Dissertation prospectus:

Can agroforestry increase reliability of subsistence agriculture under future climate in southern Africa?

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Abstract

Agroforestry – the integration of trees into farm landscapes – has been promoted throughout the developing world as a solution to many environmental and socioeconomic challenges. Now, with the advent of global climate change, agroforestry is being proposed as a carbon sink for climate mitigation. But it is still unclear how climate change might alter the effectiveness of agroforestry systems from a farmer's perspective. Some agroforestry practices may help farmers adapt to a warmer, drier, increasingly variable climate. Other agroforestry practices may become a liability, as trees compete with crops for limited water.

For my dissertation, I will perform field experiments in Zambia and Malawi to determine how the yield of three different agroforestry system designs – improved fallows, relay intercropping, and hedgerow intercropping – is likely to change under future climate. My primary approach will be direct manipulation of ambient rainfall (via rainout shelters) to simulate the drier conditions expected in coming decades. In addition to measuring grain and biomass yield, I will measure the physiological parameters of the plant/soil system in order to clarify mechanisms of competition or facilitation. As a complement to this manipulation experiment, I will examine data sets from previous and ongoing agroforestry experiments in the region, and compare yield and water-use efficiency during dry and wet years.

As a distinct but interdependent part of my dissertation, I will use these data to improve the ability of WaNuLCAS, an agroforestry simulation model, to predict the behavior of these agroforestry systems under future climates. My overall goal is to provide information that will be useful to smallholders, land-use planners, and policymakers in southern Africa and throughout agricultural regions in the tropics.

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1. Introduction: the southern African context

"If we need any more proof that life is unfair, it is that subsistence villagers here in Africa will pay with their lives for our refusal to curb greenhouse gas emissions."

~ *Nicholas Kristof in The New York Times, June 28, 2007*

Global climate change poses a threat to agricultural production in many world regions, most particularly developing countries in the tropics (Lal et al. 2005; Cline 2007; Easterling et al. 2007). Despite uncertainties in the extent and timing of future climate change, it is clear that significant changes will continue well into the 21st century, regardless of mitigation efforts. Thus, the need for climate change adaptation is now unavoidable (IPCC 2007).

The problems of climate change adaptation are not only ecological and economic, but also moral (as reviewed by Paavola and Adger 2006). To date, developing countries have made only a minor contribution to the increase in radiative forcing; however, they will bear a disproportionate share of the impacts and the adaptation costs (Mendelsohn et al. 2006). In the agricultural sector – which is particularly vulnerable to climate change – research on adaptation is urgently needed, and the scope of the challenge demands international action (World Bank 2007).

As a small contribution to this immense task, I have chosen to focus my dissertation research on one particular question about agricultural adaptation to climate change:

> **How and why will climate change affect the performance of agroforestry systems in southern Africa?**

In the pages that follow I will outline the motivation for my research, the relevant theory, my questions and methods, and the outcomes that I hope to achieve.

1.1. Existing challenges to food security in southern Africa

Southern Africa[1] is endowed with abundant natural resources, biodiversity, and cultural diversity. Many parts of the region are also beset by chronic poverty and food insecurity. The causes of this paradox are too complex for a full discussion here, but I will briefly outline some of the key factors.

1.1.1. Technical and biophysical

Despite dramatic increases on other continents, per capita agricultural production has declined throughout sub-Saharan Africa since 1970, not only due to population growth

[1] Here defined as the Southern African Development Community: Angola, Botswana, Lesotho, Malawi, Mozambique, South Africa, Swaziland, Tanzania, Zambia, and Zimbabwe.

but due to a lack of agronomic technology (DeRose et al. 1998; World Bank 2007). Africa saw almost no benefit from the Green Revolution, partly because crop varieties were not developed for African conditions, and partly because some of its staple crops (such as cassava) were neglected altogether (Ascher and Healy 1990).

Maize is the staple crop in most of arable southern Africa, providing two-thirds of calories consumed in Zambia and Malawi (Byerlee and Heisey 1997). High-yielding maize varieties have been developed for the region, but many farmers do not use them (Byerlee and Jewell 1997), and most farmers cannot afford external inputs such as fertilizer, pesticide, or irrigation. Although much of the region is climatically suitable for maize, the crop's high nutrient demands have gradually degraded soil fertility in areas where neither fertilizer nor fallow are viable options (Young 2005). Thus, for many smallholders, meeting subsistence food requirements is a challenge at the best of times.

These challenges are exacerbated by a highly variable climate. Rainfall in southern Africa is erratic, in part due to the pronounced drying effect of El Niño (Cane et al. 1994; Hachigonta and Reason 2006). For example, the entire region suffered from severe droughts in 1991/1992, affecting over 100 million people and necessitating large amounts of food aid. Conversely, much of Mozambique experienced devastating floods in 2000, and Malawi was hit by flooding in the following year (Devereux 2002), resulting in several-fold reductions in maize yield.

1.1.2. Political and socioeconomic

It is now widely accepted that biophysical conditions alone are not the sole, or even usually the most important, causes of food insecurity (DeRose et al. 1998; Sen 1999). Poverty undermines the power to purchase food and the inputs needed to produce it. In rural sub-Saharan Africa, poverty is perpetuated by lack of access to markets, lack of available credit, inadequate and deteriorating infrastructure, poor quality of services such as education and health care, and unfavorable global market conditions (Jayne et al. 2006). Adding to these challenges are diminishing farm sizes and unequal land distribution (Smale and Heisey 1997).

In southern Africa, HIV/AIDS requires special mention. Infection rates in Botswana and Swaziland are approaching 40%, the highest in the world; for most other countries in the region the rate is 10-25% and increasing. de Waal and Whiteside (2003) suggest that this epidemic is leading to the emergence of "new variant famine," in which communities are more easily impacted by, and less able to recover from, biophysical or economic setbacks to food production. Many argue that, due to its heavy toll on the working-age population, AIDS increases the dependency ratio and reduces available labor; others (Jayne et al. 2006) dispute this. No one disputes, however, the social, cultural, and economic disruption caused by the epidemic.

In short, southern Africa is already faced with a multitude of challenges. Even in the absence of other stressors, the challenges to sustainable development are considerable.

Unfortunately, the region is expected to be severely negatively impacted by global climate change, and has few resources to spare for adaptation (Boko et al. 2007). Accurately anticipating the effects of climate change is, therefore, of utmost importance.

1.2. Future climate in southern Africa

Climate change will not manifest uniformly across the African continent. East Africa, for example, is likely to enjoy more rainfall, and predictions for the Sahel are still quite uncertain (Hoerling et al. 2006; Christensen et al. 2007). However, there is strong agreement among global climate models that most parts of southern Africa will experienced decreased precipitation (in some regions up to 40%) and will undergo a temperature increase that exceeds the continental average.

Christensen et al. (2007) summarize the consensus of current GCMs as follows:

- Most of the drying over southern Africa will take place in the austral winter and spring (May-October).
- For most of the region, this is the end of the dry season and the start of the rainy season, and can be thought of as a delay in the beginning of the rains. (However, for southwestern South Africa, this encompasses the major rainy season.)
- Temperature increase will be most dramatic in the spring as a result of decreased evapotranspiration.
- Individual rainfall events will probably become heavier and less frequent, especially in years with late-onset rains.
- The frequency of very dry winters and springs will increase to about 20%, and the frequency of very wet summers will double. (The net effect, though, is still a decrease in precipitation.)

