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Climate change adaptation in and through agroforestry: four decades of research initiated by Peter Huxley

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Abstract
Agroforestry (AF)-based adaptation to global climate change can consist of (1) reversal of negative trends in diverse tree cover as generic portfolio risk management strategy; (2) targeted, strategic, shift in resource capture (e.g. light, water) to adjust to changing conditions (e.g. lower or more variable rainfall, higher temperatures); (3) vegetation-based influences on rainfall patterns; or (4) adaptive, tactical, management of tree-crop interactions based on weather forecasts for the (next) growing season. Forty years ago, a tree physiological research tradition in aboveground and belowground resource capture was established with questions and methods on climate-tree-soil-crop interactions in space and time that are still relevant for today's challenges. After summarising early research contributions, we review recent literature to assess current levels of uncertainty in climate adaptation assessments in and through AF. Quantification of microclimate within and around tree canopies showed a gap between standard climate station data (designed to avoid tree influences) and the actual climate in which crop and tree meristems or livestock operates in real-world AF. Where global scenario modelling of 'macroclimate' change in mean annual rainfall and temperature extrapolates from climate station conditions in past decades, it ignores microclimate effects of trees. There still is a shortage of long-term phenology records to analyse tree biological responses across a wide range of species to climate variability, especially where flowering and pollination matter. Physiological understanding can complement farmer knowledge and help guide policy decisions that allow AF solutions to emerge and tree germplasm to be adjusted for the growing conditions expected over the lifetime of a tree.

Keywords Agroecology · Agroforestry models · Climate shift · Multipurpose trees · Resilience · Tree architecture

Dedicated to a celebration of the contributions the late Peter A Huxley (1926–2019) and Chin K. Ong (1948–2020) made to agroforestry research.

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1 Introduction

Global circulation models (or ensembles of such models), parameterised for a range of policy-relevant and credible greenhouse gas emission scenarios, project how temperature will increase and how rainfall, depending on location, will either increase or decrease in the coming decades (Pachauri et al. 2014). Although the land use sector can contribute to a world where global warming is capped at 1.5 °C (Roe et al. 2019), the global cohesiveness and political will needed to achieve that is lacking. With current crops and cropping patterns, without adaptation, ongoing and expected climate change challenges food supply (Smit and Skinner 2002; Fischer et al. 2002, 2005; Schmidhuber and Tubiello 2007). The predominant narrative on how agriculture should adapt to these changes is through major crop improvement programmes, supported by new genomics and gene-level change, that generate the new crop varieties with greater tolerance to drought and high temperatures, especially for the primary staple crops (Burke et al. 2009; Varshney et al. 2011; Dempewolf et al. 2014). Next to emission reduction ('mitigation'), this type of climate change adaptation is advocated as the main way to avoid global food insecurity in the future (Porter et al. 2014). Agricultural adaptation strategies suggest that farmers substitute crops, explore alternative livelihood strategies or relocate (Rippke et al. 2016), but do not think of modifying local climate by tree planting. Yet, that is what evidence shows they might do, outside the purview of mainstream research.

Recent advances in agroecology and agroforestry research (Sinclair et al. 2019; van Noordwijk 2019a, b, c; van Noordwijk et al. 2019a, b, c, d) bring important nuances and challenges to this narrative in the following four main ways that will be the entry points to this literature review.

A. Long-term persistence of AF systems in fragile environments such as Sahelian or Mediterranean drylands is based on maintenance of the buffer functions trees and soils protected by trees provide (Bayala et al. 2019b). The crop-level microclimate in any location is modified and modifiable by a change in tree cover from what climate station data and the models that are calibrated on such data (van Noordwijk et al. 2013, 2014) project. The temperature range of microclimatic effects of trees so far exceeds global warming (Ovalle-Rivera et al. 2015), whilst rainfall dependence on continental land cover may involve a 10–20% shift (increase with more upwind tree cover, decrease with upwind deforestation) in many areas relevant for agricultural production (Ellison et al. 2019). Rather than taking projected local climate change as a given (only actionable via global emission control), there is scope for local and regional actions, focusing on the water balance and hydroclimatic relations (Robiglio et al. 2017; Creed and van Noordwijk 2018), as is increasingly done in managing the cooling services provided by urban trees (Pretzsch et al. 2021).
B. Climate change is mostly climate shift, with the change in local suitability of crops and crop varieties likely to have existing solutions in adjacent or, sometimes distant, 'climate analogues' (where current climate is similar to what is projected for a target location) (Bos et al. 2015). A focus on social learning, germplasm exchange and social-ecological system governance may be more relevant than (or at least complement) crop breeding and 'tree improvement' (Sinclair et al. 2019). Given the large number of trees and the low degree of genetic 'domestication' of most species used, tree adaptation research is mostly through a combination of tree-site matching, supported by geographic informa-

tion systems, attention to local ethnobotanical knowledge and germplasm exchange and hence the consideration of whole system adaptation responses rather than focussing on only one component (Kmoch et al. 2018).

C. Tree diversity with potential relevance for AF varies over at least three orders of magnitude (1–10, 10–100, 100–1000 species in the regional tree species pools from which AF recruits its trees) depending on location (van Noordwijk et al. 2019a). Tree-site matching research has shown wide ranges of climatic tolerance and phenotypic adjustments of aboveground and belowground morphology, with opportunistic and episodic fruit and seed production as apparently adaptive traits (Huxley 1999a). Phenology data (as scarce as they are) has documented a wide range of species-level and individual variation, with differential access to landscape-level water reserves as a likely contributor (Do et al. 2005; Valdez-Hernández et al. 2010). This lack of predictability is a problem where regular production for established market channels is the norm, creating 'needs' for horticultural management (irrigation, drainage, fertilisation, pruning) (Goldschmidt 2013). In the genotype–environment–management interaction, aspects other than global climate change are likely to dominate (van Noordwijk et al. 2019b). Elsewhere, especially in high tree-diversity environments or where the focus is on wood or resins, variability in individual tree-level performance is less of an issue, and portfolio risk management under uncertainty (using principles documented for crop diversity, van Noordwijk et al. 1994) is the primary line of defence (Ordoñez et al. 2014).

D. The conventional view of the development trajectory for agriculture, namely a general trend of simplification, specialisation and increased inputs, is challenged by agroecology (Altieri and Nicholls 2017; HLPE 2019). The alternative of complexity, diversity and recycling, that includes trees and AF, has been shown to increase resilience to climate change in specific contexts, but its widespread adoption is likely to be constrained by market failures, maladapted policies and the paucity of evidence about the performance of agroecological practices across contexts that 'locks-in' industrial models of agricultural improvement and adaptation (Sinclair et al. 2019).

