angle into account. This overestimates interception because of grouping of foliage within crowns and space

between crowns that lets far more light through than a homogenous canopy would, leading to the development of models with two dimensional distributions of leaf area confined within discrete crowns, coupled to models of photosynthesis and transpiration (Wang and Jarvis, 1990). While this approach predicts light interception, photosynthesis and transpiration well, parameterization requires specifying leaf area distributions that are laborious to measure (Sinclair and Jarvis, 1993). Architectural models of trees that specify positions of individual leaves in three dimensions have also been developed allowing modeling of the growth of tree crowns over time but they require an even greater effort to parameterize (Parveaud et al., 2008). So, modeling requirements for light capture in agroforestry have largely been met, and modelers are now faced with choices related to the accuracy and spatial resolution of predicting light interception that they require, set against the effort needed to parameterize more sophisticated models (Muetzelfeldt and Sinclair, 1993). Emerging new methodologies, such as LIDAR, may alleviate this challenge in the future (Moorthy et al., 2011).

2.4. Microclimatic effects

An important effect of trees in agroforestry systems is the modification of the microclimate for annual crops or livestock (Ong et al., 2000). Compared to an open environment, the modified micro-climate under trees is characterized by reduced solar radiation, a more moderate temperature regime, higher humidity, lower rates of crop transpiration and higher soil moisture levels (Singh et al., 2012) affecting both crop growth and livestock performance. Micro-climate modification by trees also provides ecosystem services like shade that benefit livestock, especially in hot areas. For example, in semi-arid central Ethiopia, animals are prone to heat stress leading farmers to rank shade, after wood fuel, as the second most important reason for maintaining and managing trees on farm (Muthuri et al., 2014). In many temperate regions of the world, trees are used to protect livestock from cold winds, especially during lambing periods with sheep (Bird, 1998). Many species alter the local environment in a way that may be beneficial to other organisms in their surroundings (Lin et al., 2015). This effect is often mentioned as a strategy for adapting to climate change, because temperatures under tree canopies can be substantially lower than in an open field, potentially reducing heat stress for plants and animals, particularly during the hottest hours of the day. This can be very important during anthesis (Lin et al., 2015) or other temperature-sensitive crop development stages. Similarly, air humidity may be higher under tree canopies, accompanied by lower wind speed, reducing crop transpiration and thereby water stress to plants (Cleugh and Hughes, 2002).

Reductions in wind speed are directly beneficial to crops, because they reduce the mechanical damage to crops, such as leaf tearing and crop lodging (Cleugh et al., 1998). Research in Australia has shown that trees acting as windbreaks in wheat fields decreased sandblasting of crops (Bennell et al., 2007b), and lowered temperatures downwind. The latter effect may be particularly beneficial in regions where flower abortion due to high temperature is common (Bennell et al., 2007a).

A particular challenge is the quantitative estimation of the combined effects of microclimate modification and shading on understory crop growth. While reduced photosynthetically active radiation through shading often has negative implications for crop growth, higher air humidity and reduced temperature have positive effects in hot climates.

2.5. Wood production and other ecosystem services

Agroforestry can provide a wide range of benefits in addition to the effects of trees on crop yields, and in some circumstances the value of these benefits may outweigh the negative impacts on crop yield. A reduction in crop production might be acceptable to a smallholder farmer, if fruits are sold or wood produced on-farm and substituted for collected or purchased firewood or for animal dung, which can then be used as

soil amendment. Saving labor through producing fodder and firewood on farm rather than having to collect it can be a key feature of small-holder system intensification (van Ginkel et al., 2013). Many farmers also state the provision of shade as one of the primary benefits of trees on their farms, since it reduces heat stress on plants, livestock and people (Muthuri et al., 2014). Comprehensive evaluation of agroforestry practices within the farming and livelihood systems in which they are embedded may call for the inclusion of these effects. Important ecosystem services derived from trees in farming systems potentially include timber production, erosion control, carbon sequestration in soil or tree biomass (Paul et al., 2002), habitat for indigenous wildlife (Bhagwat et al., 2008), decreased risk of salinization (Stirzaker et al., 1999; Paydar et al., 2005), water quality protection (Smethurst et al., 2012), buffering of stream flow variation (Carroll et al., 2004), and shelter for crops or stock (Bird et al., 1992). Recent progress in modeling ecosystem service flows allows evaluation of the impact of introducing trees in agricultural landscapes on multiple ecosystem services and the trade-offs and synergies amongst them (Jackson et al., 2013). Trees in grazing lands can increase water infiltration and the fertility of soils beneath them and increase the quality of pasture grasses as feed for stock (Wilson et al., 1990; Wilson, 1998; Scanlan, 2002). Insectivorous birds and beneficial insects hosted by trees have been shown to regulate insect pest populations and pollinate crops (Morandin et al., 2011). Rain interception by tree crowns of some species can also reduce raindrop forces at the soil surface, lowering erosion rates. For example, Hall and Calder (1993) reported up to nine-fold differences in the kinetic energy of drops from the canopies of *Eucalyptus camaldulensis*, *Tectona grandis* and *Pinus caribaea* due to differences in leaf size, shape and texture affecting drop size, a principle well understood and applied by Nepali farmers in managing tree-crop interactions (Thapa et al., 1995). Research on forest plantations in China has recently confirmed significant differences in the kinetic energy of throughfall amongst tree species (Goebes et al., 2015). This makes it important to consider canopy properties when selecting trees to integrate with crops, where splash erosion may be a problem, and farmers managing agroforestry systems often classify trees accordingly (Cerdán et al., 2012). Intact litter layers under trees add to surface roughness, reducing the potential for erosion (Hartanto et al., 2003), and help to maintain soil fertility.