Rainfall patterns in southern Africa are coupled to the ENSO phase in the Pacific (Cane et al. 1994; Hachigonta and Reason 2006); historically, droughts in southern Africa have been associated with El Niño conditions. The changes described above are largely due to a predicted increase in the frequency of El Niño events. There is some evidence (Tadross et al. 2005) that the onset of rains in southern Africa has already gotten later, i.e. that the expected pattern is already appearing.

1.3. Agricultural forecasts

Predictions of climate change impacts on the agricultural sector in southern Africa are, without exception, pessimistic. Cline (2007) predicts[2] that by 2100 agricultural productivity will decrease by more than 25% in South Africa, Zimbabwe, Botswana,

[2] Cline used a Ricardian model (which allows for some adaptation), and assumed IPCC's A2 scenario and no CO_2 fertilization effect.

Namibia, Angola, Zambia, and Malawi. Although some of these impacts could in theory be avoided by irrigation (Kurukulasuriya et al. 2006), widespread irrigation in sub-Saharan Africa is neither technically nor economically feasible for the foreseeable future.

Maize in southern Africa is likely to be the hardest hit of any crop and region (Stige et al. 2006); the accentuated El Niño conditions may, in bad years, lead to a 20-50% decrease in production, though with considerable spatial heterogeneity (Jones and Thornton 2003). Semi-arid regions that are already marginal for maize production will be worst off; for example, Chipanshi et al. (2003) predict an average 36% decline in maize yield in central and western Botswana under $2 \times CO_2$.

These grim outcomes, of course, are not inevitable; adaptation is both possible and necessary. By "adaptation" I do not mean only technological interventions; they are part of a broader palette of climate adaptation strategies, which I will outline below.

1.4. Managing climate variability and change

Farmers and pastoralists throughout the world have millennia of experience dealing with climate variability. These reservoirs of local knowledge are of immeasurable value in adapting to climate change. However, changes in social and economic conditions, and the unprecedented nature of current perturbations to the climate system, necessitate new approaches as well.

1.4.1. Definitions of key terms

In discussing social responses to climate change, one immediately encounters the problem of vague and overlapping terms. Here I will try to clarify several, with the caveat that these definitions are by no means used consistently in the literature!

- *Coping*: Short-term activities, carried out within existing structures, to compensate for a climatic disturbance (Eriksen et al. 2005).
- *Adaptation*: Long-term structural changes to improve a system's suitability for a different climate (Eriksen et al. 2005).
- *Stability*: ability of a system to return to equilibrium after a temporary disturbance (Holling 1973, in Mortimore 1989). Also called *resistance*.
- *Resilience*: capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain similar functions (Walker et al. 2004).
- *Adaptability*: capacity of actors in a system to affect resilience (Walker et al. 2004).
- *Transformability*: capacity to create a new system when ecological, economic, or social conditions make the existing system untenable (Walker et al. 2004).
- *Vulnerability*: potential to be adversely affected by an event or change (Eriksen et al. 2005); can be divided into exposure, sensitivity, and adaptive capacity.

- *Risk*: magnitude of a hazard × probability of its occurrence (Rochlin 1993, in Roe et al. 1998); not synonymous with uncertainty.

Some insights that arise here are: (1) *coping* strategies can inform, but are not synonymous with, *adaptation* strategies; (2) *stability* of a system is distinct from *resilience* in that the latter implies variability and change, and seeking stability in systems that are inherently variable can be not only futile but counterproductive; and (3) when a system's resilience is insufficient, the system may need to be *transformed* altogether.

1.4.2. Indigenous coping strategies

There exists a rich literature on indigenous practices for coping with climatic disturbances. Within these diverse practices, several consistent themes emerge.

First of all, subsistence producers seek to create systems that can survive climatic disturbance. A comparison of villages in Sweden and Tanzania (Tengö and Belfrage 2004) revealed several universal strategies: *diversification* of agroecosystems both in space and in time; *protection* of natural ecosystems and wild species; use of natural *indicators* to predict climate variability; and careful *maintenance* of key ecosystem services such as nutrient cycling and pest control. In an unpredictable climate, risk cannot be avoided, but can be effectively managed by keen attention to the environment (Roe et al. 1998).

If the subsistence system itself fails, community members must fall back upon other options. A common response to drought-induced food shortage is the use of wild foods: in Sierra Leone, bush yams and palm hearts (Leach 1994); in Malawi, mushrooms (Devereux 2002); in Kenya, native fruit (Eriksen 2005); in Botswana, bushmeat and mopane caterpillars (Dube and Sekhwela 2007). Natural ecosystems are often less vulnerable than agroecosystems to climate variability (a point to be revisited later).

Pursuing income-generating opportunities is also a common response to the failure of subsistence food production. These could include casual labor, brick-making, charcoal burning, handicrafts (Eriksen et al. 2005), semi-permanent migration and sending of remittances (Ziervogel et al. 2006); and, under more dire circumstances, prostitution (Devereux 2002) and sale of assets such as livestock and land (Mortimore 1989).

Finally, social networks play an important role: food-scarce households may solicit aid from relatives, or seek credit from local businesses (Eriksen et al. 2005); they may be assisted by village-level "social security." Several authors (Mortimore 1989; Dube and Sekhwela 2007) argue that disintegration of traditional social networks – due to cultural, economic, or population pressures – has undermined the capacity of communities to respond to climate stress. Other authors (e.g. Fairhead and Leach 1995) caution that the view of "traditional" societies as more socially coherent and more adept at managing their resources is not always accurate.

1.4.3. New frameworks for natural resource management

In an effort to combine the best of traditional and modern approaches, natural resource managers have increasingly sought out *community-based* (democratic) and *adaptive* (experimental) approaches. These approaches are not applicable to all systems, but they may be especially well-suited to enable communities to deal with climate change (Tompkins and Adger 2004) by building local institutions and bolstering social networks.

However, Fortmann et al. (2001) discuss the need to use a continuum of different management approaches depending on the intensity of use of the ecosystem. The trial-and-error component of adaptive management, they argue, makes it unsuitable for the highest intensity of ecosystem use, in which a serious error can result in loss of livelihoods. Negotiating these tradeoffs between local involvement and central oversight, and between relaxed versus precise control, is a difficult task that becomes even more difficult with climate change as a complicating factor.

1.4.4. Models and forecasts

The effectiveness of any management practice or coping strategy can be enhanced by more accurate information about the disturbance to which it must respond. Seasonal climate forecasts, though they have yet to realize their full value, are already a useful tool for farmers and land managers (Vogel and O'Brien 2006). Should a production failure or other threat to food security arise, famine early warning systems can provide weeks or months of advance notice, giving governments and NGOs time to react.

Integrated Assessment Models (IAMs) go beyond these more straightforward models in an attempt to formalize relationships between climate, natural resources, and economic and social factors. Their complexity is both their greatest benefit and their greatest drawback: they integrate many relevant (and fundamentally inseparable) factors, but as a result become less transparent and more subjective (Desanker et al. 2005). They are not yet a substitute for biophysical models, but are a useful complement.

1.4.5. The role of technical interventions

In light of all the approaches to climate change adaptation described above – indigenous knowledge, new management frameworks, integrated assessments – it may seem relatively unimportant, even counter-productive, to study the performance of a particular agricultural technology in isolation from its context. Certainly, humankind has not always been well-served in the past by a focus on optimizing agricultural production without consideration of its broader effects (Giampetro 2004).

