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Article

Agroecosystem Analysis of the Choke Mountain Watersheds, Ethiopia

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Abstract: Tropical highland regions are experiencing rapid climate change. In these regions the adaptation challenge is complicated by the fact that elevation contrasts and dissected topography produce diverse climatic conditions that are often accompanied by significant ecological and agricultural diversity within a relatively small region. Such is the case for the Choke Mountain watersheds, in the Blue Nile Highlands of Ethiopia. These watersheds extend from tropical alpine environments at over 4000 m elevation to the hot and dry Blue Nile gorge that includes areas below 1000 m elevation, and contain a diversity of slope forms and soil types. This physical diversity and accompanying socio-economic contrasts demand diverse strategies for enhanced climate resilience and adaptation to climate change. To support development of locally appropriate climate resilience strategies across the Blue Nile Highlands, we present here an agroecosystem analysis of Choke Mountain, under the premise that the agroecosystem—the intersection of climatic and physiographic conditions with agricultural practices—is the most appropriate unit for defining adaptation strategies in these primarily subsistence agriculture communities. To this end, we present two approaches to agroecosystem analysis that can be applied to climate resilience studies in the Choke Mountain watersheds and, as appropriate, to other agroecologically diverse regions attempting to design climate adaptation strategies. First, a full agroecoystem analysis was implemented in collaboration with local communities. It identified six distinct agroecosystems that differ systematically in constraints and adaptation potential. This analysis was then paired with an objective landscape classification trained to identify agroecosystems based on climate and physiographic setting alone. It was found that the distribution of Choke Mountain watershed agroecosystems can, to first order, be explained as a function of prevailing climate. This suggests that the conditions that define current agroecosystems are likely to migrate under a changing climate, requiring adaptive management strategies. These agroecosystems show a remarkable degree of differentiation in terms of production orientation and socio-economic characteristics of the farming communities suggesting different options and interventions towards building resilience to climate change.

Keywords: climate change; adaptation; agroecosystem; Ethiopia

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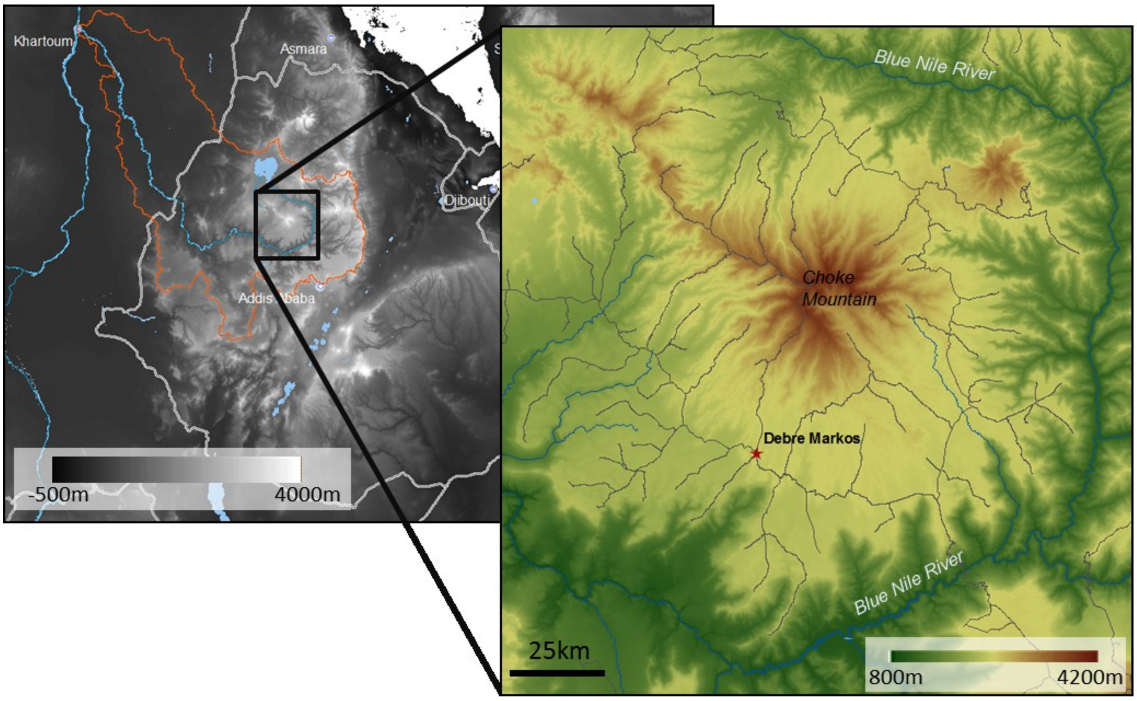
1. Introduction