Economic outputs and other ecosystem services provided by most agroforestry systems are more complex than in monocultures (Stigter, 2015). Even just for timber production, issues of marketability and wood quality are important, including tree shape and stem size distribution for saw logs, pulpwood and veneer billets, and the value of thinnings differs for different purposes (firewood, fence posts or construction). In contrast to annual crops, the time to market for timber can be several years to several decades, resulting in discounting of returns unless trees are planted under a lease or other arrangement where farmers receive regular payments (Price, 1995b). In particular when it comes to payments for carbon sequestration, or for trees grown for timber, such considerations are critical for evaluating the viability of agroforestry options (Price, 1995a). Furthermore, many tree species provide multiple products, such as fruit, fiber or medicine, each with their own markets and economic complexities.

Agroforestry can also provide ecosystem disservices. These are unintended side effects that are not desirable, for example, trees near crop fields may increase seed predation by birds (Schäckermann et al., 2014). A concern regarding the introduction of agroforestry in arid and semi-arid regions is a potentially negative impact on water resources (Ghimire et al., 2014). By accessing deeper water than shallow-rooted plants, trees have the potential to lower water tables, reduce groundwater recharge, and reduce base flow in streams, but positive effects of lower water tables are also possible (Brooksbank et al., 2011). The balance between what water trees add through increasing infiltration (Carroll et al., 2004) and what they use in transpiration is species and context specific, demanding a whole-system cost-benefit analysis.

3. Modeling requirements for agroforestry

The previous sections established the needs and challenges for modeling tree-crop interactions in agroforestry systems at field scale. In this section we examine structural and other requirements for modeling agroforestry that address these challenges. There can be a tradeoff between how widely applicable models are and how accurately they can model the processes that most affect yield prediction for a particular system. If one aims to model a particular agroforestry system as accurately as possible, the challenges presented above (and in particular the high variability that characterizes agroforestry systems) probably call for ad hoc (situation-specific) modeling – that is ‘to tailor models to specific problems by building new models or extensively modifying old ones, instead of systematically using existing models’ (Sinclair and Seligman, 1996). A fundamental underpinning of ad hoc modeling is that some processes should be modeled at low detail, if increasing the level of detail in a model does not improve its performance but instead would increase the total error arising from estimating an increasing number of parameters (Passioura, 1996). Key decisions are then what basic processes to retain, and which ones to ignore. Affholder et al. (2012) suggested three ways to achieve this. First, summary functional relationships, requiring a limited number of parameters, can be obtained from a sensitivity analysis of a comprehensive set (Baudron et al., 2015). Second, a conceptual model may be developed from what is known about the processes to be modeled (Muetzelfeldt and Sinclair, 1993). Third, multivariate methods may be used to understand the hierarchy of drivers of variability (Tittonell et al., 2008). All these approaches, however, require mathematical and/or modeling skills, and, therefore, exclude ‘model users’ who lack those skills.

Ad hoc modeling is well adapted to accurately simulating a particular case (as opposed to a range of cases) and for use by model developers. Modeling frameworks within which a number of well calibrated and tested models can be combined in a modular structure (Muetzelfeldt and Sinclair, 1993) represent an intermediate option between the complete flexibility of ad hoc modeling, and the rigidity of a single fixed model structure. Modeling frameworks have the general applicability of comprehensive models, while providing the possibility of combining different sub-models for different situations, so that the resulting analysis capabilities are appropriate for addressing specific problems. Since several well calibrated families of crop models already exist, there is expediency in adding the capacity to model trees and their interactions with crops to these, rather than starting a new agroforestry modeling effort from scratch. The following is a list of the major additions that could make crop modeling frameworks suitable for simulating agroforestry.

3.1. Trees

Basic functionality is currently lacking for simulating tree growth in most existing modeling frameworks, and sub-models for different tree species would have to be developed. These should be capable of simulating the development of foliage, wood and branches, as well as roots. Such models already exist (Landsberg and Waring, 1997; Battaglia et al., 2004; Almeida et al., 2010; Pinkard et al., 2010; Van Noordwijk et al., 2011; Holzworth et al., 2014; Ghezehei et al., 2015), but modifications are needed to make them compatible with crop growth models. For example, some tree models do not operate at a daily time step, which has emerged as the standard in most field crop models. Notable exceptions are tree sub-models in WaNuLCAS, APSIM, Hi-SAFE, YieldSAFE, CABALA and 3PG.

The inclusion of trees in crop modeling frameworks will require substantial expansion of the spatial representation of the models (Muetzelfeldt and Sinclair, 1993). Tree roots extend much further in vertical and horizontal directions than roots of annual field crops. Since relevant processes could occur anywhere in the space occupied by trees, the entire volume should be included in the modeling domain.