Nevertheless, a successful agricultural system cannot exist without successful technologies. As Sayer and Campbell (2004, p. 57) write, "High-technology research on the components of agricultural systems is still vital, but it has to be constantly reviewed to ensure that it is correctly placed in the context of changing local biophysical and socio-economic conditions."

This is the philosophy that will guide my dissertation work. My technology of interest, agroforestry, is not a solution to climate change adaptation in itself. I wish to study the conditions under which agroforestry can ameliorate the biophysical disturbances of climate change, in order to provide land managers with one more tool to use.

2. Agroforestry and climate adaptation

Agroforestry, put simply, is the integration of trees into farm landscapes. It can take a variety of forms and resists strict definition (Wojtkowski 1998). Agroforestry has existed as long as agriculture itself; farmers have always valued trees for their multiple uses. It has only been a topic of academic interest, however, since the 1970s (Huxley 1999), and many biological and socioeconomic questions remain to be answered (Sanchez 1995).

2.1. The scope of agroforestry

There are many ways in which the components of an agroforestry system can be integrated in space and time. In some systems, trees are grown in perpetual association with crops: for example, trees as windbreaks, isolated trees in fields, or trees providing cover for a shade-loving crop (such as coffee or cocoa). In other systems, the spatial arrangement changes over time: for example, in the *taungya* systems of southeast Asia, high-value timber trees are planted amongst annual crops and are permitted to eventually overshadow the crop. And in other systems, such as improved fallows, the trees and the annual crop are never physically adjacent.

The central biophysical hypothesis of agroforestry (Cannell et al. 1996) is that, in order for the system to outperform a monoculture, the *trees must acquire nutrients, water, or sunlight that would have been wasted by the crop*. However, even when this is not the case, agroforestry trees can benefit the crop indirectly via effects on microclimate, pest control, and soil and water conservation. They can also provide the farmer with timber, fuelwood, fodder, fruit, nuts, honey, and medicine (all of which can generate income).

Agroforestry is practiced in both tropical and temperate climates. In temperate climates, especially in developed countries, the emphasis is usually on large-scale static systems (such as riparian buffers) to confer environmental benefits. By contrast, in tropical developing countries, agroforestry systems are usually more complex in space and time (e.g. Kumar and Nair 2004), and practiced on a smaller scale, with emphasis on food production and income generation.

With such a diversity of systems and locations, is it possible to make any generalizations about agroforestry? There are some elements that are common to nearly all agroforestry systems as compared to crop monocultures:

- greater *diversity* of species and growth forms;

- *perennial* species as a central component;
- greater potential for *competition* and *complementarity*;
- greater *complexity* in use and management.

With these commonalities in mind, let us now examine how global climate change might affect the performance of agroforestry systems. Will agroforestry still benefit farmers? Might it be a useful tool for adaptation to climate change? Or will it become an increasingly unwise investment from the farmer's point of view?

2.2. Climate mitigation versus adaptation

Much attention has been devoted to agroforestry for climate change *mitigation*, that is, carbon sequestration. However, no one has yet systematically investigated agroforestry as a means of climate change *adaptation* (Verchot et al. 2007). Adaptation and mitigation are not necessarily mutually exclusive; in fact, for agroforestry they may be synergistic. However, I am concerned that this assumption is often made without critical evaluation.

Studies on the carbon sequestration potential of agroforestry (e.g. Makundi and Sathaye 2004) usually do ask whether farmers would benefit in a general sense. Sanchez (2005) estimates that tropical agroforestry could sequester 390 Mt C per year, and suggests that the resulting carbon payments could help alleviate poverty. Sampson and Scholes (2000) give a similar estimate of 315 Mt C per year, noting that in the absence of carbon payments, carbon-maximizing agroforestry practices do not maximize farmer income. According to Wise and Cacho (2005), this is not necessarily a problem: "a less intensive, more sustainable approach to farming can be encouraged by carbon payments."

None of these authors, however, address what seems to me a crucial question: will agroforestry practices actually help their users adapt to climate change? It would be both ironic and unfair if, in the process of sequestering carbon emitted by first-world citizens, smallholders were to compromise their own adaptive capacity.

2.3. How agroforestry might facilitate climate change adaptation

Fortunately, there are many reasons to expect that agroforestry could help farmers maintain the productivity of their land under warmer, drier, more variable climates. In the most general sense, agroforestry may buffer against adverse climate conditions by:

- physically protecting crops (e.g. from heat, flooding, soil erosion)
- accessing different resources when resources become scarce
- diversifying sources of food and income generation
- increasing overall agricultural productivity (and/or income)

These effects have already been well described in the literature, though not specifically in the context of climate change adaptation. I will review them below, before addressing potential drawbacks.

2.3.1. *Moderation of microclimate*

Shade from mature trees reduces air and soil temperature (and, as a result, can increase soil moisture). If these benefits outweigh competition for light and water, crop productivity may be enhanced. This could be especially important where temperatures begin to exceed the maximum physiological tolerance for a staple crop, as is expected to happen in many locations throughout the tropics (Sanchez 2005).

An example of this effect is the agroforestry "parklands" in the Sahel (reviewed by Sanchez 1995), in which mature *Acacia albida* trees are interspersed throughout millet and sorghum fields, approximately doubling the yield of the crop in their vicinity. *Acacia albida* is an ideal agroforestry species because of its "reverse phenology": it sheds its leaves during the growing season, when the crop's light and water demands are highest.

Other microclimatic benefits have been demonstrated: for example, shade trees on coffee farms not only help to moderate temperature (Lin 2007) but also increase infiltration (Lin and Richards 2007) due to changes in soil microtopography.

2.3.2. *Soil and water conservation*

Agroforestry practices such as hillside terraces and riparian buffers can be highly effective in preventing erosion and protecting water quality (Rocheleau et al. 1988). If precipitation events increase in intensity, erosion control will become even more important – especially since in many countries, lack of available land has forced farmers to cultivate steep hillsides that are vulnerable to erosion.

2.3.3. *Increased soil organic matter*

Several different types of agroforestry systems have been shown to substantially increase soil organic matter after only a few years (Albrecht et al. 2004). This is more obviously a mitigation benefit than an adaptation mechanism. However, soil carbon (and improved soil structure) can increase soil water-holding capacity, thus enabling the soil to retain moisture for longer after a precipitation event. Phiri et al. (2003) directly demonstrated this benefit in *Sesbania* improved fallows in Zambia. Soil water-holding capacity could become especially important if precipitation tends to fall in fewer, larger events, regardless of changes in total precipitation.

2.3.4. *Augmentation of soil nutrients*

Soil nutrient replenishment, although potentially one of the most attractive aspects of agroforestry systems (Mafongoya 2006), is not obviously an adaptation to climate change. However, it could be important for two reasons: first, nutrient availability to plants is in part determined by soil moisture, so an increase in soil nutrients may partly compensate for a decrease in soil moisture. Second, enhanced soil fertility allows a farmer to produce more during good years, potentially providing her with savings to fall back upon in years when unfavorable temperature or precipitation result in poor yields.

2.3.5. *Access to alternate water sources*

If trees are able to access a deeper layer of the soil water profile than crops, they may be able to consistently produce useful biomass – even in drought conditions – while not interfering with crop growth. Even if they do not increase crop yields, they may provide the farmer with an auxiliary food or income source. However, it can be difficult to design agroforestry systems with this degree of complementarity in water use (Ong et al. 2002). Unless the trees have access to groundwater, direct competition is likely.