Tropical highland regions are among the areas most vulnerable to climate change [1]. This vulnerability is frequently characterized in terms of the magnitude of observed or predicted change and associated physical sensitivities: tropical highlands are experiencing rapid warming [2] that threatens species and ecosystems adapted to relatively cool conditions, they tend to include erosion-prone steep lands with weathered soils that can be destabilized by changes in precipitation patterns and intensity, and upland meadows, forests, and wetlands are often sensitive to seasonal water stress that will increase as potential evaporation rises. But vulnerability of ecosystems and human systems to climate change is a function of adaptive capacity as well as physical exposure. The degree to which natural ecosystems are pressured by deforestation and the encroachment of agriculture, for example, will influence the availability of biodiversity refugia as the alpine zone retreats. These land use pressures also affect the vulnerability of agricultural systems, as land degradation associated with over-cultivation of headwater regions impacts watershed wide erosion rates and water value for downstream users. Within active agricultural zones, investment capacity and access to production-enhancing technologies will influence farmers' ability to maintain yields and conserve soil resources under changing climate conditions. This, in turn, strongly influences the total agricultural area needed to support the food security and economic aspirations of the population.

The adaptation challenge is further complicated by the fact that highland regions tend to be characterized by high internal diversity, both physical—dissected topography and associated climatic and hydrological contrasts—and cultural, due in part to the isolating effects of terrain. This diversity of conditions leads to diversity in the character of vulnerability and in the most physically and culturally appropriate adaptation strategies. Furthermore, highland populations are often poorer, marginalized groups with relatively low economic capacity to invest in adaptation.

Choke Mountain and its associated watersheds, located in the Blue Nile (Abay) Highlands region of Ethiopia (Figure 1), is broadly representative of many of these adaptation challenges. Though the mountain is located in the Ethiopian Highlands, with a peak elevation of more than 4000 m, its watersheds drain in three directions to the Blue Nile gorge, where elevation drops to below 1000 m. Over a distance of less than 70 km, then, one finds hot, dry valleys, gently rolling, deep soil midland plains, and cool, wet alpine zones. Complex topography makes for strong local contrasts in precipitation and temperature, and soils are deeply weathered and erodible over most of the mountain. While we are not aware of any published studies of rainfall intensity in the Choke Mountain watersheds, work in the northern Ethiopian Highlands has found that rains in that neighboring region are characteristically intense and erosive [3]. Given the observed severity of erosion in the Choke Mountain watersheds, it is possible that erosive rains affect this region as well. The landscape is dominated by low-input subsistence agriculture, with cultivation extending from the Blue Nile gorge up to near the summit of the mountain. The alpine zone was, historically, covered in forest and natural grass and shrublands, but increasing population and associated deforestation and land degradation have caused cultivation to be extended as high as 3800 meters elevation [4].

Figure 1. The location and topography of Choke Mountain watersheds. In the regional map, the red line indicates the outline of the Blue Nile River basin and shading is topography. In the Choke Mountain region inset, colors are topography, blue lines are major rivers, and grey lines are roads. The watersheds considered in this study run from the mountain peak to the Blue Nile River.