These four challenges to a 'business as usual' model of agricultural development in response to the climate change challenges call for a multi-pronged approach to policy and practice for adapting agricultural and food systems to global climate change. It may have to go beyond what current 'climate-smart' approaches to agriculture set out to achieve (McCarthy et al. 2011; Carter et al. 2018; Kimaro et al. 2019; Rosenstock et al. 2019b), and build on earlier ideas of AF at the interface of climate change adaptation and mitigation (Verchot et al. 2007; Schoeneberger et al. 2012). A new appreciation of the relevance of AF and related practices for the climate change agenda is emerging as part of the recent IPCC land-use report (IPCC, 2019; Smith et al. 2019). The 2019 update of the IPCC guidelines for national greenhouse gas inventories for the first time explicitly includes default data (for Tier 2 accounting) for a range of AF land uses (Cardinael et al. 2018; Ogle et al. 2019). National Adaptation Plans increasingly make explicit reference to agroforestry (Meybeck et al. 2020).

The wide diversity of extant AF practices across the (sub)tropics (Nair 1993; Beer et al. 1987; van Noordwijk et al. 2019b) was the main focus during the first two decades of formal AF research, but this focus lacked a tractable approach to measuring performance across contexts that has now become a major focus of AF research 'in' development (Coe et al. 2014; Sinclair and Coe 2019). A fresh look at microclimatic effects of trees, adaptive social-ecological systems (and their germplasm exchange in search of locally suitable

trees, crops, and tree-crop combinations) and the phenological and adaptive responses of trees to temporal variability in water availability and temperature may help us identify relevant concepts and research methods that stem from earlier physiological research that have traction in addressing the current climate emergency.

The passing in November 2019 of one of the founding fathers of tropical AF research, Peter A Huxley (Lundgren et al. 2020), and the availability of his synthesis volume (Huxley 1999a), stimulated us to explore his potential contributions to current scientific questions. At the start of AF research, three lines of research were developed that not only cross-fertilised but also competed for limited research budgets and time allocations.

The first focussed on trees, often 'multipurpose trees', that differed from the timber-oriented tree interest in conventional 'forestry' research. Beyond rapid production of straight poles, trees were identified that helped maintain or improve soil fertility and provided fodder, fruits, resins, medicinal bark, or other products, as well as appropriate levels of shade and complementary rooting habits that ensure compatibility with crops (Sinclair 1996). At least some trees exhibit niche differentiation with crops (Anderson and Sinclair 1993; Cannell et al. 1996; Bayala and Prieto 2019; Bayala et al. 2019a). Large databases were set up to document the hundreds (or thousands) of trees with recorded uses. An ongoing debate on 'prioritisation' addresses the challenge that explicit genetic 'tree improvement' can only deal with a few tree species at the required level of research intensity (Dawson et al. 2011, 2014; Jamnadas et al. 2019), whilst farmers and rural communities may require tree diversity to ensure the productivity and resilience of their livelihoods and landscapes (Vandermeer et al. 1998; Smith-Dumont et al. 2019; van Noordwijk et al. 2019a, 2019b).

The second AF research line looked at the structure–function interactions for any tree in combination with (annual) crops and livestock from the perspective of resource (especially light, water, nutrients) capture, interpreting aboveground and belowground architecture from the perspective of active leaf area and fine-root presence (Luedeling et al. 2016). The third line of research started from a classification (typology) of 'AF systems' based on the trees, crops and livestock components (Nair, 1985; Sinclair 1999), exploring which systems have emerged under what conditions, which ones are expanding and which ones contracting. These three lines of research resulted in correspondingly different emphases of research activity (Table 1). For research lines I and III, it has been a challenge to tease apart climate change as a driver of change from the many other factors (e.g. demography, rural–urban interactions, physical and economic access to markets) that influence farm dynamics. Two types of climate change adaptation have been identified in the literature: firstly, an increase in tree diversity in order to be prepared for increased variability and have options available for adaptive management decisions, and secondly, targeted interventions in order to be prepared for a projected trend in conditions (van Noordwijk et al. 2011a; de Leeuw et al. 2013; Hoang et al. 2014; Catacutan et al. 2017). In funding streams for climate change adaptation, there is a preference for the second type of adaptation, but most farmer surveys have so far provided evidence of the first type (Bayala et al. 2014).

Examples of debates that seek to reconcile different types of evidence and generalisations can be found, for example, in the recent challenge to a basic hypothesis of shade tree–based resilience in coffee and cocoa production systems (Vaast et al. 2016). A recently published study (Abdulai et al. 2018) provided evidence that shaded cocoa in a specific location became more rather than less vulnerable to climate variability, and that previously presumed contributions of AF to resilience of cocoa production are not universal (type II evidence in Table 1). It became clear in the ensuing scientific debate that the research results only applied to a specific fast-growing tree that did not complement the rooting pattern of cocoa and left substantial amounts of subsoil water

Table 1 Agroforestry (AF) research lines and the types of evidence it supports for climate change adaptation through AF

	AF research lines:	Actionable steps at the farm level	Evidence of climate change adaptation through AF
I	Trees on farm, supporting rural livelihoods in multiple ways, to be enhanced by 'tree improvement' or 'domestication' and increased access to and quality of tree nurseries, supported by spatially explicit data of which trees occur where and what farmers know and think about them	A. Increase of presence, quality and/or diversity of trees on farm in view of directly harvestable (and marketable) products, support services for soil quality and land health and/or adequate shade levels for main crops B. Explicit portfolio management for diversity-based risk reduction C. Explicit choice of tree germplasm ~ expected climate	A generic increase (or slowdown of ongoing decreasing trend) of the presence and diversity of trees in agricultural landscapes because of farmer decisions (including but not restricted to climate change as rationale)
II	Generic principles of tree-soil-crop interactions deliberately managed for increased overall resource capture, captured in process-based simulation models	A. Shade management B. Strategic adjustment of tree cover (amount, species choice) to moderate tree water use in view of crop needs and desirability of groundwater recharge, whilst protecting soil, reducing soil evaporation and maintaining soil infiltration rates C. Adjusted tree cover for regional hydroclimate effects	An increase or decrease of tree cover (and its seasonal management) that is related to expected change in (variability of) resource availability (e.g. water)
III	Specific tree–crop–livestock combinations, managed to match farmer targets in any given context, with due attention to the farm economics of labour/land ratios and market-based cash flows	Tactical (within a year) adjustment of tree canopies (e.g. by pruning) in response to expected weather for next growing season	Explicit change in the management of specific trees with specific spacing, pruning and harvesting regimes within defined crop and livestock production systems, responding to cropping season weather forecasts

unutilized at the time of drought-induced tree mortality (Norgrove 2018; Wanger et al. 2018). In terms of type II evidence, the initial experiments suggested this had not been the 'right tree for the right place', rather than a generic test of whether shaded cocoa systems can contribute to climate resilience. This echoes many other incidences of where generic claims are made from quite specific experiments. For example, measured effects of a few individual trees of three species (including *Senna spectabilis*, known to be an aggressive competitor with crops) exacerbating negative impacts of reduced tillage on maize yield in Rwanda and Ethiopia led to claims that combining conservation agriculture with trees was not viable across East Africa (Ndoli et al. 2018) despite its adoption by farmers with a range of other tree species and contexts in the region (Iiyama et al. 2017; Nyaga et al. 2019). Representativeness of case studies is easily overclaimed (Dewi et al. 2017). Further evidence of climate-buffering impacts of trees on coffee, wheat and rice will be discussed below.

