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Agroforestry systems in a changing climate — challenges in projecting future performance

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Agroforestry systems are complex assemblages of ecosystem components, each of which responds to climate. Whereas climate change impacts on crops grown in monocultures can reasonably well be projected with process-based crop models, robust models for complex agroforestry systems are not available. Yet impact projections are needed because of the long planning horizons required for adequate management of tree-based ecosystems. This article explores available options for projecting climate change impacts on agroforestry systems, including the development of process-based models, species distribution modeling, climate analogue analysis and field testing in climate analogue locations. Challenges and opportunities of each approach are discussed.

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Introduction

Climate change is projected to affect agricultural and natural ecosystems around the world, and there is no reason to expect that agroforestry systems will be spared. Like all other plants and animals, those existing within agroforestry systems will be exposed to temperatures that are higher than those of the past [1], to higher carbon dioxide concentrations, and they may also experience changes in precipitation [2]. These changes will probably affect all system components, and they may even modulate interactions between components.

For all agricultural systems, appropriate adaptation to climate change requires an understanding of how well existing and potential future systems will perform in future climates. The development of tools and methods for reliable climate change impact projections on agricultural systems has therefore been a research priority for agricultural and climate modelers in recent years, and several robust crop models are now available for agricultural adaptation planning [3,4,5••]. Most of these tool development efforts have focused on annual crops grown in monocultures [3,4], for which climate change impacts can therefore be projected quite reliably [6–8].

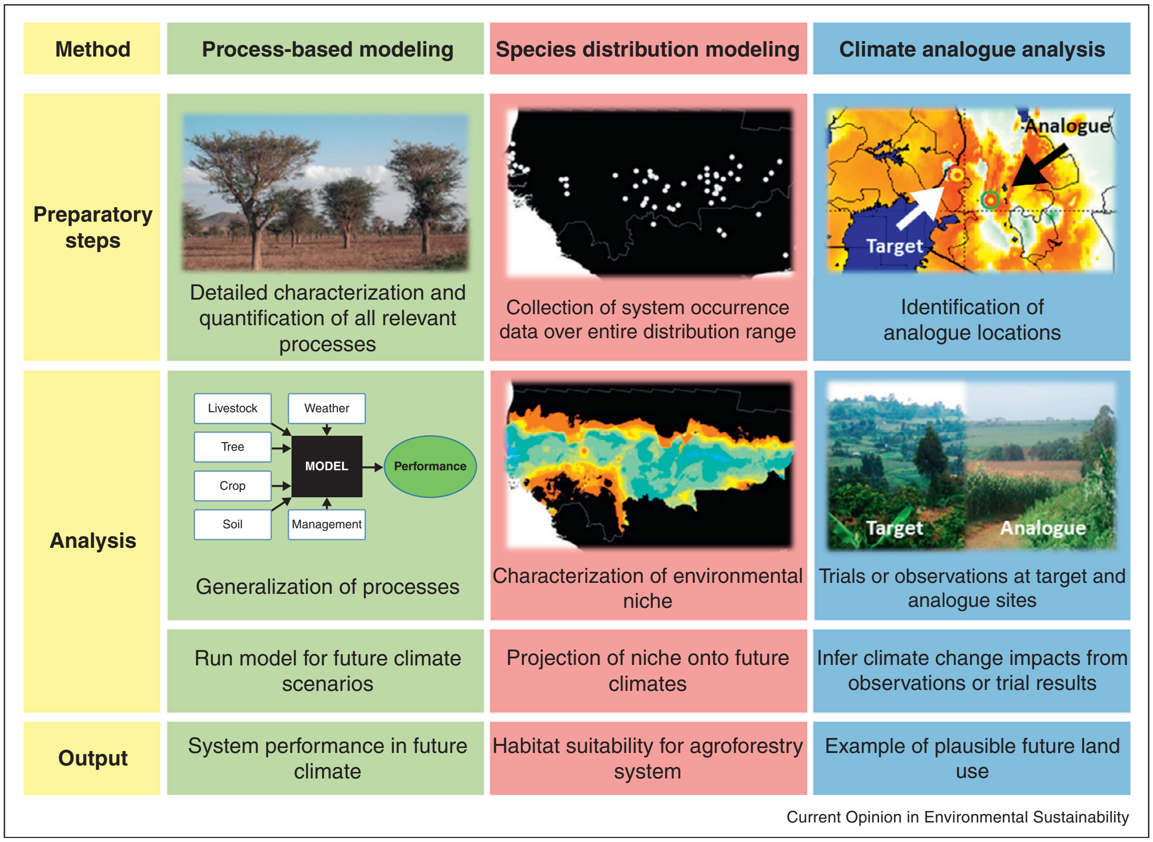
Agroforestry systems are more complex than monoculture situations. They consist of annual and perennial plants, which are often integrated with livestock. Temperature, humidity and ambient CO_2 concentration affect all organisms involved in an agroforestry system, possibly in very different ways, and climate change is projected to alter all of these factors. In light of the high potential of agroforestry for food security [9•], climate change adaptation and mitigation, tree-based agricultural systems are currently being promoted in many parts of Africa [9•], and they have successfully been established in many regions [10]. Many of the trees that are introduced are long-lived species that are expected to grow on farmers' fields for several decades. These long planning horizons make consideration of climate change impacts on trees particularly important. After all, many trees planted today may still be in place by the middle or even end of the 21st century.