However, in some cases, relevant soil zones extend to 30 m and more in depth (Stone and Kalisz, 1991), which makes model parameterization and validation challenging.

Biological nitrogen fixation by trees is sometimes a primary function in agroforestry and in those cases it needs to be included in a tree-crop modeling framework. This capability already exists in some tree and crop models. Tree phenology varies amongst species and is often different from that of crops and so needs to be included in a general modeling framework, to enable simulation of competition for light, water and nutrients. Depending on the trees that are used, simulation of fruit and fuelwood production may be important, since these are amongst the major benefits that some agroforestry practices provide. In some contexts, fruit quality (determined by size, shape, color and water content) may be as important as yield.

3.2. Tree management

Some tree management practices such as planting, weeding, fertilizing and possibly harvesting can be simulated by sub-models developed for field crops. Other practices are specific to trees, and adequate simulation modules would have to be developed, or adapted from existing agroforestry or forestry models like Yield-SAFE, WaNuLCAS and CABALA. Amongst the most important aspects are the pruning and coppicing of trees. Both of these practices can dramatically alter interactions between trees and crops, and they can also affect the growth of trees in subsequent years (Tracy et al., 2015). For systems that rely on such practices their inclusion is essential. This includes the practice of root pruning, which can reduce below-ground competition between trees and crops and increase C input to the soil.

Methods of tree establishment used by farmers can greatly influence tree development. For trees originating from farmer-managed natural regeneration, growth rates are often higher than for trees that are actively planted as seeds or seedlings, because natural regeneration often starts as coppicing from stumps or lignotubers that provide trees with a greater resource base to spur initial growth. For some systems, specific aspects of the spatial layout may also have to be simulated. Seedling size can affect tree survival and establishment, spacing of trees can influence the proportion of a field crop that is affected by competitive or complementary interactions, and row orientation in alley cropping can be a major determinant of how much light reaches field crops between tree rows.

Besides the ability to simulate different tree management strategies, an agroforestry modeling framework needs to consider farmer decisions, which can vary substantially amongst farmers. Decisions reflect farmers' outcome priorities (e.g. crop, livestock or fruit production), as well as their personal characteristics (e.g. risk-averse, proactive, conservative). Such decisions determine which management measures are employed at particular stages during the trees' life cycle.

There are several candidate tree or forest models that could be considered for an agroforestry modeling framework (Smethurst, 2007). Most of these model water and light mechanistically to some extent, but N cycling and C allocation are variably represented, and competition for nutrients is either absent or included empirically. All models use a time-step useful for plantation scenarios. Some models simulate growth at monthly increments, many work at daily time-steps, and some at even finer time scales. Of the plantation tree models reviewed (3PG, CABALA, G'DAY, PGSM, and TREGRO), only CABALA (Battaglia et al., 2004) has a high degree of silvicultural flexibility, detailed processes for light, carbon, water and N and daily-dynamic C allocation. It runs on a daily time-step with several soil layers.

Farming systems models (GrazPlan – Moore et al., 1997; APSIM – Keating et al., 2003) have a long history of dynamic modeling of decision making processes of land managers based upon changing environmental conditions, feed requirements for livestock, or farm logistical and economic drivers (Power et al., 2011). In these systems, scripting languages have been devised to describe management logic, even for

multiple field enterprises including a variety of land uses, limited resources (e.g. irrigation water or animal feed) and machinery constraints (Moore et al., 2014). These components are well placed to assist in modeling the management of complex agroforestry systems.

3.3. Tree–crop interactions

Modeling competition and complementarity in capture of light, water and nutrients must often be considered in attempts to predict yield of tree-crop mixtures. The impact of trees on crop microclimate can be of key importance (Ong et al., 2015). In all crop models, crop growth is simulated as a response to available water and ambient temperature, often also to light capture. All of these are substantially altered by trees, and the impact will depend on tree canopy structure and, for water, on rooting patterns (Anderson and Sinclair, 1993). Accurate simulation of these interactions is one of the major challenges in agroforestry modeling, since they are central for verifying one of the primary pathways through which agroforestry is expected to contribute to climate change adaptation in hot climates.

Likewise, competition and complementarity below-ground is an area for model development. How water and nutrients are partitioned between different parts of the tree, as well as between trees and crops is one of the more complex questions in agroforestry modeling. To what level of detail these processes should be simulated is amongst the central decisions that an agroforestry modeler has to take. There are certainly arguments for simulating many nutrient and water acquisition processes at the root level, including hydraulic lift, but the complexity that this might add to a model, its parameterization needs and processing time during simulation runs may often not be desirable.

3.4. Crops

Crop models are widely available, and for many crops they are probably sufficiently accurate for inclusion in agroforestry models without much modification. There is also no particular barrier to the development of models for important crops for which no current models exist, and extant modeling platforms facilitate such developments (Brown et al., 2014). It will be worth examining, however, to what extent the relationships between site conditions, especially temperature and rainfall, remain valid when models are used in agroforestry contexts. Most, if not all, existing crop models simulate growth processes based on empirical relationships between ambient temperatures and observed crop growth. They generally fall short of simulating crop temperature, which could approximate the conditions at which major physiological processes, such as photosynthesis or transpiration, occur. While trees in a field may have only a minor effect on standard air temperature (as measured with standard measurement protocols that prescribe shaded conditions), their shade can reduce crop canopy temperature in a way that may have implications for plant growth. This is of particular interest where temperatures during certain parts of the day exceed physiological limits of crops, and shading could overcome this constraint. The accuracy of crop model simulations in such cases will require validation.