In some cases, trees can bring water up from depth and release it into the surface layers of the soil in a process called hydraulic lift (Caldwell et al. 1998). This effect has been demonstrated in the agroforestry species *Cajanus cajan*, though no such effect could be found for *Sesbania sesban* (Sekiya and Yano 2004). Under dry conditions, a tree is unlikely to release water into surface soils, thus its net effect on nearby shallow-rooted species will likely still be negative (Ludwig et al. 2004). Hydraulic lift may in some cases facilitate crop growth, but to my knowledge this has not been demonstrated in the field.

2.3.6. *Biodiversity conservation*

It has been suggested (Hannah 2004) that agroforestry can play an important role in ecosystem adaptation to climate change by creating habitat corridors through which species can migrate. This can be the case even when trees are sparse or isolated (Harvey et al. 2004). Although this does not benefit farmers directly, it could serve as justification for ecosystem service payment schemes. It is also possible that increased biodiversity in agroforestry systems could help to reduce climate-related pest outbreaks, though this has not been demonstrated so far.

2.3.7. *Diversification of income sources*

This may be the most important of all the potential adaptation functions of agroforestry, but it is also the least straightforward. In general, a diverse agroecosystem can buffer against risk if its constituent species respond differently to disturbances (van Noordwijk and Ong 1999). In the case of agroforestry, the perennial species is indeed likely to have a different response function; however, it usually does *not* produce a staple food, so for food security to be enhanced by this diversity effect alone, the farm must be embedded within a functioning market system. Fortunately, that is usually the case, and, as mentioned above, sale of tree products has long been an important coping strategy in cases of crop failure (Eriksen et al. 2005; Dube and Sekhwela 2007).

2.4. How agroforestry might hinder climate change adaptation

2.4.1. *Tree-crop water competition*

If trees and crops directly compete for water (the reverse of Section 2.3.5), productivity of one or both will be diminished, depending on which is a more effective competitor. Output of a staple food is often the least substitutable component of any system, and trees often win the competition for water. Therefore, where trees and crops use overlapping water supplies, and water is potentially a limiting resource, the agroforestry system may become increasingly unsuitable as climate change reduces water availability. Ong and Leakey (1999) argue that many agroforestry species used in semi-arid Africa are not physiologically suited for the climate and are likely to provoke water competition.

2.4.2. *Reduced success of tree germination and establishment*

Tree seedlings, during their germination and establishment phases, can be very sensitive to environmental extremes. In any agroforestry system, but especially those that require frequent establishment of seedlings, high temperatures and/or water stress due to climate change may kill enough young trees to render the system worthless. Farmers may lack the time and resources to water the tree seedlings by hand.

There are many cases of current climate variability causing establishment failures. For example, Kwesiga et al. (1999) describe a trial of *Sesbania sesban* fallows in eastern Zambia: "Rainfall was low and sporadic during the 1994/95 season. Trees in two-thirds of the trials had to be re-seeded or gapped, one to two times. We estimate that 60% survival of the fallow species in the first three months is required for satisfactory biomass production at the end of two years. In 1994/95, [only] 48% [of farmers] for sesbania achieved this level of survival."

2.4.3. *Loss of trees as a long-term investment*

Related to the issue above, but on a longer time scale, mature trees may be killed by drought, in which case the farmer loses a long-term investment. Another possibility is that shifting climate conditions may necessitate temporary or permanent migration, in which case land tenure is likely to be weak or absent, and investment in trees will be not only unlikely but unwise. This effect has already been seen in the Sudan and Sahel regions of Africa due to current climate variability and change (Ziervogel et al. 2006).

2.4.4. *Distraction from more effective solutions*

Even if agroforestry practices confer no harm under future climate, they ought not to be pursued if they conflict with more effective solutions – for example, improved crop varieties that are tolerant to higher temperatures; micro- or large-scale irrigation schemes; or even diversification of the economy away from staple crops to cash crops, or out of agriculture altogether. Agroforestry's "aura of unassailable green goodness" (Walker 2001) ought never to interfere with its ultimate goal of benefiting land users.

2.5. Summary: Possibilities and research needs

The role of agroforestry in climate change adaptation is an important but almost wholly unexplored question (L. Verchot., pers. comm., 2/2007). Based on the evidence above, I propose that agroforestry has the potential to reduce the vulnerability of smallholder agriculture to climate change. However, promotion of agroforestry technologies *without* regard to future climate could be unhelpful or even detrimental to the farmers they are intended to benefit. Given the inevitability of some amount of anthropogenic climate change, this question needs to be examined systematically across systems and locations.

I have chosen to begin answering this question for southern Africa, because of its special vulnerabilities to climate change as described above, and also because a wealth of agroforestry knowledge and experience exists in the region.

3. Agroforestry in southern Africa

3.1. Agroforestry research in Southern Africa to date

In Southern Africa, due to constraints on farm size, soil fertility, and agricultural inputs, modern agroforestry research has mainly focused on "fertilizer trees" (Kwesiga et al. 2003) – leguminous trees that are grown along with the staple crop, nitrogen-hungry maize. A variety of different trees have been used, in a variety of configurations.

3.1.1. Tree species used

The agroforestry species that has generally produced the greatest increase in maize yields is *Sesbania sesban*, a fast-growing leguminous tree endemic to Africa (Kwesiga et al. 1999; Ikerra et al. 2001). It has two main drawbacks, however: first, it cannot be directly seeded onto field plots, but must be first cultivated as seedlings in a nursery; and second, it cannot be coppiced, so it is not suitable for hedgerow intercropping.

Other leguminous trees that have produced good results include *Tephrosia vogelii* (Mafongoya et al. 2003), which is also known locally as a useful fish poison (ICRAF 2006), and *Gliricidia sepium* (Chirwa et al. 2007), which if unpruned can grow to an attractive medium-sized tree with lilac flowers (favored by honeybees). These species both coppice well and are suitable for use in hedgerows. *Leucaena leucocephala*, a species used for soil restoration and cattle forage throughout the world, has also been tested in southern Africa (Mafongoya 2006), but has usually not performed as well as the above species. Native mature *Acacia albida* trees, mentioned in Section 2.3.1 for their microclimatic benefits in the Sahel, have also long been valued on southern African farms (Saka et al. 1994), though their use in this region has not been well studied.

Cajanus cajan, or pigeon pea, is a perennial shrub that produces an edible seed and is widely used throughout the region, especially in Malawi (Chirwa et al. 2007; Sirrine et al. 2007). It is valued for its use as a supplementary food crop, but can also provide some of the same soil fertility benefits as the tree species described above. The species upon which I will focus are summarized and compared in Table 1 below.

Table 1. Some characteristics of agroforestry species used in Southern Africa.

Species	***Sesbania sesban***	***Tephrosia vogelii***	***Gliricidia sepium***	***Cajanus cajan* (pigeon pea)**
Extent of current use	Limited	Moderate	Limited	Widespread
Native to	Africa	Tropical Africa	C. America	India
Propagation	Transplants	Direct seeding	Direct seeding	Direct seeding
Coppicing	No	Yes	Yes	Limited
Auxiliary uses	Fodder	Fish poison, insecticide	Fodder, honey, timber	Edible seeds, fodder
Growth form	Small tree	Small tree	Medium tree	Shrub
Max rooting depth (m)	>4 m	no data available	5.6 m	1.5 – 2 m

Sources: (Akinnifesi et al. 2004; Cook et al. 2005; ICRAF 2006)

These trees can be used in a variety of designs, although not every tree can be used with every design. Following are descriptions of three of the most common agroforestry system designs in southern Africa.