Seven interrelated research questions that arise from such considerations (Fig. 1) and are addressed in this review are as follows:

1. How can farmers adapt to global climate change through introducing or better managing trees on farms and in agricultural landscapes?
2. How are site-level impacts of global climate change relevant for tree growth influenced by topography and 'upwind' vegetation?
3. What change in tree phenology, growth and production can be expected for a given variability and/or trend in local climate?
4. How does tree cover, managed on-farm, influence microclimate at the crop level relative to weather station data and the climate models calibrated to such data?
5. How does belowground resource capture by trees and crops (including fodder grasses) interact with modified resource availability under projected climate change regimes?
6. What are the options for farmers to manage AF practices in the context of expected climate change?

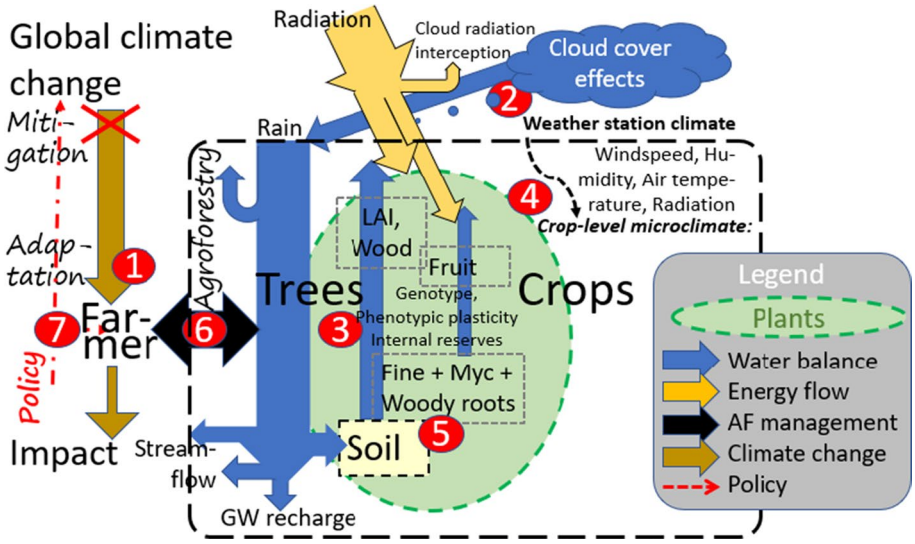


Fig. 1 Schematic representation of the main relationships and 7 research questions discussed in the text

7. How do social and economic changes associated with the changing climate and response to it affect the adoptability of AF?

We leave question 1 to be addressed together with question 7 at the end of this review. A restriction to the general applicability of ideas and results is that silvo-pastoral systems (Jose and Dollinger 2019; Jose et al. 2019) with trees and livestock, rather than annual crops, as main components and a dominant form of AF in Latin America (Somarriba et al. 2012) offer different challenges and opportunities on the adaptation side but will get little attention here. The focus of our review is on the opportunities for as well as limits to adaptation (van Noordwijk et al. 2011a; Dow et al. 2013) through agroforestry and the research efforts and methods to derive location-specific answers, but we leave the more specific guidance on how to apply this knowledge to other texts referred to.

2 Method

We re-read early publications of AF research on agro-climate, tree phenology and tree-based microclimate modification, identifying aspects relevant for current discourse, and assessing recent progress or gaps in such progress. We traced citations in the recent literature of publications from the early days of AF research. Teams of authors with a direct connection to early AF research were formed with those with current cutting-edge research experience in climate change adaptation research in and through AF.

2.1 Agroforestry in the eyes of Peter A Huxley

In one of his first publications after starting the research effort at the newly established International Council for Research in Agro-Forestry (ICRAF), Peter Huxley (1980) wrote: 'Is there really a place for yet another research discipline? I believe there is, on two main counts. The first, and more pragmatic is that any new amalgam of research ideas needs to be positively encouraged and identified as such, whether it springs from entirely original concepts and practices or not. This is especially so when the component research disciplines, in this case of agriculture and forestry, have established themselves almost as separate entities. The second is that a positive thrust towards the multiple use of land through AF techniques generates a definite need to appraise and re-assemble our research tactics, to consider the increased complexities in space and time which must be dealt with in such systems. We might add, also, that we have to enquire whether our methods of evaluating the outputs of AF systems, in terms of the multiple products and benefits which can accrue, are up to the job.'

> 'Very few existing agroforestry systems have been studied critically and so far, many still await even broad description. Most agroforestry systems have arisen through the enterprise of indigenous rural communities who have, themselves, evolved them. Whether it is a home garden in Indonesia, a multi-storeyed mixture of trees and agricultural crops in Central America, or a silvo-pastoral system of fodder shrubs and grasses in the Sahel, suggestions for changing the inputs in terms of spatial arrangements, the temporal sequences of crops, or the very plant components themselves are unlikely, in many cases, to be based on measurement data because we have so few to work with.'

Peter Huxley came to ICRAF with 20 years of research experience in Libya, Uganda and Kenya, with a strong interest in agriculture, climate, tree phenology and coffee, but also ideas about agricultural education and the gap between agriculture and forestry in terms of educational traditions. In his Tropical Agroforestry book (Huxley 1999a), Peter handed over the baton to the next generations of AF researchers with '…the first book to provide a comprehensive, analytical account of the principles as well as the practical applications of agroforestry. The focus is on understanding how agroforestry systems function whilst considering the conflicts and compromises that arise because of the farmers' requirements and the biological potentials and restraints of growing woody plants with crops.' 'We should always remember that *people* are the key elements in agroforestry. Being inclined towards biology I can only refer to some of the socio-economic aspects in this book (and without claiming much authority)'.