These pressures have taken a toll on the natural resources of the region. Consultations with community leaders, agricultural experts, farmers' cooperatives and other small-scale agri-business (e.g., tool and grain retailers), and farmers show substantial agreement that Choke ecosystems are under threat from multiple sources, each posing its own management challenge [5,6]. The natural resources base (land, water, and biodiversity) is under intense pressure from population growth and erosion-inducing traditional farming and management practices. The livelihoods of farming communities face severe constraints related to intensive cultivation, overgrazing and deforestation, soil erosion and soil fertility decline, water scarcity, livestock feed, and fuel wood demand. Climate change may already be contributing to these challenges. There has been a perceived increase in extreme rain events, and regional temperatures have exhibited an upward trend over the past 20 years [5,7]. There has been a documented decline in yields in some areas, and portions of the mountain have deteriorated from food surplus to food deficit areas within 20 years [5,6].

Persistent poverty and declining production within Choke Mountain watersheds has not gone unnoticed. Government and non-governmental organizations have launched a series of initiatives promoting agricultural technologies to improve productivity and conserve natural resources. Few of these initiatives have had a lasting effect, however, as the implementation of new technologies is often followed quickly by retreat from technology adoption, possibly due to underappreciated local socioeconomic, cultural, or physical constraints that limit the sustained use of a promoted technology or technique [8]. “Local” , in the context of a tropical highland region like Choke Mountain and its watersheds, must be understood to refer to the unique combination of physiography, climate, ecology, agriculture, and socio-cultural conditions that define a community’s exposure, adaptive capacity, and vulnerability in the face of resource constraints and climate change. The present study, which is a foundational component of an ongoing initiative on climate resilient development in the Blue Nile Highlands region [5], is motivated by the conviction that vulnerability analysis and the design of resilience building interventions in tropical highlands like the Choke Mountain watersheds region are inherently location-specific because of the connection between economic development and the local natural resource base.

The structure of an agroecosystem is a consequence of its environmental setting (e.g., climate, soil, topography, various organisms in the area), agricultural technologies and practices, and farmers’ social setting (e.g., human values, institutions and skills) [9]. The primary purpose of mapping agroecosystems, as carried out for rural land-use planning, is to separate areas with similar sets of potentials and constraints for development. Specific adaptation strategies and programs can then be formulated to provide the most effective support for each zone.

The general objective of this study was define the different agro-ecosystems of the Choke Mountain watersheds *i.e.*, to define areas with fairly homogenous biophysical and socioeconomic conditions to suggest promising direction for further in-depth research and development plans. The analysis reveals key agricultural, forestry and socio-economic issues and problems for each zone, for which solutions can be proposed, some through research and others by extension and development.

The specific objectives of the present study are to identify and describe the important components of the different agroecosystems (system definition) using participatory and objective approaches, to identify constraints and opportunities for management of the different agroecosystems (pattern analysis), and to assess possible ways to overcome constraints to design research and development options (formulation of adaptation strategies).