There is thus great need for methods to project climate change impacts on agroforestry systems. Three main approaches are available: (1) process-based models, (2) species distribution models and (3) climate analogue analysis (Figure 1). As part of a Special Issue of Current Opinion in Environmental Sustainability focusing on 'Agroforestry, Climate Change and Food Security in Africa', we summarize challenges and opportunities of each of these approaches for projecting climate change impacts on agroforestry (Figure 2).

Process-based models

Where all major processes of a particular system are reasonably well understood, process-based modeling approaches are feasible. System performance is then modeled as a response to factors such as soil, climate or management, which affect system processes, such as plant transpiration, nutrient uptake, photosynthesis, biomass accumulation or interspecific competition for resources.

Figure 1



Method	Process-based modeling	Species distribution modeling	Climate analogue analysis
Preparatory steps	Detailed characterization and quantification of all relevant processes	Collection of system occurrence data over entire distribution range	Identification of analogue locations
Analysis	Generalization of processes	Characterization of environmental niche	Trials or observations at target and analogue sites
	Run model for future climate scenarios	Projection of niche onto future climates	Infer climate change impacts from observations or trial results
Output	System performance in future climate	Habitat suitability for agroforestry system	Example of plausible future land use

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Overview of available approaches for projecting climate change impacts on agroforestry systems.

Process-based models simulate such biophysical processes in agricultural systems, often looking to project economic or environmental outcomes of land management choices. In recent years, process-based models have frequently been used to develop land use strategies that mitigate climate risk [11], for simulations of climate change impacts [12,13] and mitigation [6] and for evaluating agricultural policy scenarios [14]. Models are also commonly used for exploring adaptation options to climatic changes projected by global or regional circulation models [15]. Such analyses have been undertaken for sugarcane [12], broad acre agriculture [8,13] and smallholder crops [16]. None of the advanced modeling frameworks available currently are capable of simulating processes in agroforestry systems. Trees are typically not included in these models, and tree-crop interactions can generally not be simulated. An exception is the inclusion of *Eucalyptus*-crop interactions into the Agricultural Production Systems Simulator (APSIM; [17]). Yet some other models have tackled the complexity of agroforestry systems [5••,18–20]. Among these, the Water, Nutrient and Light Capture in Agroforestry Systems model (WaNuLCAS; [5••]) is capable of simulating tree–crop interactions in great detail. However, it does not operate at a daily (or even sub-daily) time step, so that the level of detail in simulating crop growth processes that is included in advanced crop models cannot be achieved.