4. Existing models or modeling frameworks for agroforestry

Several agroforestry models have already been developed and should be considered in any new effort to model agroforestry. The main models are reviewed here and summarized in Table 1.

4.1. WaNuLCAS

The Water, Nutrient and Light Capture in Agroforestry Systems (WaNuLCAS) model was developed to provide a generic framework for agroforestry systems of widely different geometries and temporal patterns. The core processes are above- and below-ground resource

Table 1Overview of agroforestry models (X indicates that the respective model includes a particular feature; — indicates that the feature is absent).^{a, b}

Model	Tree component	Crop component	Below-ground tree-crop interactions	Above-ground tree-crop interactions	Last update	Reference
WaNuLCAS	X	X	X	X	2011 ^a	Van Noordwijk and Lusiana (1998)
APSIM	X	X	Prototype	Prototype	2014 ^a	Keating et al. (2003)
Hi- Yield- and Farm-SAFE	X	X	X	X	2014 ^a	Dupraz et al. (2005), Graves et al. (2007) and Palma et al. (2014)
SCUAF	X	X	X	—	1998 ^b	Young and Muraya (1990)
HyPAR	X	X	X	X	1997 ^b	Mobbs et al. (1997)
HyCAS	X	X	X	X	1997 ^b	Matthews and Lawson (1997)

^a Model still under active development.^b Last published evidence of active model development.

capture with interspecific interactions primarily acting via resource supply (Van Noordwijk and Lusiana, 1998). WaNuLCAS has been programmed in an open-source environment, so that users can modify it, although its complexity makes this difficult in practice. The model is broad enough to cover wide ranges of parameters, yet narrow enough to cater for specific needs.

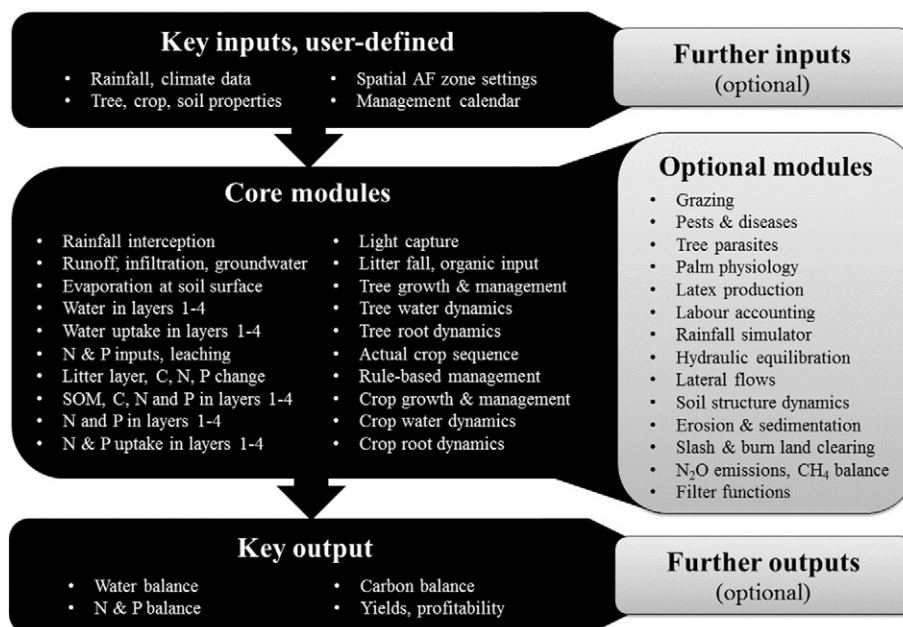
WaNuLCAS is organized around a set of inputs that define initial conditions of the soil and tree properties plus dynamic inputs such as rainfall. It includes a management scheduling calendar, spatial definition of the agroforestry system, core modules that keep track of water, nitrogen, phosphorus, crop and tree roots in four vertical soil layers by four horizontal zones defined in terms of their distance from the tree, as well as crop and tree growth. This leads to a primary set of outputs in terms of the water and nutrient balances, standing stock of vegetation, harvested products and profitability (as Net Present Value). A large number of optional sub-models are available for providing additional processes, inputs and outputs, which interact with the core sub-models (Fig. 4).

A key feature of the core modules is that competition is described by first calculating the potential uptake of the combined root (+ mycorrhizal hyphae) systems of all plants in all layer-by-zone cells using a zero-sink model of uptake maximization of water and nutrients, and secondly by introducing the expected down-regulation in each plant based on its overall supply:demand relation on a given day. This approach was

developed as an alternative to approaches such as the one used in the HYPAR model (see below) whereby crop and tree uptake are programmed in separate sub-models linked to a common soil resource base. The sequence in which equations are applied in such models (first tree, first crop or alternating) matters, a problem avoided in WaNuLCAS.