3.1.2. Improved fallows

Improved fallows (also called "planted fallows"), like natural fallows, involve a cessation of cropping on the land for one or more years in order to restore soil fertility. However, unlike in natural fallows, the fallowed land is intentionally planted with a nitrogen-fixing tree species. Usually the fallows are allowed to grow for two years, to be followed by two or three years of continuous maize monoculture. Improved fallows can result in such drastic yield increases that, even taking into account the fallow years, they can increase net maize yields by 50-100% or more (Kwesiga et al. 1999). They also have the additional benefits of providing firewood, timber, fodder, and weed suppression.

3.1.3. Relay intercropping

This system is mostly used in Malawi, where high population density makes it difficult for farmers to take land out of production. In relay intercropping, tree seedlings are sown with the maize, grow up underneath it, and finish maturing after the maize senesces with the end of the rainy season in early fall (Kwesiga et al. 2003). The trees are allowed to continue growing for a total of 8-9 months; they are then cut and their leafy biomass is incorporated into the soil shortly before the next round of maize planting. The soil fertility benefits and wood production are often of lesser magnitude than in improved fallows (Ikerra et al. 2001), but can still be significant.

3.1.4. Hedgerow intercropping

Hedges of the desired tree species are kept growing between rows of the maize crop in perpetuity (for five years or more, depending on the species). Aboveground biomass is pruned once or several times a year and added to the plot (Chirwa et al. 2007); some species, e.g. *Gliricidia*, can be lopped off at the ground and will resprout vigorously (Hauser et al. 2005). Roots are sometimes also pruned to minimize water competition (Ong et al. 2002). Names for this system vary somewhat; Kwesiga et al. (2003) call it simply "intercropping," as distinct from hedgerow intercropping, which they consider synonymous with alley cropping. Terminology notwithstanding, its main distinguishing feature is the severe pruning of the hedgerows.

3.1.5. Constraints to adoption

Although improved fallows are often adopted by a large fraction of the farmers who receive extension assistance to test them (Keil et al. 2005), they are not yet widespread in southern Africa overall, with adopters numbering roughly 80,000 as of 2001 (Kwesiga et al. 2003). Conventional wisdom suggests that adoption of improved fallows is impeded by lack of available land, but a cross-comparison of studies suggests that many other factors, such as information barriers and lack of access to seeds, govern the adoption of improved fallows (Ajayi et al. 2003).

Debate continues about the usefulness of improved fallows: Sanchez (1999) described their great potential to restore soil fertility and improve livelihoods throughout the tropics, but Hauser et al. (2006), in a survey of 590 studies across West and Central Africa, found that improved fallows usually conferred no net productivity increase.

I was not able to find information specifically on adoption rates for relay intercropping or hedgerow intercropping in southern Africa, but it can safely be said that adoption is not widespread, with the exception of pigeon pea intercropping (Sirrine et al. 2007). Biophysically, there exists great adoption potential for all three of these systems in southern Africa (Kwesiga et al. 2003); however, as with any new agroforestry technology, adoption is slowed by the complexity of the practice, the lack of information and materials, and farmers' concerns about risk and uncertainty (Mercer 2004).

Yet agroforestry can still be a useful option, given farmers' lack of access to other soil-improving technologies. Nearly all the authors cited in this section believe that these agroforestry systems can benefit southern African smallholders if used *appropriately*. My concern is that the definition of "appropriately" may change as the climate changes. Next, I will outline my specific questions and how I plan to investigate them.

4. Questions

I wish to test the performance of these three agroforestry systems in the field under simulated future climate. Here I outline my general approach and my questions; in the following section I describe specific aspects of my experimental design.

4.1.1. Simplifying assumption: Precipitation decrease is most important factor

As described above, southern Africa is expected to experience reduced rainfall and later onset of rainfall as a result of climate change. Since low and variable rainfall already curtails agricultural production in much of the region, I expect precipitation decrease to be the most important aspect of global climate change in the region. Thus, I will *simulate precipitation decrease* and no other factor. (I acknowledge that size of precipitation events, and increased average and maximum temperatures, are also likely important.)

4.1.2. Question 1: Will tree-crop water competition increase?

Currently, the performance potential of these agroforestry systems does not necessarily seem to be compromised by tree-crop water competition during normal rainfall years (Chirwa et al. 2007). However, several studies (Ong and Leakey 1999; Ong et al. 2002) have called into question the appropriateness of simultaneous agroforestry systems with fast-growing trees, especially in semi-arid climates. I will attempt to quantify whether water competition is likely to arise under expected future precipitation regimes.

4.1.3. Question 2: Will establishment success of seedlings decrease?

Several authors (Kwesiga et al. 1999; Ikerra et al. 2001) have already observed that dry years in southern Africa can cause establishment failures of agroforestry seedlings. I will investigate whether this is likely to happen more frequently under future climate.

4.1.4. Question 3: Will these systems still confer yield benefits?

Even if the answer to the above two questions is "Yes," it is still possible that agroforestry systems could continue to provide an increase in net maize yields as compared to an unfertilized maize monocrop. Question 3, then, is the most important and obvious question: would farmers still want to use the systems?

4.1.5. Question 4: Will any one system design outperform the others?

Under current climate, each of the systems has different advantages. Improved fallows usually enjoy the biggest yield increase, but relay intercropping is more popular for small farms, and hedgerows can minimize necessary labor.

In theory, improved fallows might enjoy the biggest advantage under reduced precipitation, because they can confer the same benefits of soil nutrient and carbon augmentation without directly competing with the crops for water. Following the same reasoning, I expect relay cropping to achieve an intermediate level of success, and hedgerow intercropping to perform most poorly, despite the pruning regime that is designed to limit competition. However, these predictions are very tentative, as it is not clear whether water competition will become a problem (Question 1).

5. Proposed research design

I propose to do two years of rainfall manipulations on these three types of agroforestry systems in the field, and compare them with several different controls. To my knowledge, no one has yet done intentional, controlled climate manipulations on any type of agroforestry system. In fact, there are very few field-based manipulations to simulate future climate change for any type of agriculture in sub-Saharan Africa.

5.1. Potential field sites

Although I wish my work to be broadly applicable throughout Southern Africa, maintaining multiple field sites would be logistically difficult. Therefore, I intend to learn as much as possible about the mechanisms at work in a particular location, and use that mechanistic understanding to generalize my findings to the extent possible.

5.1.1. Country selection: Malawi and Zambia

Among southern African countries, "modern" agroforestry technologies are most widely practiced in Zambia, Zimbabwe, and Malawi (Kwesiga et al. 2003). (Tanzania also has relatively high adoption, but due to its geography and culture, is often considered part of East Africa rather than southern Africa.) Dissemination in Mozambique is limited, and Angola, Botswana and South Africa are too arid to sustain the types of agroforestry used elsewhere in the region (Ngugi 2002). Due to political instability in Zimbabwe, I believe the most practical locations for this field project are Malawi and Zambia.

5.1.2. On-station versus on-farm trials

In empirical agroforestry research, there are tradeoffs between on-farm trials (with the cooperation and participation of farmers) versus trials on agricultural research stations. The former have the advantage of realistic conditions, but greater logistical difficulty and uncontrolled variables. The latter are easier to set up, monitor, and control, but may not reflect the conditions experienced by farmers on the ground. Since my study is primarily biophysical, and since precise control and measurement will be essential, I intend to conduct my fieldwork at an established research station.