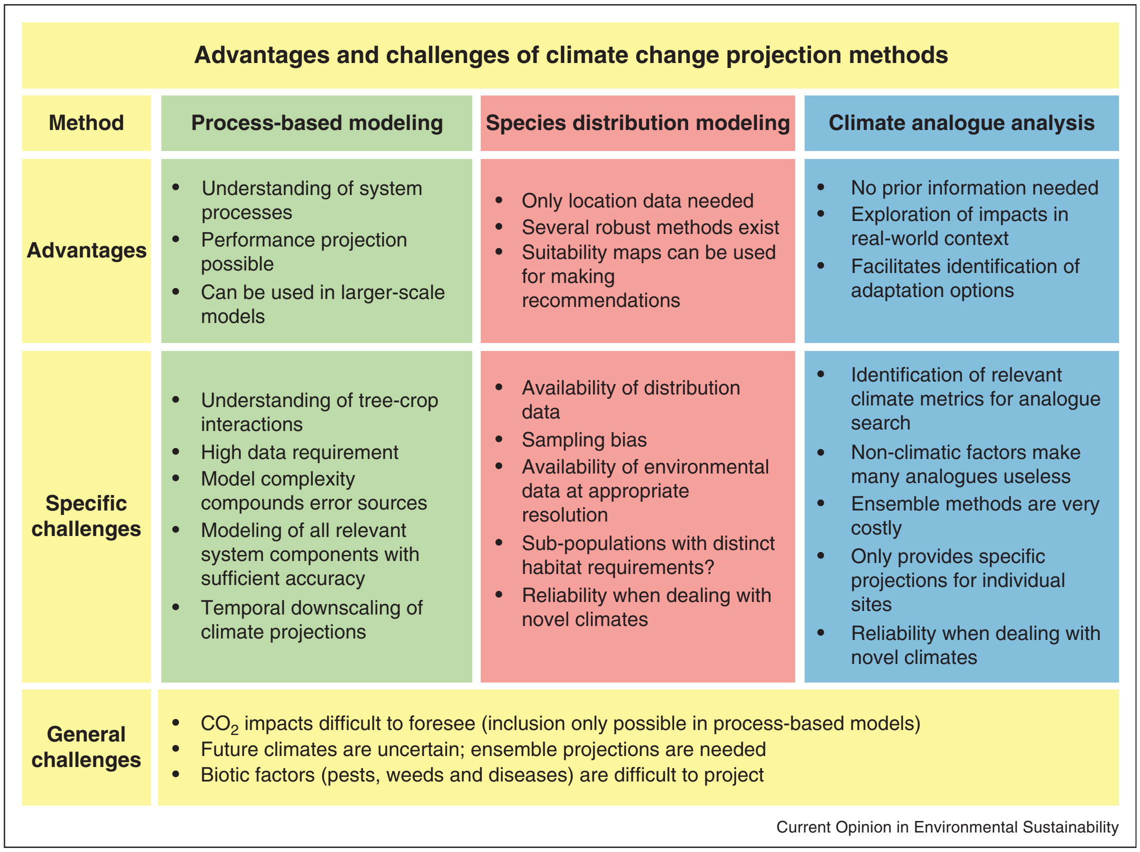
Challenges and opportunities

The adequacy of existing agroforestry models for projecting climate change impacts is currently difficult to gauge. Unlike mainstream crop models, agroforestry models have only been used in a small number of climatic and environmental settings. They should therefore not be expected to contain accurate representations of the climate sensitivity of all system components. Much more validation and probably some improvements to the models are needed before climate change impact projections derived from them can be fully trusted.

Particular challenges to process-based modeling are:

- Processes in agroforestry systems are complex and many interactions are difficult to measure or model.
- The diversity of agroforestry systems makes it difficult to develop models that are valid in a wide range of climatic and environmental settings.

Figure 2



Advantages and challenges of climate change projection methods

Method	Process-based modeling	Species distribution modeling	Climate analogue analysis
Advantages	• Understanding of system processes • Performance projection possible • Can be used in larger-scale models	• Only location data needed • Several robust methods exist • Suitability maps can be used for making recommendations	• No prior information needed • Exploration of impacts in real-world context • Facilitates identification of adaptation options
Specific challenges	• Understanding of tree-crop interactions • High data requirement • Model complexity compounds error sources • Modeling of all relevant system components with sufficient accuracy • Temporal downscaling of climate projections	• Availability of distribution data • Sampling bias • Availability of environmental data at appropriate resolution • Sub-populations with distinct habitat requirements? • Reliability when dealing with novel climates	• Identification of relevant climate metrics for analogue search • Non-climatic factors make many analogues useless • Ensemble methods are very costly • Only provides specific projections for individual sites • Reliability when dealing with novel climates
General challenges	• CO_2 impacts difficult to foresee (inclusion only possible in process-based models) • Future climates are uncertain; ensemble projections are needed • Biotic factors (pests, weeds and diseases) are difficult to project		

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Advantages and challenges of climate change projection methods for agroforestry systems.

- Errors and uncertainties of all components are compounded in complex agroforestry models, so that extensive calibration and validation across climatic gradients is required.
- Experimentation and data needs for model development are very high, with controlled trials with mature trees constituting a particular challenge.