The model is usually parameterized with measured data on crop and tree root length density within the soil profile, but there are options to have overall allocations to root growth (functional equilibrium response), as well as locations of new root extension (local response — see van Noordwijk and van de Geijn, 1996), driven by plant needs. As discussed by Mulia et al. (2010), an algorithm is used that reconciles the plasticity of fine root growth with the architectural constraints of a dynamic pipe-stem transport system of coarse roots that conforms to fractal branching rules.

WaNuLCAS makes use of zones that describe spatial patterns in an agroforestry setting and are used to simulate system processes. The model is coded in the STELLA environment, a common user-friendly ecological modeling platform. The model has been used to address a wide range of issues. For instance, Smith et al. (2004) used it to explore water competition in agroforestry systems. The impact of evergreen and deciduous trees in semi-arid Central Kenya was modeled with WaNuLCAS (Muthuri et al., 2004) to evaluate effects of tree leafing phenology on crop performance and soil water balance. In sub-humid

**Fig. 4.** Key elements of the WaNuLCAS modeling environment, including optional modules.

Western Kenya, [Radersma et al. \(2005\)](#) used the model to simulate tree effects on maize growth in phosphorus-limited soils. [Bayala et al. \(2008b\)](#) explored what the most limiting biophysical resources were in a parkland system. [Pansak et al. \(2010\)](#) used the model to assess the impact of soil conservation strategies for upland cropping in North-east Thailand. Recent applications compared tree pruning and stand thinning strategies for teak + maize intercropping systems in Indonesia ([Khasanah et al., 2015](#)) and assessed resource competition at the crop–soil–hedge interface in Thailand ([Hussain et al., 2015](#)). These applications rely on farmer management decisions (zone specific) on continuing or abandoning annual crop production, depending on tree size and the results of the most recent crop ([Santos-Martin and van Noordwijk, 2009](#)).

A module for palm growth, incorporating the specific architecture and physiology of palms, particularly oil palm, was developed and is currently undergoing further tests. Recent developments include the exploration of peat soils and the potential for agroforestry systems to combine low greenhouse gas emissions with profitability in this environment ('Peaty WaNuLCAS', work in progress).

4.2. APSIM

The main motivation behind the development of the Agricultural Production Systems Simulator (APSIM) modeling framework was to provide the capacity to simulate biophysical processes in farming systems, in order to predict the economic and environmental outcomes of management practices and policy measures. More recently, forecasting the implications of climate risk and climate change has emerged as an additional objective. APSIM has been widely used in many contexts, including on-farm decision making, farming systems design, assessment of seasonal climate forecasts, analysis of agribusiness supply chains, development of waste management guidelines, risk assessment for government policy and as a research and education exploration tool ([Keating et al., 2003](#)). APSIM's modular structure ([Holzworth et al., 2010](#)) allows interactions between individual models via a common communication protocol ([Moore et al., 2007](#)). Sub-models and sub-routines within them are easily added, removed and interchanged through a system of 'plug in–pull out', which allows for a flexible recombination of routines. Modules for over thirty major crop, pasture and tree species have been implemented in the APSIM framework ([Robertson et al., 2002](#); [Wang et al., 2002](#); [Paydar et al., 2005](#)). Sub-models exist for all main soil processes that affect agricultural systems, including water, C, N and P dynamics, and erosion ([Probert et al., 1998](#)). APSIM is capable of simulating diverse agricultural management strategies ([Moore et al., 2014](#)), enabling the user to specify complex crop rotations and land management regimes ([McCown et al., 1995](#); [Holzworth et al., 2014](#)). One of the strengths of APSIM lies in the use of rigorous scientific and software engineering approaches to ensure model integrity ([Holzworth et al., 2011](#)).

APSIM is not primarily an agroforestry modeling framework, but its modular structure has enabled some forestry and agroforestry applications including:

- the hydrology and salt balance of eucalypt woodlots grown in pasture systems to assist in the discharge of water from areas with shallow saline water tables ([Paydar et al., 2005](#)),
- the economic viability of windbreaks in low rainfall areas, considering the tradeoff between competition for water and improved crop shelter provided by trees ([Huth et al., 2002](#)),
- soil conditions required to minimize seedling mortality in variable rainfall conditions ([Huth et al., 2008](#)),
- timber production and nutrient cycling in effluent-irrigated woodlots ([Snow et al., 1999](#)),
- growth and production responses to nitrogen fertilizer management for oil palm plantations ([Huth et al., 2014](#)),
- fodder production and water use of saltbush alley systems in southern

Australia ([Descheemaeker et al., 2014](#)), and

- habitat value of eucalypt woodlots of varying design ([Huth and Possingham, 2007](#)).