ICRAF[3] has since 1987 participated in an agroforestry research collaboration with SADC (Southern African Development Community) at field stations in Tanzania, Malawi, Zambia, Zimbabwe, and Mozambique. I propose to carry out my work at one of these existing stations: either Makoka Research Station (near Zomba, Malawi) or Msekera

[3] The International Centre for Research in Agroforestry, now the World Agroforestry Centre.

Research Station (near Chipata, Zambia), depending on which is more suitable in terms of available space and interested collaborators. The locations are similar edaphically and climatologically; site characteristics are described in Table 2.

Table 2. Characteristics of Makoka and Msekera Research Stations.

Attribute	*Makoka (Malawi)*	*Msekera (Zambia)*
Latitude / longitude	15°30′ S, 35°15′ E	13°39′ S, 32°34′ E
Average annual T	10°-21°C win; 19°-34°C sum	15°-18°C win; 22°-30°C sum
Average annual rainfall	1024 mm (range 560-1600)	900 mm (range 672-1128)
Elevation	1030 m	1030 m
Soil texture	52% sand, 37% clay	52% sand, 35% clay
Soil type	Oxic Haplustalf	Ustic Rhodustalf
Reference	(Ikerra et al. 2001; Chirwa et al. 2007)	(Mafongoya et al. 2003)

5.2. Experimental treatments and controls

Although I would like to test the performance of multiple different agroforestry species, I anticipate that in order to make the scope of the research clear and manageable, I will need to focus on a single species planted in several different configurations. Though I would prefer to focus on a deep-rooted species, I will use whichever is already established at the research station and is most convenient for my use. (This will probably be either *Gliricidia sepium*, *Cajanus cajan* or *Tephrosia vogelii*. *Sesbania sesban*, although widely tested for improved fallows, is not used for hedgerow intercropping).

5.2.1. Rainfall treatments

I will have two levels of precipitation: ambient, and ambient -30% (manipulated via rainout shelters; see Section 5.3 below for technical description). Other climate variables will not be directly manipulated.

IPCC predictions indicate that the average annual precipitation decrease over most of Zambia and Malawi will be approximately 10% by 2080-2099 (Christensen et al. 2007). However, since temperature is also expected to increase by approximately 3.5°C, soil moisture is likely to decrease by more than would be expected due to precipitation decrease alone. It is for that reason, as well as the fact that substantially below-average rainfall years will become more frequent, that I propose a rainfall treatment that is somewhat more severe than the expected future decrease.

As mentioned earlier (Section 1.2), spring rains will probably decrease by a much greater amount than will summer or autumn rains. It may be possible to incorporate this pattern into the rainfall manipulations (with the caveat that farmers actively respond to late-onset rains by planting later or planting different varieties).

5.2.2. *Agroforestry treatments*

I will test the three different agroforestry technologies described above:

1. Improved fallows (IF);
2. Relay intercropping (RI);
3. Hedgerow intercropping (HI).

5.2.3. *Controls*

I intend to use three different controls, each with a slightly different purpose:

1. Unfertilized maize (the status quo in the region);
2. Fertilized maize, receiving roughly the same amount of N that the agroforestry species provide (to separate the effect of N addition);
3. Intercrop of an annual legume, e.g. bean or groundnut (to try to separate the effect of shallow-rooted annual versus deeper-rooted perennial species).

In nearly all agroforestry experiments, unfertilized maize is used as a control. Fertilized maize is sometimes used as an additional control. However, it is relatively rare to include non-woody intercrops as a control. Nevertheless, it is a useful comparison to make, because these annual leguminous intercropping systems are commonly used by and easily accessible to farmers (D. Sirrine, pers. comm., 10/2007).

5.2.4. *Plot size and replicates*

Depending on the field space that is available to me, I would prefer at least 5 (preferably more) replicates of each treatment. This would result in a sample size as follows:

$$(3 \text{ agroforestry treatments} + 3 \text{ controls}) \times (2 \text{ precipitation levels}) \times (5 \text{ replicates}) = 6 \times 2 \times 5 = 60 \text{ plots.}$$

Based on prior work (e.g. Phiri et al. 2003; Chirwa et al. 2007; Sirrine et al. 2007), I think it will be advisable to make the sampled area of each plot approximately 5 m × 5 m. The actual plots should be somewhat larger, (the periphery must be discarded because of edge effects, this being especially important in the reduced-precipitation plots, because of the limitations of the rainout shelters). This would lead to a total required area of:

$$(60 \text{ plots}) \times (25 \text{ m}^2) = 1500 \text{ m}^2 = 0.15 \text{ hectares}$$

(which is roughly one-quarter of the average farm size throughout much of southern Africa). Of course, additional space (probably at least 50% extra) would be needed for buffer zones between the plots.

Maize in southern Africa is usually planted at a spacing of 90 cm within rows, and either 75 cm or 90 cm between rows (Chirwa et al. 2007; Sirrine et al. 2007). The agroforestry trees, if present, are sown in between the maize stations, either on the ridges or in the furrows. Assuming a spacing of 90 × 75 cm, this would allow for (5 m / 90 cm) × (5 m / 75 cm) = 5 × 6 = 30 maize individuals (plus, where applicable, 30 individual trees) in a 25 m^2 plot. Given the coarseness of the row spacing compared to the size of the plot, it will be *imperative* to ensure that the same number of individuals are present in each plot – and that there are the same number of maize rows as tree rows, a point that is often neglected (Hauser et al. 2006).

5.3. Rainfall manipulations

5.3.1. The technology

The most common method for experimental rainfall reduction is a covered shelter that intercepts 100% of rainfall (e.g. Fay et al. 2000; English et al. 2005). These are usually left in a fixed configuration throughout the growing season, though some designs feature an open roof that closes (manually or automatically) only in the case of precipitation (Nam et al. 2001). With these designs, a controlled amount of water is usually added back to the plot via sprinklers or irrigation drips.

An alternate approach intercepts a consistent fraction of the rainfall while allowing the rest to reach the ground. (Yahdjian and Sala 2002) describe a design in which a series of fixed gutters mounted over the plot remove a fraction of precipitation roughly equal to the fraction of area covered by the gutters (Figure 1). This design is low-cost and low-labor, but once constructed, cannot easily be modified to change the interception fraction. Nor can it control timing of precipitation events.
A third approach (T. Dawson, pers. comm., 10/2007) involves a shelter with a roof made of panels that can be tilted to intercept a varying fraction of incoming precipitation. These are more exacting in their construction than the above two designs, but have the advantage of flexibility.

I will need to do further investigations to determine which of these designs is most suitable for my purposes. Due to the expense, difficulty, and artificiality of sprinklers and irrigation, I prefer either of the second two designs over the first one. One major consideration will be the height of the rainout shelters: mature maize (and mature fallow trees) can grow to well over 2 m tall, so I will need to choose materials that can reliably support a structure of that height.