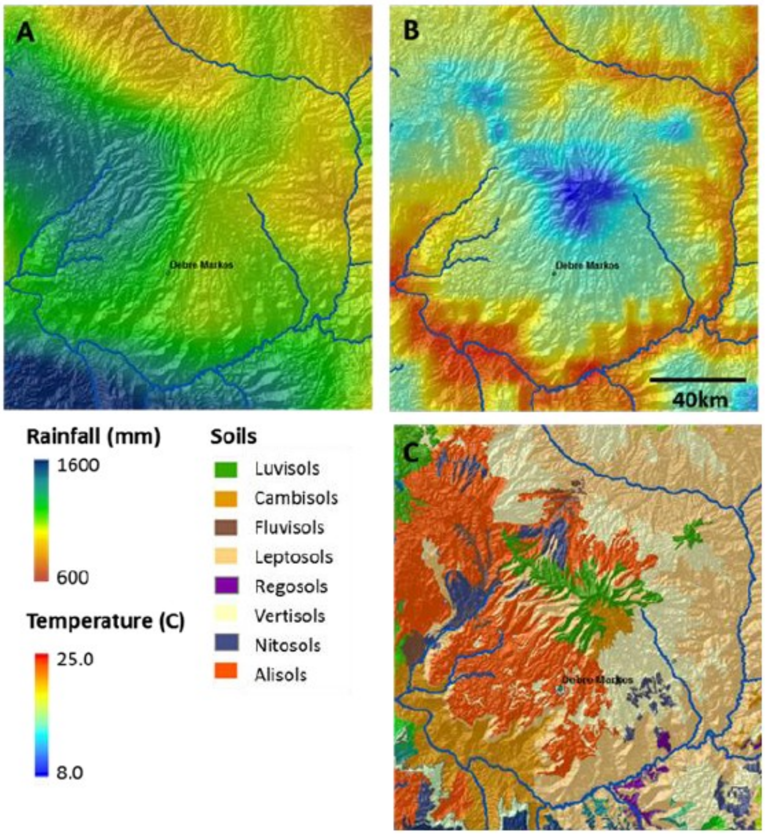
2. The Choke Mountain Watersheds

Precipitation in the Choke Mountain region is tightly correlated with the annual migration of the Inter-tropical Convergence Zone (ITCZ), with most rain falling during the May–October *kiremt* rainy season. As shown in Figure 2A, the distribution of precipitation across the mountain is not uniform; the western slopes tend to be wetter than the eastern slopes, with driest conditions found in the Blue

Nile gorge. Interannual variability in precipitation has significant impacts on agricultural production and soil erosion rates. Mean annual temperature declines with elevation (Figure 2B).

Prevailing soil types (Figure 2C; described in Section 3.1.) are volcanic in origin, derived from Mio-Pliocene shield volcano lavas and, at lower elevations, Oligocene flood basalts [10]. Under undisturbed conditions, soils tend to be deep: natural depths can extend to several meters, with rooting depths in this portion of the Ethiopian Highlands extending to one meter [11]. These deep, weathered tropical soils are highly susceptible to erosion, and on lands in the western Ethiopian Highlands cultivated using traditional methods the rate of soil loss can exceed the rate of soil generation by a factor of 4 to 10 [11]—a pattern that has been attributed in part to the prevalence of traditional ox-drawn tillage systems that have been found to promote rapid erosion on other regions of the Ethiopian Highlands [12], and that have been implicated in enhanced erosion in the Choke Mountain region [6]. High rates of on-field erosion are particularly problematic given that nutrients in soils of this region tend to be concentrated in the upper portion of the soil column [13]. On-field soil loss also leads to reduced water holding capacity and faster concentration of water on the landscape, which contributes to large volume gully erosion and sediment transport [14]. Combined erosion processes have led to dramatic soil loss, particularly from steep slopes, and significant declines in soil productivity.

Figure 2. (**A**) Mean annual rainfall from the Tropical Rainfall Measurement Mission (TRMM) satellite, product 3B42, as described in [15], (**B**) Mean annual temperature downscaled from Global Data Assimilation System [15], and (**C**) dominant soil types from the FAO global soil map (nominally at scale 1:5,000,000) [16] for Choke Mountain watersheds.



Agriculture in the Choke Mountain watersheds is diverse, but can generally be characterized as crop-livestock mixed systems, practiced by independent farmers on small plots. Choke Mountain watershed farms average 0.5 hectares in size, and farmers in the cereal production zone cultivate tef, maize, and wheat, supplemented by barley and potato for home or local consumption [4,5]. Animals include cows, oxen, sheep, and horses. A defining characteristic of cropping systems throughout the Ethiopian Highlands is the use of the ancient Ethiopian *ard* (or *maresha*) plow for tillage. This simple wooden ox-drawn plow is well suited for tropical vertic soils because it breaks through hard, dry topsoils. It is also, however, an instrument associated with tillage practices that lead to high rates of on-field erosion, particularly on steep slopes, and the development of a hard, infiltration-limiting plow pan. Overgrazing and deforestation have also contributed to erosion and soil fertility decline in Choke Mountain watersheds, and livestock feed shortages and fuel wood demands continue to exert significant pressure on the resource base.