4.3. Hi-SAFE and Yield-SAFE

The Hi-SAFE model was designed in response to the need for a process-based model that could simulate tree-crop interaction and management options in a temperate region ([Dupraz et al., 2005](#)). The typical agroforestry systems to be simulated by the model are walnut (*Juglans* spp.), wild cherry (*Prunus avium*), poplar (*Populus* spp.) or Mediterranean oaks (*Quercus* spp.) with winter and summer annual crops, grass and alfalfa. Simulated management options include tree stem pruning and canopy thinning, tree stand thinning, tree root pruning, tree-crop distance adaptation, and precision crop management. Other existing agroforestry models such as WaNuLCAS ([Van Noordwijk et al., 2011](#)) and HyPAR ([Mobbs et al., 1999](#)) were designed mainly for tropical regions. The main features of the Hi-SAFE model compared to other existing models are:

- three-dimensional simulation of interactions both above and below ground (other models only use 2D representations)
- combination of the generic and validated STICS crop model ([Brisson et al., 1998](#)) with a generic tree model
- four interaction sub-models (light, water, nitrogen, microclimate) that link the tree and the crop sub-models
- the toric symmetry principle (the model mirrors the right side to the left of the simulated area and vice versa, similar for upper and lower) is implemented to avoid edge effects both in above-ground and below-ground simulation
- a new approach to modeling tree root system dynamics is developed with the voxel (a unit volume element, the 3D equivalent of a pixel) automata principle ([Mulia et al., 2010](#)). The tree root system is sensitive to local soil environment and its coarse root topology is self-generated by the root voxel automata sub-model, allowing prediction of the impact of coarse root pruning
- extraction of soil water and water competition between plant components are managed at the voxel scale (based on plant and voxel potentials) allowing dynamic water extraction in 3D heterogeneous soil

The model runs at a daily time step and is suitable for typical runs of 1–5 simulation years. Within the same project that saw the development of Hi-SAFE, a separate parameter-sparse model called Yield-SAFE was also developed ([van der Werf et al., 2007](#)). It was developed as a spreadsheet-based model of tree and crop interactions in agroforestry systems that are sensitive to solar radiation, temperature and rainfall. Hi-SAFE was used to model a walnut-maize system in China ([Holst et al., 2012](#)). The same project also produced Farm-SAFE ([Graves et al., 2011](#)), which integrates biophysical outputs of Yield-SAFE with financial data for simulating environmental outputs at the farm scale. Both are for a typical run of 20–180 years. Farm-SAFE was based on the POPMOD ([Thomas, 1991](#)) and ARBUSTRA ([Liagre, 1997](#)) models.

The AGFORWARD (AGroFORestry that Will Advance Rural Development; www.agforward.eu) project is currently working to extend the capacity and use of the SAFE suite of models to integrate life cycle assessment and allow their use in silvopastoral systems ([Palma et al., 2015](#)).

4.4. SCUAF

Development of the model to estimate Soil Changes Under Agriculture, Agroforestry and Forestry (SCUAF; [Young et al., 1987](#); [Young and Muraya, 1990](#); [Young et al., 1998](#)) was initiated in the 1980s, with a primary focus on the tree effects on soil conservation and soil carbon

content. It also aimed to predict the effects of land use under defined climate conditions on soil loss and medium-term productivity. SCUAF focuses on the ability of trees to improve soil fertility in the humid tropics (Young and Muraya, 1990). While soil processes are incorporated in some detail, there is no representation of competition between trees and crops for light, nutrients and water, and even the growth rates of trees and crops are exogenous to the model. It allows interpolation amongst well-characterized situations, and limited extrapolation to longer time frames or other parameter conditions. SCUAF operates at an annual time scale, which severely limits options to simulate crop growth processes with the level of detail and accuracy achieved in models such as APSIM and DSSAT. SCUAF has been used to model maize and Miombo woodlands in Tanzania (Vermeulen et al., 1993) and for a cost-benefit analysis of hedgerow intercropping in the Philippines (Nelson et al., 1996). Although developed over two decades ago, the model has been used in recent studies (Table 1; Lojka et al., 2006; Wise et al., 2007; Lojka et al., 2008; Das and Bauer, 2012).

4.5. HyPAR

The HyPAR model (Mobbs et al., 1997; Mobbs et al., 1998) combines the Hybrid tree growth model (Friend et al., 1997) with the PARCH (“Predicting Arable Resource Capture in Hostile environments”) model for grain crops and legumes (Bradley, 1995). In the Hybrid model, trees are modeled using a ‘gap model’ that simulates competition between individual trees of different physiological types and determines nutrient fluxes at different canopy heights and soil depths for each tree (Mobbs et al., 1997). Energy interception, photosynthesis, stomatal conductance and transpiration are described by a ‘big leaf’ model, in which processes are simulated at different layers of the leaf canopy and then averaged horizontally across a large plot (Mobbs et al., 1997).

The PARCH crop model (Bradley, 1995) simulates growth of crops based on light, water, nitrogen and phosphorus availabilities, which are converted into growth efficiency factors. PARCH also adds additional stress factors that can account for adverse effects of high or low temperature. Since crop growth processes are not explicitly modeled but only captured as process efficiency factors, this model is less physiologically explicit than its counterpart on the tree side (Hybrid) or several other available crop models (e.g. DSSAT, APSIM).

HyPAR provides a tool for examining alternative agroforestry options over a range of soil types, climatic conditions and management practices. It can run with either growing trees, or with trees of fixed age and structure, and runs with a daily time step. Crop development responds to thermal time and drought stress, but microclimatic interactions between trees and crops are not included. HyPAR can represent up to 15 soil layers, and considers five different pools of soil organic matter, plus humus. Uptake of water and nutrients by trees and crops depends on their root-length density.