3 Local climate characteristics relevant to tree growth

3.1 Huxley's contributions

Before the rise of global circulation models that account for climates across the globe, local observers of weather patterns that contribute to the long-term mean (30 years by definition) climate had developed a rich language that related wind direction to the type of weather that could be expected, interacting with local topography (e.g. forested mountain slopes, lakes). Huxley and Beadle (1964), for example, analysed short-range variation in weather patterns in Uganda as part of that tradition. It led to a focus on cloudiness as a factor in determining radiation energy, with attention to the diurnal pattern of, for example, morning sunshine and afternoon clouds and rainfall (Huxley 1965). For the humid tropics, seasonal variation in cloud cover may be as important for plant growth as variation in rainfall, especially for deep-rooted trees that can make use of the sunny dry season. The extent of *Acacia-Commiphora* dry bushland in Africa was found to relate to bimodal versus unimodal rainfall regimes, rather than annual isohyets (White 1983).

Relevant metrics for characterising the climate in which trees are known to occur, and can be expected to thrive elsewhere, were a major issue at the start of AF research (Huxley et al. 1983). There was reason to expect that beyond temperature and mean annual rainfall, other aspects played a role. Early observations of differences in tree distribution by isohyet on sandy and clay soils in Sudan (Jackson 1957; Harrison and Jackson 1958; van Noordwijk 1984) pointed to the importance of local water buffering rather than rainfall as a determinant of tree growth. Given the headquarter location of ICRAF in Kenya, the bimodal rainfall patterns around the equator demanded attention, as both the 'long' and 'short' rainy season were highly variable and, in some years, defying their names. For some trees, the relatively short dry period between these two rainy seasons does not lead to leaf senescence and a new leaf flush; on the other hand, others do respond. The way climates are perceived by trees and crops can thus differ (Huxley 1985b, 1999b). Whilst the location of the Machakos research station in Kenya (1° 14′ S, 37° 27′ E) in the bimodal rainfall zone was initially seen as an advantage (two and contrasting cropping seasons per year yielding interesting data; Huxley and Westley, 1989), the limited 'representativeness' of its climate for the tropics as a whole played a role in abandoning it in the 1990s. Beyond merely the presence/absence of tree species, a more detailed observation of tree phenology in response to seasonal and climatic variation was deemed to be important (Huxley et al. 1989).

3.2 Current state of the art

With the wealth of climate data now available and the 'Big Data' toolbox of analysis, the question of which climate variables have the most skill in accounting for tree distributional patterns can be tackled more directly. For example, Rana et al. (2018) developed MaxEnt models of recorded *Alnus* species distribution data in Nepal, using a subset of least correlated bioclimatic variables for current conditions (1950–2000), topographic variables and Land Use Land Cover (LULC) data. The major climatic factor that contributes to *Alnus nepalensis* distribution in Nepal appears to be precipitation during the warmest quarter of the year and precipitation during the driest quarter for *Alnus nitida*. Neither of these climatic variables has so far been captured in standard AF tree databases. Booth (2018) recently compared phenomenological (correlative) models with mechanistic (physiological) models and suggested that further progress is possible in bringing these strands of knowledge together.

The choice of climate data for determining site suitability for a wide range of tree species can now be left to a final analysis of multiple empirical pathways (Ranjitkar et al. 2016; Lu et al. 2017; Gaisberger et al. 2017; de Sousa et al. 2019). An 'ensemble habitat suitability' can be calculated as the weighted average of suitability estimates predicted by different algorithms (Kindt 2018). Analysis by Noulèkoun et al. (2018) suggested that the climate parameters for predicting tree growth in the year of establishment (longest dry spell in rainy season) differ from those for the subsequent growth of trees with established root systems (overall balance of potential evapotranspiration and rainfall). There is also literature describing the way tree distribution and dynamics respond to rainfall trends over periods of several years and the interactions of these with human activity (Maranz 2009; Mbow et al. 2015; Brandt et al 2016, 2017). Where large-scale tree mortality is noted, anthropogenic disturbances of the water balance and pest and disease outbreaks linked to reduced tree genetic diversity can be hard to distinguish from the effects of extreme events and climate change. Statistical downscaling of climate data to finer resolutions as in the WorldClim data that is widely used in species distribution modelling (http://www.worldclim.org/version1) is reliable for means, but has more uncertainty for the extremes, where the degree of spatial and temporal autocorrelation of events is uncertain.

The relationship between locally generated clouds and rainfall has received considerable attention, as evidence of 'terrestrial recycling' of rainfall, beyond ocean-derived precipitation. Early Global Circulation Models (GCMs) used elevation–temperature relations as they focussed on the global energy balance (modified by atmospheric greenhouse gas concentrations) as a driver of atmospheric pressure differentials and circulation, but ignored many other local features, including a two-way interaction between vegetation and rainfall. Even though the basic data that allow the analysis of terrestrial recycling have been around for nearly two decades (Bosilovich and Schubert 2002) coupled with compelling analysis by van der Ent et al. (2010) that drew attention to the strong geographic patterns in source and sink areas of terrestrial rainfall recycling, it has taken a long time for the upwind-downwind relationship in rainfall and land cover with high rates of evapotranspiration (wetlands, lakes, forests, irrigation schemes) to be noticed (Ellison et al. 2017, 2019; Wang-Erlandson et al. 2018). Important aspects of underlying mechanisms in rainfall triggering by atmospheric particles of biological origin (Morris et al. 2014; van Noordwijk et al. 2015a) and direct influence of forests on air circulation ('biotic pump' Sheil and Murdiyarso 2009) remain frontiers of this science

(Creed and van Noordwijk 2018). It appears that there is less geographic variation in the mean residence time of atmospheric moisture (around 8 days; van der Ent and Tuinenburg 2017) than in the windspeeds, and thus, the distances travelled before water vapour leads to rainfall (from around 200 km at windspeeds of 1 km/h to 2000 km at 10 km/h or more). Accounting for effects of cloud cover on radiation (Park et al. 2017) can help translate scenarios that differ in fire/haze production and/or forest-based cloud cover to local climate consequences.

4 Tree phenology response

4.1 Huxley's contributions

Trees are not a taxonomic entity and many plant families contain both trees and non-woody annuals, suggesting that 'woodiness' is an adaptive life-history trait with pros and cons. Huxley (1999a, b) explored the 'woodiness' question in detail. Perenniality postpones the risky phases of seedling establishment and allows plants to make use of 'windows of opportunity' for reproduction that open at long intervals. It also allows for the accumulation of growth resources and gains made in exploring aboveground and belowground space, with leaves and fine roots as ephemeral extensions of the woody architecture that persists. Cannell and Huxley (1969) analysed seasonal differences in the pattern of assimilate movement in branches of *Coffea arabica*, a study that informed later thinking about plant research and AF (Huxley 1983). The direct observational records of tree flowering, fruiting, leaf flush and leaf senescence in Huxley and van Eck (1974) remained an inspiration for the deeper analysis of tree phenology (Akunda and Huxley 1990), but the resources and patience needed to record the basic data have become hard to assemble.