There is hope, however, for developing better agroforestry models. Modern crop modeling frameworks provide a means for integrating diverse models into one unified model (e.g. [21•]). This is an important prerequisite because of the range of system components that need to be simulated including trees, crops, soils, livestock and decisions by the farm manager. Models for each of these components need to be closely linked to allow simulation of the overall system. Developers of the next generation of agroforestry models can benefit from building upon existing, well-tested agricultural modeling frameworks, many components of which can be used directly or after slight modification. Yet integration of tree–crop interactions, such as competition for water and nutrients, as well as effects of tree canopies on crop microclimate, will still require some major additions to existing frameworks, and it seems unlikely that such components can become as robust as single-crop modules.

Species distribution modeling

Under the assumption that agricultural systems can be evaluated with methods typically used for studying organisms [22], species distribution modeling (SDM; [23••,24,25]) provides an alternative approach to projecting climate change impacts. It has been applied for modeling vegetation communities [26,27], agricultural systems [28,29••] and entire biomes [30].

SDM is based on a statistical method to determine the environmental niche of a species, system, biome or genotype, which then allows mapping the distribution both in environmental and (future) geographic space. Environmental variables used in SDM typically include available resources, limiting factors and disturbances [25,31]. These variables are usually combined with information on the point locations where a particular species is known to occur. SDM has recently become very powerful through introduction of machine-learning algorithms

[32•,33,34], application of ensemble approaches [35,36,37•] and the availability of high resolution raster datasets ([38], but see [39] for problems associated with excessive precision).

Challenges and opportunities

Although modern SDM methods are now available (for example in the open R environment with the dismo, biomod and BiodiversityR packages; available at http://cran.us.r-project.org/), several pitfalls are associated with the application of SDM, including:

- Lack of samples: the current distribution of a system is not sufficiently known [40]. This is particularly problematic if system occurrences in particular climatic niches are overlooked.
- Sample bias [41]: a particular agroforestry system may not be encountered under present conditions for various reasons (e.g. soil conditions or marketing infrastructure), even though the current climate is perfectly suitable.
- Lack of environmental data at adequate resolution: for example, soil information is usually not available at the same resolution as bioclimatic data. Bioclimatic conditions often vary widely over short distances, especially in mountainous terrain, which is often not reflected in available datasets.
- Genetic variation and adaptation: tree species usually consist of populations that are adapted to slightly different environmental niches [42,43]. Likewise, the composition of agroforestry systems varies within broad agroforestry types. Not all manifestations of a particular system may thus remain viable, even though SDM indicates continued suitability.

Predicting future trends for agricultural systems while considering complex and interlinked environmental and socio-economic factors is a complex challenge. Without modeling processes in detail, SDM can reproduce change patterns in an intuitive way. Given the limitations of the methodology, we expect that SDM can provide a conservative projection of the potential distribution of the 'climatic niche' of a particular agroforestry system, which could either be considered an 'optimistic' (e.g. ignoring future pests) or 'pessimistic' (e.g. ignoring adaptation strategies) view of the future distribution of systems.

Climate analogue analysis

Where knowledge about a system is insufficient for process-based modeling and information on the system's distribution is insufficient for SDM, climate analogue analysis offers a last-resort alternative for projecting climate change impacts. For a given location of interest, this technique searches for different locations where the current climate is similar to that predicted for the site of interest [29••,44••,45]. Study of a site's analogue locations provides a glimpse of the range of climatic futures that are projected. System performance at analogue locations can illustrate climate change impacts if similar land use exists, and different land uses may indicate useful adaptation options.

Climate analogue analysis has been used to illustrate climate change impacts by shifting the locations of US states and European cities on maps to their closest analogue sites [46,47]. Some studies have also used spatial statistics, such as the bearing and the geographic distance to the closest analogue site to express the magnitude of the adaptation challenge in quantitative terms [44••,48•]. Some researchers have argued that many locations do not have modern analogues of future projected climates [49]. For such locations, model-based simulations cannot easily be validated by experimentation. A current weakness of most analogue studies is that analogue searches are based purely on climatic data and geographic position, while very few have attempted to assess current land use or land cover at analogue locations. Exceptions include an assessment of current land cover for analogue locations to cities in Wisconsin based on a geospatial dataset [44••] and an evaluation of habitat suitability (modeled using SDM) for parkland agroforestry at three locations in the West African Sahel [29••]. Analogue analysis has also been proposed for identifying well adapted germplasm for temperate fruit trees [50], and experimental results from analogue locations have been used to project future performance of *Pinus* plantings in Brazil, Colombia and South Africa [51•]. Farmer visits to analogue locations have been facilitated to assist in sourcing land management options for adaptation to climate change [45].