While the HyPAR model constituted a significant advance over SCUAF, it does not appear to have found many applications after the end of the project that led to its development. This was partly due to shifting priorities in the primary funding agency in favor of the flexible modeling environment SIMILE (Muetzelfeldt and Massheder, 2003) rather than a specific model, and partly because of the realization that the ‘quick-fix’ solution of letting existing crop and tree models interact with a single soil representation had limitations that could only be overcome by a fundamental reformulation. HyPAR and WaNuLICAS were developed in parallel for a number of years, with cross-fertilization of model concepts, before HyPAR as a separate model was effectively stalled.

A variant of HyPAR is the HyCAS model (Matthews and Lawson, 1997), which simulates cassava growth in agroforestry systems. This modification was achieved by coupling the Hybrid tree growth model not with PARCH, but with GUMCAS (Matthews and Hunt, 1994), a cassava model from the DSSAT family. This combination laid the groundwork for simulating production of other crops included in DSSAT in a

similar manner. Yet similar to the main variant of HyPAR, we have not been able to find evidence that this model has been used in recent years.

4.6. Forest and plantation models

Several models have been used to simulate production of tree plantations, including 3PG (Landsberg and Waring, 1997), CABALA (Battaglia et al., 2004), G'DAY (Corbeels et al., 2005) and PGSM (Chen et al., 1994). The TREGRO-ZELIG model (Weinstein et al., 1991) has also been used for single-species plantations, and it has the capability to model mixed forests. ForNBM (Zhu et al., 2003) and TREE-BGC (Korol et al., 1995) have specifically been designed for simulating mixed forests.

The level of detail with which processes are modeled, as well as the simulation time step, varies greatly amongst these models. For example, 3PG and ForNBM simulate tree growth at monthly intervals, while TREGRO-ZELIG has an hourly resolution. Most other models use a daily time step, which would be compatible with the approach most commonly taken in process-based crop models. In most forest and plantation models, certain processes are simulated in a relatively crude manner, limiting their potential uses in agroforestry modeling. Some models represent the soil as a single homogeneous layer, and amongst the different approaches used to model radiation interception, many are not promising for simulating competition for light (Medlyn et al., 2003).

4.7. Below-ground interaction models

Several models for below-ground interactions between species have been reviewed by Matthews et al. (2004). Besides the already mentioned SCUAF, WaNuLICAS, HyPAR, HyCAS and APSIM, they also mention COMP8 (Smethurst and Comerford, 1993), WIMISA (Windbreak Millet Sahel; Mayus et al., 1998), CropSys (Caldwell and Hansen, 1993), Almanac (Agricultural Land Management Alternatives with Numerical Assessment Criteria; Kiniry et al., 1992) and GAPS (General-purpose Atmosphere-Plant-Soil Simulator; Rossiter and Riha, 1999). Several of these models adequately simulate below-ground processes of supply, uptake and competition for water, carbon, nitrogen or other nutrients for particular applications. However, these models were primarily research tools and not always well-linked to other parts of the ecosystem, e.g. food or wood production. A strong case was made by Matthews et al. (2004) and authors of these models for building such links.

4.8. Comparative comment

Many of the models discussed above were built for certain purposes and certain users (Matthews et al., 2004; Lusiana et al., 2011). While they may provide valuable insights for agroforestry modeling, they cannot easily be converted into a general modeling framework for agroforestry systems. Amongst the models that specifically aim at simulating agroforestry systems, SCUAF, HyPAR and HyCAS have been used very rarely in recent years, and it seems they are not actively maintained or extended. Hi-SAFE is a relatively new model that has been used at least once outside its original European development domain (in Northern China; Holst et al., 2012), although some problems were encountered in adapting it to the new context. Reasons for the limited use of Hi-SAFE may be its extensive data requirement for parameterization, and the fact that it was developed specifically for application in European agroforestry systems, rather than aiming at more general applicability. The Yield- and Farm-SAFE models are easier to use, but their applications have so far been restricted to the European domain of the SAFE project. Further development of the SAFE family of models is ongoing in the AGFORWARD project (2014–2017).

The only specialized agroforestry model that has been consistently updated, refined and regularly used over many years in a range of geographic settings is WaNuLICAS, but even this model has not been used as widely as current scientific interest in agroforestry might lead one to

expect. The high level of detail in WaNuLCAS requires substantial understanding of the underlying processes on the part of the model user. Model users without this level of expertise have often been unable to decide whether unexpected model outputs resulted from real and previously unconsidered phenomena or from user error. The choice of the STELLA environment for programming contributed initially to model transparency, but at the cost of options for linking with data standards framed elsewhere.

5. The way forward

There are a number of constraints to using existing agroforestry models to reliably predict tree and crop yields in agroforestry that future modeling initiatives should attempt to overcome. Support for most of the early models ceased shortly after the models were developed, when the key researchers involved in their development shifted interest to other arenas or funding agencies shifted priorities. Many models were not updated or maintained. The choice of computing environment did not favor widespread use of some models, and gradual extensions to other models (WaNuLCAS in particular) have made them so complex that they have become difficult to use. Some models have been successful in simulating tree growth but perform poorly with respect to crop production or vice versa. So, there is still no single model or modeling framework that can reliably be used for predicting tree and crop performance in agroforestry across the range of conditions over which there is an interest in practical development of agroforestry systems. Key elements of a modeling framework that fill this gap are set out below.