4.2 Current state of the art

The search for genes that make a tree a tree (Groover 2005) has clarified that genes responsible for wood production are also present in plants that do not have the tree habit (Petit and Hampe 2006). Genes involved in the vascular cambium of woody plants are also expressed in the regulation of the shoot apical meristem of Arabidopsis (Groover 2005). This might explain why woodiness can (re)emerge so readily, as observed in many island radiations (for example Böhle et al. 1996).

Predicting changes in tree phenology in response to climate change remains a major challenge for most tree species (Schwartz 1999). There is still often no clarity on what exactly drives transitions between phenological stages. Even greater uncertainty surrounds the sensitivity of tree phenology to changes in these drivers. Reasonable descriptions of tree development during periods of active growth have been achieved with relatively simple thermal time models (Linkosalo et al. 2006), yet it is unclear to what extent such relationships will hold as the climate changes. Whilst this question could be resolved, to some extent, by multi-environment studies, such research is absent for most species (Schwartz 1999).

What remains even more in the dark, but is arguably more critical for adaptation planning, are the mechanisms behind the resumption of active tree growth after a period of inactivity (Campoy et al. 2011). Such phase transitions are observed for most species in locations with pronounced cold or dry seasons (Campoy et al. 2011), and they

often involve a dormant period during which trees drop all their leaves and suspend active growth. A difference in leaf phenology can impact water use efficiency, gaseous exchange, tree growth and productivity of accompanying crops (Muthuri et al. 2009). In exceptional cases, such phases can even occur during periods that feature climatically favourable conditions, as has been widely reported for *Faidherbia albida*, a species that thrives in semi-arid environments, even though it loses its leaves during the wet season (Roupsard et al. 1999, 2020). What drives such transitions is often unclear, with variation in photoperiod (Heide, 2008), temperature (Guo et al. 2015), water availability, and insolation (Borchert et al. 2015) reported as influential factors in various situations. The relative importance of all these factors is often ambiguous, and systematic experiments that could overcome this uncertainty are usually lacking. To some extent, and where sizeable datasets exist, statistical methods can elucidate some relationships (Luedeling and Gassner 2012; Ranjitkar et al. 2013), but such studies rarely generate the physiological insights that might allow reliable predictions under conditions that are different from those under which tree behaviour has been observed (Luedeling 2012).

Even for the winter dormancy period of deciduous trees in cold-winter climates, possibly the most extensively modelled phenological phenomenon, our quantitative understanding of the environmental cues and physiological processes involved is insufficient for reliable predictions of climate change impacts (Luedeling 2012). Whilst there is a general agreement on the importance of chilling and forcing temperatures, the role of other drivers, such as humidity, daylength and management, is still under debate (Schwartz 1999). Even though a few models have been developed for predicting dormancy release, the empirical basis of most of these models is slim, prediction successes have been modest, and model development has been stagnant for several decades (Luedeling 2012). Especially when it comes to the critical environmental signal of chill accumulation, existing models are unreliable when used along temperature gradients (Luedeling and Brown 2011; Luedeling et al. 2009), casting doubt on any phenology predictions for future climate scenarios.

What remains elusive in phenology research is a prediction framework that is based on a sound understanding of the physiological processes that underlie tree phenology. There is some hope, however, that such a framework will eventually become possible. For example, recent research has generated increasing clarity on dormancy-related processes, including the genetics of dormancy (Bielenberg et al. 2008), epigenetic regulation (Rios et al. 2014), the role of plant hormones (Liu and Sherif 2019) and oxidative stress (Beauvieux et al. 2018), regulation of intercellular communication (Rinne et al. 2018) and carbohydrate dynamics (Dietze et al. 2014). The current frontier in tree dormancy modelling — and in phenology modelling more generally — is the integration of the knowledge generated over the past few decades into a comprehensive process-based understanding of the drivers of tree phenology and the processes they trigger.

In AF research, a next step is that tree phenology matters for shade impacts on intercropped cereals, with late-flushing trees shading crops after their flowering stage, reducing yield but increasing protein content of the grain (Artru et al. 2017). In a study of phenology of a W. Amazon fruit-bearing shrub, *Eugenia stipitate*, flowering and fruit production was found to be influenced by the companion trees used in AF when tested in Costa Rica (van Kanten and Beer 2005), whilst the balance between vegetative growth and fruit production in other fruit-bearing shrubs was found to depend on AF context (Delgado et al. 2016). Phenotypic plasticity of roots in mixed tree species AF systems (Kumar and Jose 2018) can alter tree-soil-crop interactions.

5 Microclimate modification by trees relevant for crops and livestock

5.1 Huxley's contributions

Before joining ICRAF, Huxley became interested in 'systematic spacing designs' in intercropping research (Huxley and Maingu 1978). Spacing influences both aboveground and belowground distances between plants, and microclimate effects (shade, windspeed, humidity) on water demand for transpiration. It interacts with the volume of soil available per plant for buffering water supply to roots, and the degree of common access and thus competition. As a research approach, Huxley proposed both experiments with tree and crop densities as a primary variable, and direct observation of the microclimatic effects and belowground interactions (Huxley 1985a, b, c, 1987, 1996; Huxley and Mead 1988; Huxley et al. 1989, 1994). Microclimate effects also play a role in the incidence and management of pests and diseases in AF (Huxley and Greenland 1989). In the overview of a physiological approach to tree-crop interactions (Ong and Huxley 1996), the direct coupling of water and energy balances is discussed as the determinant of 'production possibility frontiers' in mixed tree-crop systems, with nutrient cycling and erosion control as manageable constraints.

5.2 Current state of the art

Microclimate research traditions provide important insights to local ways to deal with global climate change (Stigter 2007, 2016). Shading has been represented in increasingly refined 1D, 2D and 3D models of tree canopies (Quesada et al. 1989; Reid and Ferguson 1992; Charbonnier et al. 2013; Rosskopf et al. 2017). Simple models for light competition in discontinuous tree stands within AF shifted to a 2D representation of space (Talbot and Dupraz (2012). Canopy development was linked to the C (Nygren et al. 1996) and N balance (Nygren and Leblanc 2015), as in the shade and mulch model of alley-cropping systems (van Noordwijk 1996). More comprehensive process-level understanding of tree-soil-crop interactions, informed by various tree-crop interface experiments, has been captured in the 2D Water, Nutrient, Light Capture in Agroforestry Systems (WaNuLCAS) model (Van Noordwijk et al. 2011b), and used, for example, in a bioeconomic exploration of plant density and thinning scenarios for teak (*Tectona grandis*)–maize systems (Khasanah et al. 2015), water use in trees of different leafing phenological stages in semi-arid Kenya (Muthuri et al. 2004) and exploration of intercropping options for oil palm (Khasanah et al. 2020).