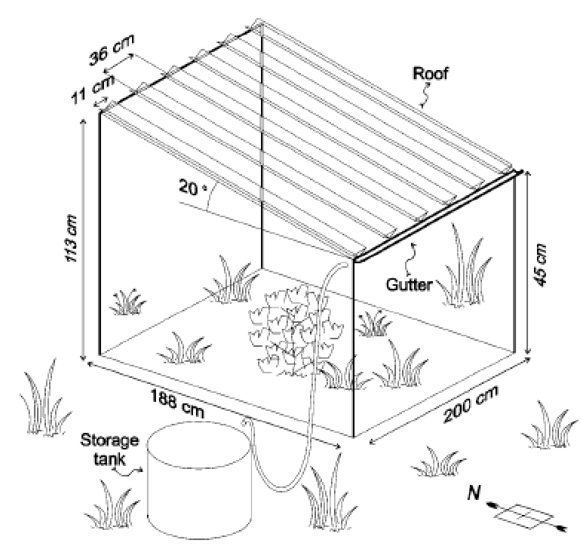

Figure 1. Rainout shelter to intercept 30% of incoming precipitation (from Yahdjian and Sala 2002).

5.3.2. Unintended effects

As well as affecting precipitation itself, rainout shelters can increase temperature, decrease wind speed, decrease insolation, and even change precipitation chemistry (Hanson 2000). It would therefore be useful to control for the effect of the equipment itself – i.e., to install similar structures that do not actually intercept rainfall (Fay et al. 2000). I will do this if time, space and budget permit.

5.3.3. Duration of manipulations

In Zambia and Malawi, the growing season (which corresponds exactly with the unimodal rainy season) is from approximately November to April. I will carry out manipulations for two consecutive growing seasons: the 2008-2009 season and the 2009-2010 season. The rainout shelters will be left in place throughout the year.

5.3.4. Manipulate new systems or established systems?

One unresolved methodological question is whether it makes more sense to establish each type of agroforestry system from scratch shortly before beginning the manipulations, or whether it would be preferable to manipulate systems that have already been established for several years. Each option has benefits and drawbacks.

Manipulating a newly established system may not provide useful data, because it often takes several years for any of the soil improvement benefits of agroforestry to be realized. On the other hand, manipulating an established system does not allow for the possibility of climate change affecting the establishment success of the system, and the subsequent gradual improvements of soil quality.

On balance, I believe that the manipulation of existing systems is likely to provide more useful data. At least, data from this approach can be used to infer how the systems will perform during especially dry years, even if the implications for long-term climate change are more ambiguous.

5.3.5. How manipulate improved fallows?

Improved fallows pose a dilemma for this two-year design, since they take at least four (sometimes five years) to go through a full cycle from maize to fallow and back again.

One option is to omit improved fallows from consideration altogether, and focus only on relay intercropping and hedgerow intercropping. However, I would prefer to include this technology if possible, since it has been widely tested and fairly widely adopted throughout southern Africa, and since I expect it may be the technology that is best suited to future climate, due to its avoidance of tree-crop competition for water.

Another possibility would be to focus the manipulations only on the first two years of the cycle (the first and second year of tree growth) and to measure the effects of decreased rainfall on the establishment, growth, and soil inputs of the trees. This could be combined with manipulations of sole maize grown on post-IF soil (to determine whether the IFs affect the soil in a way that helps maize survive low-rainfall conditions).

At this point, I prefer to manipulate each of the two-year stages separately over the two years of the experiment, realizing that such data will have limited applicability.

5.4. CO_2 manipulations

Additionally, if I am able to obtain the germplasm of the agroforestry species, it may be possible to carry out CO_2 enrichment experiments in greenhouses at UC Berkeley, since there is evidence that this could be an relevant effect. As (Cline 2007) and others point out, optimism over the beneficial effects of increased CO_2 have often not been borne out in the field. Greenhouse manipulations are fraught with artificialities, but may provide a useful additional piece of the puzzle.

5.4.1. Seedling establishment, growth, and competition

Previous work indicates that elevated CO_2 can enhance survival and growth of several of the agroforestry species used in southern Africa. For example, Tissue et al. (1997) found that CO_2 stimulated growth (by 84%) and N fixation (by 25%) of 70-day-old *Gliricidia* seedlings, even when N levels were already quite low (contrasting with earlier results by the same group, in which limited soil N curtailed the CO_2 enhancement effect). Two *Sesbania* species (*S. vesicaria* and *S. exaltata*) have also been shown to exhibit a significant growth response to CO_2 even at very early stages of development (Tischler et al. 2000). No one has yet, to my knowledge, tested *Tephrosia* or *Cajanus* response to elevated CO_2.

It could be informative to look at success of seedling establishment under water stress in ambient and elevated CO_2. Also, to my knowledge, no one has grown these tree seedlings in a competitive environment with maize under enriched CO_2. It could be interesting to investigate whether CO_2 enrichment changes the balance of competition.

5.4.2. Below-ground allocation and coppicing success

Bond and Midgley (2000) suggest that increased atmospheric CO_2 may facilitate tree invasion in savannas by (1) enhancing belowground C allocation and thus resprouting ability; (2) increasing the speed at which trees are able to escape the topkill[4] zone. The first of these hypotheses is relevant to coppicing agroforestry systems. (In order for elevated CO_2 to make any difference, the trees would have to be C-limited, or they would have to use C as a currency to trade for their limiting nutrient.) The effect of increased below-ground C allocation would be difficult to test in a greenhouse, as it requires the use of mature trees; however, it is a question that I will keep in mind.

5.5. Other shortcomings of this design

I realize it would be preferable to have a longer time horizon in order to simulate longer-term effects. Although I am not able to do this within the constraints of a Ph.D. dissertation, it is my hope that this project may be extended beyond the two years and

[4] Height zone in which the crown of a tree is likely to be killed by fire.

continue to provide useful data. Also, even though the manipulations are short in duration, these data will help demonstrate how agroforestry systems respond to drought years, which is useful information to have even in present-day climate.

Ecosystem climate manipulations (e.g. (de Valpine and Harte 2001; Suttle et al. 2007)) often take several years, if not longer, to reach a new equilibrium in terms of species composition and ecosystem function. Often, the change in species composition is, itself, an essential factor causing the change in function. Thus, allowing time for equilibration of species composition change is essential for getting useful data from a natural ecosystem. Agricultural systems do not have this problem, so a brief manipulation is probably more relevant than it would be in a natural ecosystem.

The shortcoming about which I am most concerned is that both years of my study may have above-average rainfall, in which case I would not expect the imposed 30% decrease in precipitation to have any effect on system performance. If this eventuates during year 1, I may need to consider a different manipulation protocol for year 2.

6. Data collection and analysis

Following is a description of the data I intend to collect from each system in order to gauge its performance, and to elucidate the mechanisms underlying that performance.

6.1. Performance metrics

6.1.1. Maize yield

The most obvious data to collect are data on the grain yield of maize. This is usually done by waiting for the maize to mature, harvesting all the cobs, shucking and weighing them, then measuring a subsample of cobs to determine average moisture content and grain/cob ratio. This information is used to calculate total dry yield in tons/ha. (Typical yields in the region are 0.5 - 4 tons/ha, depending on maize variety and soil quality.)

Since this work will be done on research stations rather than on farmers' fields, it would be possible to determine the *exact* maize yield without the use of subsampling, since the maize does not have to be immediately returned to the farmer. This might allow for more precise statistical analysis, because the yield data points would then have no associated uncertainty. (However, this approach may be too labor-intensive.)

Sometimes biomass of the maize stover (the aboveground vegetative part of the plant) is also recorded; this information may be useful to construct a system nutrient budget.

6.1.2. Above-ground biomass of the agroforestry species

The above-ground biomass of agroforestry trees is of direct value to farmers, hence I include this data set in the "performance" category.