5.1. Flexibility

For models to be widely used, it is essential that they are flexible, that is that they can be applied in a wide range of contexts. They should provide the option of either running as a stand-alone model or as a sub-model within a larger modeling framework. For instance, a model user interested in agroforestry responses to a wide range of climate scenarios may want to include a model in an automated batch procedure that feeds it with different future time series of weather data. A land use planner may want to supply a model with different land characteristics; a researcher modeling livelihood resilience may be interested in making the model part of a bioeconomic simulation at the household scale; and a landscape hydrologist may want to include simulation of plot-scale agroforestry practices in large-scale hydrological models. For all such applications to be possible, a model should not be tied to specific modeling software that cannot easily be combined with other modeling tools.

5.2. Simplicity

A modeling framework needs to provide users with options on the level of detail that is modeled. Because agroforestry is complex, it is easy to get lost in detail, such as modeling the competition amongst individual roots throughout hundreds of cubic meters of soil. While this much detail may be necessary to answer specific research questions, it is unlikely to be necessary for reliable yield prediction at larger scales, where such detailed representation could lead to unreasonable run times and large errors in outputs due to parameterization errors. The principle that models should be the simplest possible representation to meet their objective remains a useful maxim (Muetzelfeldt and Sinclair, 1993). The option to choose between simple and complex versions of major system process representations is necessary for an agroforestry modeling framework to be generally applicable across the range of objectives that users are likely to have. An important consideration in this context is the need to balance the level of detail amongst model components. There is little benefit in modeling certain processes, for example nutrient uptake, at a high level of mechanistic detail, while other processes of equal or greater importance such as tree management, are only crudely represented.

5.3. Software quality, interoperability and model longevity

Experience with many past attempts to model agroforestry points to a risk that they may not be much used after their initial development. This is particularly true for stand-alone implementations that are not easily combined with other models. If there is no easy way to adapt a model to new circumstances, its use will invariably be limited. Similarly, if a model is not actively maintained and regularly updated, it may soon become outdated, no longer reflecting the scientific 'state-of-the-art' or making effective use of technological progress. Model development should be directed by a plan for taking the model into the future, overseen by adequate governance procedures and guided by thorough version control (Holzworth et al., 2014). Good component design is also critical to ensure that different sub-models are able to interact effectively (Holzworth et al., 2010). Regular and thorough testing of model capabilities is important for instilling trust in a modeling framework and promoting its use (Holzworth et al., 2011).

5.4. Cautious expectations

Some doubts are justified about the feasibility of developing a generic agroforestry modeling framework that can provide reliable *ex-ante* projections of system performance. A flexible agroforestry model will likely rely on a large number of factors to be specified, and reliable simulations may not be possible without extensive calibration under local conditions. The long life span of trees in most agroforestry contexts and the absence of mature agroforestry systems in many places where the possibility of their introduction is being explored are major constraints to such parameterization. We see no prohibitive obstacles to major progress in agroforestry modeling, but any user of such models should be aware that the complexity of agroforestry requires simplifications that may in some cases lead to unrealistic simulation results. There will probably always be substantial uncertainty about many critical model input parameters. With these caveats in mind, we believe that improved agroforestry models will be useful for appraising the potential of agroforestry in new locations and changing climates, and improve upon expert opinion alone, which relies on implicit, rather than explicit assumptions. Even more than with the much simpler field crop models that are widely used, users of agroforestry models should accompany their simulations by assessments of model sensitivities to uncertain site factors and by appropriate estimates of model errors. Procedures for formal estimation of errors should be explored.

5.5. Conclusion

If agroforestry is to enter and sustain its place in the mainstream discourse on agricultural development and food security that many people are now suggesting it should (Glover et al., 2012), it is hugely important that reliable predictions of tree and crop performance can be made for a wide range of agroforestry practices, across a wide range of environmental conditions, to inform global and national debates as well as local action. This requires a flexible, modular modeling approach. For any specific modeling task, this approach should allow combining appropriate tree, crop and other components to obtain new system configurations, and to simulate all relevant aspects of their performance under the environmental conditions of interest. Well tested frameworks that offer such functionality for crops are already available and widely used (Huth et al., 2002), although their application to intercropping systems of any kind has so far been limited. Extending such frameworks to include capabilities to model trees and their interactions with crops is an efficient strategy towards achieving reliable yield prediction in agroforestry that builds on, rather than replaces, past modeling efforts. A modular framework allows for alternative sub-models for processes to be developed and compared and for an agroforestry modeling capacity to be developed in a step-wise manner, so that progress can be made on individual processes and tree and crop species, in specific sub-models,

without having to tackle the full complexity of the system while sub-model details are worked on. Rooting agroforestry modeling efforts in a widely used and actively maintained modeling framework reduces their vulnerability to shifts in donor or researcher priorities, which have negatively affected past endeavors. Finally, including agroforestry options into a widely used framework enables many agricultural modelers to simulate agroforestry systems with tools they are familiar with. Such greater ease of model application would likely expand the agroforestry modeling community and lead to greater use of simulation results in agroforestry research and development.

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