Similar ideas informed a more detailed 3-dimensional tree canopy–crop model (Dupraz et al. 2019) and efforts to make existing crop models responsive to the presence of trees (Luedeling et al. 2016; Smethurst et al. 2017; Burgess et al. 2019). Stand-level light interception models have been modified for horizontally and vertically heterogeneous canopies (Forrester 2014), and used to study latitudinal influence on the light availability for intercrops in an AF alley-cropping system (Dupraz et al. 2018). Detailed microclimatic effects of tree canopies were modelled by Vezy et al. (2018), building on earlier concepts (Wang and Jarvis 1990; Wang et al. 2006). Modelling short-wave radiation distribution in an AF system (Zhao et al. 2003), competition for water (Wanvestraut et al. 2004) and shading response (Zamora et al. 2009) has helped in understanding the cotton/pecan alley-cropping systems in the USA. Tree shelterbelt design and management requires predictive

understanding of wind flow patterns associated with shelterbelt structure, tree height and optical porosity (Zhou et al. 2005; Mize 2008).

Aboveground microclimate interacts with the soil water balance, with tree effects including hydraulic equilibration. Bayala et al. (2015) reviewed advances in knowledge of processes in soil–tree–crop interactions in parkland systems in the West African Sahel, focussing on coupled energy and water balance and two-way hydraulic redistribution (Bayala et al. 2008) as a mechanism by which moisture in deeper soil layers, accessed only by tree roots, becomes available to crop roots. The degree to which such processes contribute to the agronomically proven positive effects on millet and cowpea in *Ziziphus*-based cropping systems remains to be explored (Bado et al. 2020). Hydraulic equilibration in intercropping deeper and shallower rooted plants (Kizito et al. 2012; Izumi et al. 2018) has been portrayed as 'bio-irrigation' (Bogie et al. 2018). It depends, however, on conditions where deeper soil water reserves are replenished during episodes with temporary rainfall excess over evapotranspiration (van Noordwijk and Ong, 1999; van Noordwijk et al. 2014).

Panwar et al. (2020) investigated the diurnal response of surface and air temperatures to evaporative conditions for different vegetation types and found that surface temperature, in contrast to air temperature, reflected evaporative cooling in short-stature vegetation. In forests, however, aerodynamic conductance dominated over evaporative cooling, and surface temperature was not a good predictor of current evapotranspiration.

Shade trees in coffee and cocoa have been analysed for the disadvantages and desirable characteristics of a range of shade trees (Beer 1987; 1988; 1991), and translated to farmer-level management options (Beer et al. 1997). Specific AF practices that may improve agricultural performance responding to climate change include shade trees buffering rising temperatures to stabilise the yield of crops like coffee (Rahn et al. 2014, 2018), and increasing the yield of food staples through lowering daytime temperatures and reducing heat stress (Sida et al. 2018; Wangpakapattanawong et al. 2017). Agroecological research beyond AF has demonstrated the relevance of diversity, increasing the resilience of crops to climate-induced pest and disease pressures (Harrison et al. 2019) or increased soil carbon and mulch associated with increased water infiltration and holding capacity and reduced soil evaporation (Ilstedt et al. 2016; Bayala et al. 2019b), improving the resilience of crops to drought (Minasny and McBratney, 2018). A recent meta-analysis of studies carried out in sub-Saharan Africa showed that on average, AF systems in sub-Saharan Africa increase crop yield whilst maintaining delivery of regulating/maintenance ecosystem services (Kuyah et al 2019).

6 Belowground interactions

6.1 Huxley's contributions

Before joining ICRAF, Huxley had gained experience with direct observation (Huxley and Turk, 1975) and ^{32}P tracer studies of coffee (Huxley et al. 1974). He was keen to bring a 'whole-plant physiology' approach to the study of aboveground and belowground trees and the way woody architecture defines the bounds of opportunistic resource capture (Huxley 1994, 1999a). Root system research was constrained not only by the spatial variability of the soil as substrate and the adaptive responses of plant root systems to such heterogeneity but also by the challenges of graphical representation (Rao et al. 1993). Woody root architecture proved to be a direct basis not only for understanding belowground competition for

water resources (Ong and Huxley 1996) but also for clarifying complementarity, as water can flow in both directions: towards the shoot and from wetter to drier layers of soil.

6.2 Current state of the art

Bayala and Prieto (2019) reviewed water acquisition, sharing and redistribution by roots in AF systems. Van Noordwijk et al. (2015b) summarised the current understanding of the way woody root system architecture relates to tree physiology via adjustments in shoot/root ratio (van Noordwijk and de Willigen 1987) and local response to soil heterogeneity. Fractal branching rules apply for woody parts aboveground and belowground, but their parameters may be unrelated (Van Noordwijk and Mulia 2002). Aboveground allometry differs for solitary trees from those growing in closed stands, but tree shape plasticity is species-dependent (Harja et al. 2012). A recent fractal branching study on the shea tree (*Vitellaria paradoxa*) in Mali analysed differences in tree architecture between climate zones, with consequences for allometric relations (Sanogo et al. 2021). Mulia et al. (2010) reconciled a generic fractal branching pattern with such opportunistic response, operating at different time scales. Van Noordwijk et al. (1998) reviewed the understanding of plant roots in relation to global climate change, exploring the internal resource economy of maintaining fine-root biomass versus the carbon costs of new root expansion when favourable conditions for nutrient and water uptake return. Empirical research showed very different root system responses amongst tree species to soil drying and shoot pruning (Jones et al. 1998), incorporating the avoidance of hydraulic redistribution by cutting off the fine roots that might leak night-time water into zones that are not functional for the tree. There is little direct physiological evidence yet on how genotypic variation deals with such trade-offs. The few available estimates of fine-root turnover (van Noordwijk et al. 2004) match the theory so far, but progress in compiling relevant datasets has been slow. Kuyper et al. (2004) reviewed mycorrhiza management in AF, but there is still a need to clarify the role of common mycorrhizal networks in hydraulic redistribution mechanisms as an ecological mechanism to buffer against droughts and ensure productivity in regions with increasing variability in rainfall (Bayala and Prieto 2019).

Many tree-soil-crop interactions in AF have focused on N availability (Haggar and Beer 1993; Haggar et al. 1993; Rowe et al. 1998) and N retention (Harmand et al. 2007). Studies of nutrient cycling in traditional AF systems (Glover and Beer 1986; Kass and Somarriba 1999) and intensively managed AF systems of cacao and timber species (Imbach et al. 1989; Somarriba and Beer 2011; Somarriba et al. 2014) helped to understand generic patterns and their site-specific manifestation.