Challenges and opportunities

Several challenges stand in the way of wider application of analogue analysis for projecting climate change impacts on agroforestry:

- While a range of methods has been proposed for analogue analysis [29••,44••,45,47,51•], all have shortcomings when it comes to quantifying climatic requirements of complex systems and their components. A number of technical issues, such as the most useful ways to normalize and weight different climate variables, have not sufficiently been addressed.
- Important non-climatic characteristics, such as soil type, farm size, market orientation or cultural preferences may differ between target and analogue sites such that sufficiently similar systems may not be present [52]. Information on these important characteristics for inclusion in analogue search procedures is often unavailable.
- Ensemble methods that evaluate multiple climate scenarios multiply the costs of analogue analysis, if actual observations at the analogue sites are conducted.

- In contrast to process-based modeling and SDM, climate analogue analysis only provides information about particular sites, rather than allowing large-scale suitability or performance projections.

These constraints severely limit the range of circumstances, under which analogue analysis is likely to succeed. So far its only application for agroforestry systems has focused on a system that is used, with varying intensity, on a regional scale in the West African Sahel [29••]. It seems likely that applications for systems whose distribution is limited and that are dependent on very site-specific environmental and socioeconomic contexts will remain unsuccessful in the future.

Conclusions

As outlined by several other contributions to this special issue, agroforestry systems can potentially help farmers adapt to climate change while contributing to climate change mitigation through carbon sequestration [53]. However, introduction of agroforestry practices that are either entirely new, or new to particular regions, is risky, because like all other agricultural systems, agroforestry systems will respond to climate change. Many sources of uncertainty in projecting climate change impacts are not unique to agroforestry. Climate models and scenarios differ substantially in the extent of temperature and precipitation changes they project [2], impacts of pests and diseases on biological systems, especially for invasive species, can only crudely be projected (e.g. [54]), and there is substantial uncertainty about the direct impacts of elevated atmospheric carbon dioxide concentrations on plant physiology [30,55]. Species distribution modeling and climate analogue analysis can be used for impact projection, but both rely on the major assumption that observations of present performance or distribution can be used to guide estimates of future performance or distribution. Given that the effects of elevated carbon dioxide [30,55] cannot be observed at present, and many locations may experience novel climates in the future [49], both approaches have some systematic shortcomings that cannot easily be overcome.

The only approach that can comprehensively capture the effects of both CO_2 and changing climates is the development of process-based models, supported by experimentation. Such models characterize the climate sensitivity of all system components and their interactions, and when this is done well enough, they should be able to project performance even in places or climates where the particular type of agroforestry system has never been observed. Efforts at developing such models have periodically been undertaken [5••,17••,18,19], but they have generally fallen short of producing robust models, whose projections of climate responses of trees and crops could be trusted. Indeed, capturing all relevant processes in sufficient detail to produce reliable results, while avoiding excessive complexity which may compromise a model's usability, is a formidable task. Yet the promise of agroforestry for meeting the challenges of climate change, as well as recent moves to scale up tree-based agricultural practices throughout Africa and other parts of the world [9•], warrant a renewed effort at agroforestry modeling.

While process-based models emerge from our analysis as the most likely tools to produce robust and credible projections of climate change impacts on agroforestry systems, their development will require a substantial amount of time and energy, and the transferability of models across contexts is not guaranteed. SDMs and climate analogue analyses may be less reliable than process-based models, but their use is much cheaper, faster, easier and more flexible, so that they still constitute valuable tools for adaptation planning. The possibility to combine different projection approaches for planning adaptation to climate change, making use of the specific strengths of each method, deserves further exploration. For example, it may be possible to base SDM or analogue procedures on site characteristics obtained by process-based modeling of soil properties, market access etc. Species suitability scores could also be considered in analogue location searches. Such combined approaches may lead to more robust projections than application of each individual projection strategy.

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This study uses trial results from three countries in an analogue analysis framework to produce empirically derived estimates of the future performance of tree plantations. While trial sites were not strictly selected to be at analogue sites, this study is a rare case, where actual observations at analogue sites were used to make climate change impact projections.

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