When the agroforestry species is cut and incorporated into the soil (every year for relay intercrops; the second of every four years for improved fallows) I will measure the woody biomass and leaf biomass separately (by weighing all the wet biomass, and then drying and weighing a subset to determine moisture content). It will probably also be useful to measure foliar N content, if facilities are available. In addition:

- For hedgerow intercropping, the hedge stays in place perpetually, and considerably less woody biomass is harvested, but I would still measure the amount harvested.
- This approach would not account for litterfall throughout the rest of the year. I will investigate how previous studies have dealt with the issue of litterfall.
- If I end up working with the species *Cajanus cajan* (pigeonpea), I will also measure the grain yield of that species, since it can be directly consumed by humans.

6.2. Mechanisms

Sanchez (1995) lamented the lack of attention to *mechanisms* by which agroforestry can increase crop yield. Much work has been done since then, especially on belowground interactions (e.g. Schroth 1999; Ong et al. 2002), and so far, studies have upheld the value of mechanistic understanding that can be used to inform management practices.

6.2.1. *Temperature and precipitation*

These will be monitored continuously on as many plots as possible. It will be especially important to obtain good measurements of precipitation in order to ensure that the rainout shelters are having their desired effect.

6.2.2. *Soil moisture*

Ideally I would monitor this continuously along a depth gradient, probably at least down to 2 m (some of the agroforestry species used in Southern Africa have roots that extend 5 m or more). Previous studies at these field sites have used a neutron probe to measure soil moisture, so this may be the best option. It may instead be possible to install TDR probes that monitor soil moisture continuously and automatically.

6.2.3. *Belowground biomass and root distribution patterns*

Measuring belowground plant components is notoriously difficult and time-consuming. Yet, I believe my work will be considerably more meaningful and useful if I can estimate belowground biomass (and create profiles of root distribution) for the species involved. A significant overlap between rooting zones would imply possible competition.

6.2.4. *Soil nitrogen, soil organic matter, and water-holding capacity*

I will measure SOM, soil WHC, and soil nitrogen at the beginning and end of each growing season. If, as I expect, I am able to use already-established agroforestry systems, I do not expect SOM or soil nitrogen to change appreciably over the two years of manipulations, but it is possible that they will (e.g. due to changes in inputs or decomposition rates in the manipulated system). Basic soil data (e.g. pH, bulk density) already exist for the field sites I am considering.

In this region, N is almost always more limiting than other nutrients, so in the absence of new information I will not plan to measure other nutrients. Previous studies have commonly measured both inorganic and organic N; my default will be to do the same.

6.2.5. *Transpiration rates and water-use efficiency*

To more directly measure the water use of each species, and the potential for water competition between trees and crops, I will measure transpiration rates as often as possible during the growing season, and will estimate WUE for each system at the end of the growing season. The latter can be a difficult measurement if the plants have access to groundwater (Chirwa et al. 2007). Ideally, I would use sap-flow gauges, and possibly isotopic analysis, to better understand temporal and spatial patterns of water use by each species. However, this may not be possible in the timeframe and budget of the project.

6.2.6. *Success rates of seedling germination and establishment*

For the two systems in which seedlings will be planted anew for this experiment (improved fallows, and relay intercropping) I will calculate the germination rate (after several weeks), the survival rate at the end of the first year, and, in the case of improved fallows, at the end of the second year.

6.3. Metrics and statistics

The above data will, I expect, allow me to tentatively answer my four original questions:

Question 1: Will tree-crop water competition increase?
Question 2: Will establishment success of seedlings decrease?
Question 3: Will these systems still confer yield benefits?
Question 4: Will any one system design outperform the others?

It is worth mentioning that even questions 3 and 4 do not fully encapsulate the question of whether the agroforestry systems are *successful*. A multi-species agroecosystem produces components that are of incommensurate value, especially when the effectiveness of the market economy is uncertain. Furthermore, trees can confer immeasurable benefits such as watershed protection, biodiversity conservation, and aesthetic capital. Although I do not currently have an analysis framework to directly include data other than those described above, I will certainly keep this in mind.

6.4. Fallback positions

Depending on how much assistance I am able to get, it may or may not be possible to collect all the above data for all the plots. The most reduced form of this project that I think would still be useful would simply be to collect the performance data (maize grain yield, and above-ground tree biomass). Although it would be a disappointment not to be able to clarify the underlying mechanisms, the project would still be a unique and useful opportunity to demonstrate the effects of reduced precipitation in a field setting.

Reducing number of replicates would be another way to decrease the labor required, though I think it would be futile to attempt fewer than three replicates per treatment. A better option might be to eliminate one or more of the controls (e.g. the annual legume).

7. Proxy data and modeling

A manipulation experiment such as the one proposed above is necessarily very limited in time and spatial extent. It is unable to test long-term effects, or to look at a variety of different systems and locations. Thus, I propose augmenting the experimental results with two other lines of inquiry.

7.1. Interannual variability

As previously mentioned, both of the field sites at which I propose to work have been used for agroforestry experiments for several decades, and a wealth of data exists on system performance under ambient rainfall. Although these data cannot answer the same kinds of questions as can experimental manipulations, they will be very useful for providing a longer time-frame, as well as information on different species and systems.

There will be problems in interpreting and comparing the data sets. Absolute rainfall, and even rainfall relative to average, do not matter per se; what matters is whether the system is experiencing water stress, and this is a result of rainfall amount, rainfall timing, soil texture, temperature, wind speed, and other factors.

I am not yet sure exactly in what form these data exist (published studies usually do not include much climate information), but I will make it a priority to obtain as many existing data sets as possible in order to inform my experimental design, and to help with the modeling work below. A useful unifying question may be: “Do agroforestry systems usually have a higher water-use efficiency than the monocultures they replace?”

7.2. Modeling with WaNuLCAS

WaNuLCAS (Water, Nutrient, and Light Capture in Agroforestry Systems) is a well-established model for simulating above- and below-ground interactions in a two-species system containing a tree and an annual crop (van Noordwijk and Lusiana 1999). It has been applied to a variety of systems, including *Gliricidia* fallows in Indonesia (Wise and Cacho 2005), and *Tephrosia* and *Crotalaria* fallows in Western Kenya (Walker et al. 2007).

However, it has not to date been used for simulations of the effect of climate change on agroforestry systems. Although it has potential to do so, it would first need to be modified to account for changes in phenology and the effects of long-term drought (M. van Noordwijk, pers. comm., 9/2007). In conjunction with my field work, I would like to work on improving WaNuLCAS as a tool for longer-term agroforestry simulations under climate change. I first need to learn more about the model to determine how best to proceed, and in what form my data would be most useful for model improvement.

8. Expected audience

At the broadest level, I expect this research project to be of interest to governments, NGOs and multilateral organizations interested in climate adaptation. My work will, I believe, will provide a interesting case study of adaptation potential for a particular agricultural technology. More specifically, this work to be valuable to the agroforestry research and modeling community, especially because (to my knowledge) a climate manipulation experiment has never been done before on an agroforestry system.

Finally, and most importantly, I wish my research to directly benefit the smallholders in southern Africa on whose behalf I am working. I will share my results as widely as possible across disciplines, since the biophysical performance of an agricultural system is only one aspect of its overall effectiveness. The greatest value of this work, I believe, will be as a contribution to the overarching goal of achieving sustainable development in a changing climate.

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