Recent advances and perspectives on belowground functioning of AF systems (Cardinael et al. 2020) include, beyond the water and nitrogen cycle, advances on functional trait classifications of roots (Isaac and Borden 2020; Borden et al. 2020) and an understanding of how competition with winter crops induces deeper rooting of walnut trees in a Mediterranean alley-cropping AF system (Cardinael et al. 2015a, b). Further progress on tree root system is in recognition of the soil binding and soil anchoring functions that together reduce landslide risks on sloping land, subject to high-intensity rainfall events (Hairiah et al. 2020a, b).

Spatial patterns of variability of fine roots in coffee AF (Mora and Beer 2013) and fine-root dynamics of coffee in association with two shade trees (van Kanten et al. 2005) have helped to better understand niche differentiation. Spatially explicit impacts on

distribution of soil organic carbon in alley cropping combine aboveground and belowground inputs (Cardinael et al. 2015a, b). Where earlier reviews of ecological processes in tropical and temperate AF systems paid equal attention to belowground and aboveground processes (Batish et al.2007), subsequent research emphasised the close linkage between these two categories in linking nutrient and carbon cycles (Payan-Zelaya et al. 2013; Udawatta et al. (2017).

Recent reviews established that AF boosts soil health in the humid and sub-humid tropics (Muchane et al. 2020) and that it influences soil fauna and their functions (Marsden et al. 2020). Beyond general conclusions on AF and ecosystem services (Jose 2009), greater mechanistic precision becomes feasible and can help in assessing risks and potential responses to global climate change. For example, increased rates of litter decomposition increase risks of bare soil conditions during part of the year. Yet, the effects of global warming on litter decay rates appear to be mixed as temperature effects interact with moisture and litter quality (Kumar 2008). Annual litterfall rates in plantations and AF systems (2–10 mg ha^{-1} y^{-1}) are 50–100% of peak foliar biomass (Kumar 2008), with woody fractions around 15% of the total.

Belowground interactions that affect C storage in soils have been a major research interest in the past decades. Contrary to expectations of proportionality of aboveground biomass and soil C storage, a recent meta-review found that experimental effects of elevated CO_2 concentrations on soil carbon storage are inversely proportional to their effects on aboveground biomass (Terrer et al. 2021). Positive effects on soil C were found in nutrient-limited situations with small aboveground biomass responses. Neutral (or even negative) soil C changes where aboveground biomass response was strong, as was common where trees were involved in the experiments. These findings are aligned with early predictions for elevated CO_2 effects from a 'functional equilibrium' perspective on the root:shoot relations in plants in nutrient-limited situations but not where water is limiting as increased CO_2 concentrations will modify the stomata level exchange between H_2O vapour loss and CO_2 uptake (van Noordwijk et al. 1998). In the relationship between modified root biomass and soil C storage, root (and mycorrhizal hyphae) turnover will increase soil C inputs. However, root-mediated mineralisation (for example by phosphatase release) may work in the opposite direction. Whilst most of the literature on AF and C sequestration stays at the level of tree planting (Kumar and Nair 2011; Anderson and Zerriffi 2012; Jose and Bardhan 2012; Chapman et al. 2020) or measured soil C stocks (Shi et al. 2018; Chatterjee et al. 2018; Corbeels et al. 2019), some studies have delved deeper into the processes of root-aggregate interactions (Albrecht and Kandji 2003) and simultaneous effects on soil macroporosity (bulk density) and C_{org} concentrations (Hairiah et al. 2020a, b; Saputra et al. 2020). Other studies have addressed the lack of visibility of trees in agricultural lands in current C accounting systems at the national scale (Rosenstock et al. 2019a, b, c), as precondition for economic incentives to reach the farmgate.

7 Agroforestry experiments: beyond observational studies

7.1 Huxley's contributions

Huxley has left an important legacy of research methods as well as results, through the methods he used, that he wrote about and that he encouraged others to develop and describe. His approach was one of balancing careful attention to theory whilst being

practical and opportunistic (Huxley 1985b). He emphasised the specific challenges of research in AF, saying '…we cannot simply borrow analogous examples of research methodology from agriculture or forestry as they stand in order to reach a solution, but there are specific reasons why we have to adapt, develop and improvise new modifications' (Huxley 1985c). Much of Huxley's own research was at the plant level, but he saw it embedded in a process of understanding farming systems and interacting with farmers. These elements were brought together in Huxley and Mead (1988) that proposed both the flexible approach to on-farm experimentation and observational studies based on the careful measurement around existing individual trees, both of which are now widely used. He was intrigued by novel experimental layouts (Huxley et al 1994; Huxley 1985a). This included promoting the use of systematic designs in AF research and agronomy, a trend that has not continued in AF as results often proved inconclusive. His work with Roger Mead led to the development of an entirely novel class of experimental design they labelled HAHA (hedge alley hedge alley) that turned out to be interesting for design theory, but again maybe not useful given the way AF research developed (ICRAF 1988, Nester 1994). Huxley was ahead of his time in recognising the need for careful data management of highly structured datasets and supported the development of early software tools for doing that (Roger and Muraya 1991). Likewise, he was ahead of trends in using visual methods to detect and display patterns in data when these had to be drawn by hand (Huxley 1965; Huxley and Van Eck 1974; Huxley et al 1994).

7.2 Current state of the art

Many case studies provide evidence (type I in Table 1) on the relevance of AF for climate change–resilient agriculture (Nguyen et al. 2013; Coulibaly et al. 2014; Simelton et al. 2015; Gram et al. 2018; Castro et al. 2018; Quandt et al. 2019). Progress on types II and III evidence described in Table 1 is patchier yet. The systematic designs promoted by Huxley are only rarely used, as the interpretation of results is not straightforward, given confounding effects aboveground and belowground. Another layer of complexity is the landscape scale both for the observational and systematic designs that will require a combination of field-level yield mapping, remote sensing and modelling for long-term data collection/assessment to investigate how resilient to climate change AF systems are and to what extent they mitigate it (Bayala et al. 2015).

With the increased interest in temperate-zone AF, farm economic considerations are as important as biophysical ones (Wojtkowski 1998; Jose and Gordon 2007; Jose et al. 2012; Pantera et al. 2018), but there is also interest in the ways trees can help return some of the functionality lost when agricultural mechanisation and intensification homogenised the landscape (Mosquera-Losada et al. 2012; Den Herder 2017; Kay et al. 2019). Design of long-term AF field trials (Lovell et al. 2018) will often have to shy away from fully factorial designs feasible in crop monocultures and follow a farming system approach, in which a few differently managed systems are compared to controls. Instead of standard statistical approaches, biophysical modelling is used to test the fit of predicted versus measured outputs of the systems to analyse the functioning of the mixtures. Parameter-sparse AF models (Keesman et al. 2011) can zoom in on farm management decisions but will not allow exploration of conditions beyond the conditions for which models were parameterized.

On the other end of the research spectrum, the ecological toolbox of analysing diverse and spatially complex systems (Somarriba et al. 2001; De Souza et al. 2012; Deheuvels

et al. 2012; Cassano et al. 2014) needs to be coupled to the social methods to appreciate diversity in expectations, goals and management practices (Jerneck and Olsson, 2013, Jerneck and Olsson 2014; Sari et al. 2020; Mulyoutami et al. 2020).

Whilst in principle, trade-offs between crop intensification and ecosystem services exist in most forms of AF (Vaast et al. 2005; DeClerk et al. 2012; Vaast and Somarriba 2014), many systems operate so far below yield potential that considerable win–win opportunities exist, reducing risks whilst increasing performance under normal circumstances (De Beenhouwer et al. 2013; Schroth et al. 2016; Gomes et al. 2020).

8 Discussion

In the line of Huxley, research combining the best of process-level understanding with AF designs with a proven track record (Ong et al. 2015) may have been the most successful yet in the dry tropics (Bayala et al. 2015). Combining direct canopy interception and transpiration data of trees with effects on water infiltration, influenced by trees, Ilstedt et al. (2016) derived an estimate of an optimal intermediate tree density for such parklands, from a perspective of groundwater recharge. Further analysis of how such optimum depends on climate variability and climate change is in progress.

Much of the analysis of AF systems responding to climate change has been on the level of 'dealing with the consequences' of ongoing climate change and contributing to mitigation at the greenhouse gas emission driver level (Syampungani et al. 2010; Duguma et al. 2014; Mbow et al. 2014a). In terms of the AF research lines and the actionable consequences at the farm level (Table 1), progress is largely confined to line I, especially category IA. Publications from all tropical continents report farmers knowledge on the relevance of tree cover for climate buffering and preferences for specific trees in the local context (Nyong et al. 2007, Chaudhury et al. 2011; Pramova et al. 2012; Thorlakson and Neufeldt 2012; Charles et al. 2013; de Zoysa and Inoue 2014; Lasco et al. 2014a, 2014b, Pandey et al. 2015; Lasco et al. 2016; Newaj et al. 2016). This matches the recorded global increase in tree cover on farmed lands, but with regional differences (Zomer et al. 2016; van Noordwijk et al. 2019b). Explicit attention to tree diversity management on a farm (line IB) in this context is scarce yet (van Noordwijk et al. 2019b; Rosenstock et al. 2019a). Explicit adjustment of species choice to expected climate (Line IC) was discussed, for example, in Luedeling et al. (2014), Booth (2018) and de Sousa et al. (2019). Studies of tree-level response to long-term interannual climate variability are scarce yet (Mokria et al. 2017). There still also is a challenge of novel future climatic conditions without present-day climate analogue (Luedeling et al. 2014), whilst increased atmospheric CO_2 concentrations change the stomatal water use efficiency and can change the hydroclimatic requirements for tree growth.

Research line II, explicit adjustment of quantity and quality of tree cover to match expected and ongoing climate change, is still relatively scarce. The most discussed is the adjustment of shade levels in tree crops such as coffee and cocoa (Tscharntke et al. 2011). Trees are commonly selected to survive in and reduce urban heat islands (Lanza and Stone 2016; Pretzsch et al. 2017), but not yet explicitly to serve as air coolers in cropped fields that otherwise may be too hot (Ellison et al. 2017). Attention to such applications is, however, emerging (Roy et al. 2011; Tewari et al. 2014). Most of the examples in this category deal with the interface of energy and water balance. Specific attention to the relatively high

intensity of land-use change in 'water towers' is needed (Dewi et al. 2017). The trade-offs between downstream and downwind water availability depend on coherent metrics, as discussed by van Noordwijk et al. (2016, 2019c).

We are not aware yet of applications in research line III, partly as season-level weather forecasts are not yet reliable. A recent finding that may make El Niño events predictable a year in advance (Meng et al. 2020) may open new avenues for such applications. At scales above the farm level, however, there are impacts on cloud cover, biological rainfall generation (BRG, as the counterpart of biological nitrogen fixation (BNF), van Noordwijk et al. 2015a), and meso-climate/microclimate that can be influenced by land cover, and thus potentially be managed. Ambitious, quantitative schemes that relate farmer-level choice and options to interventions at landscape and regional scale that may influence rainfall patterns and interact with global circulation models include many relations that deserve further analysis and targeted data collection.

Such analysis may show that the policy agenda for climate change resilience can be more encompassing than is currently realised. At the start of an explicit interest in sustainability research 30 years ago, Huxley (1989, 1995) contributed ideas that seek system-level relevance for mechanisms and relations understood at the component level. Such an approach, as challenging as it is, can still help in fully accounting for the various ways in which tree cover at regional and landscapescales can modify the climate, interacting with global circulation and greenhouse gas effects. Ultimately, policy interest is not in achieving climate change adaptation as such (with or without the use of AF), but in progress across the totality of the Sustainable Development Goals of Agenda 2030. Prospects for growing recognition of a rural development pathway that takes agroecology and AF seriously are increasing (Mbow et al. 2014b; van Noordwijk et al. 2018, 2019d), with special attention to areas of high vulnerability such as small islands (van Noordwijk 2019c). To contribute to such progress, however, AF research methods will have to keep evolving, building on 40 years of progress (van Noordwijk and Coe 2019).

9 Conclusions

1. Agroforestry can contribute to climate change adaptation in four ways: (1) Reversal of negative trends in diverse tree cover as generic portfolio risk management strategy; (2) targeted, strategic, shift in resource capture (e.g. light, water) to adjust to changing conditions (e.g. lower or more variable rainfall, higher temperatures); (3) vegetation-based influences on rainfall patterns; and/or (4) adaptive, tactical, management of tree-crop interactions based on weather forecasts for the (next) growing season. Evidence for the generic risk reduction by increase of buffer functions and diversity is strong; examples of specific adaptations to confirmed trends in local climate are still sparse, but start to emerge, especially with respect to hydroclimatic change.
2. Quantification of microclimate within and around tree canopies showed a gap between standard climate station data (designed to avoid tree influences) and the actual climate in which crop and tree meristems or livestock operate in real-world AF. Where global scenario modelling of 'macroclimate' change in mean annual rainfall and temperature extrapolates from climate station conditions in past decades, it ignores microclimate effects of trees.

3. There still is a shortage of long-term phenology records to analyse tree biological responses across a wide range of species to climate variability, especially where flowering and pollination matter, linked to the way the plant perceives temperature and drought signals, and impacts on pollinator presence at the required time and place.
4. Physiological understanding of aboveground and belowground resource capture can complement farmer knowledge and help guide policy decisions that allow AF solutions to emerge and the choice of tree germplasm to be adjusted for the growing conditions expected over the lifetime of a tree.
5. The emerging recognition for agroforestry as part of national climate change adaptation strategies is encouraging but requires backup by quantitative risk analyses.

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