3. Methods

3.1. Agroecosystem Analysis

In this application, the Agroecosystem Analysis (AEA) methodology of Conway [9] was adapted to the circumstances of communities and research relationships in Choke Mountain watersheds (Figure 3). The structure of an agroecosystem is a consequence of its environmental setting (e.g., climate, soil, topography, various organisms in the area), agricultural technologies and practices, and farmers' social setting (e.g., human values, institutions and skills). We used a participatory, interdisciplinary approach to landscape mapping that makes extensive use of objective data but recognizes that the definitions of system boundaries and functional relationships necessarily involve subjective, locally-specific judgments about the defining elements of the agroecosystem. The definition of agroecosystems was based on the overlay of three inputs: an agro-climatic zoning based on precipitation and temperature, a soil and terrain analysis, and a map of the distribution of farming systems. The agro-climatic zones of Choke Mountain watersheds were defined using the temperature and precipitation ranges associated with traditional Ethiopian agro-climatic zones (Table 1). Soil and terrain analysis was performed using the FAO 2006 soil classification in combination with local survey. Where local biophysical data (e.g., drainage, soil depth) were not available, soil type was used as a proxy. Farming systems were defined on the basis of the dominant type of resource base and the dominant livelihood pattern of farm households [17], as determined by local agricultural experts and confirmed in a stakeholder workshop [6]. In most cases, we found that there is a gradual transition from one system to another, so the boundaries between them are not actually as sharply defined as they appear on generalized agroecosystem maps.

Figure 3. Conceptual framework for agroecosystems analysis and adaptation planning in Choke Mountain watersheds.

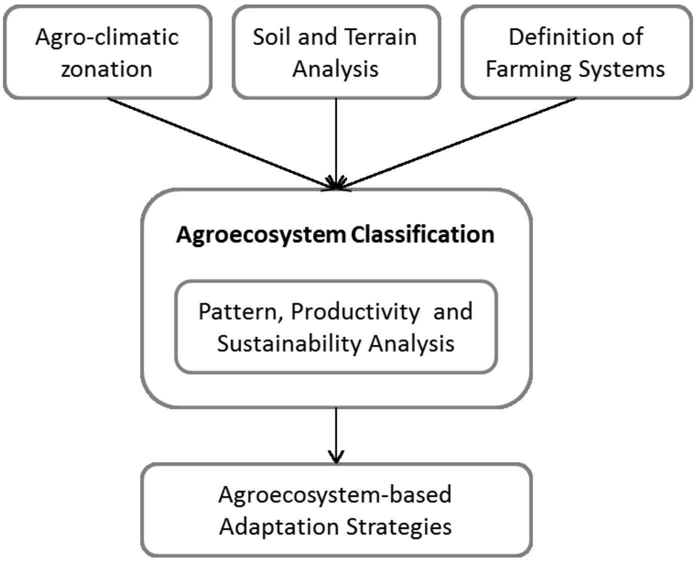


Table 1. Traditional climatic zones and their typical physical characteristics. Classifications and associated climatic conditions are from [18,19].

Traditional Zone	Climate	Altitude (m)	Average annual temperature (°C)	Average annual rainfall (mm)
Bereha	hot arid	<500	>27.5	<200
Kola	warm semiarid	500–1500/1800	27.5–20.0	200–800
Woinadega	cool sub-humid	1500/1800–2300/2400	20.0–17.5/16.0	800–1200
Dega	cool and humid	2300/2400–3200	17.5/16.0–11.5	1200–2200
Wurch	cold and moist	above 3200	<11.5	above 2200

These three sources of information were combined to define the major agroecosystems. Secondary literature was used to develop a preliminary structure and criteria for differentiation, which was subsequently refined in collaboration with experts and farmers in our discussions with Choke Mountain watershed communities. This resulted in the distinction of six major agroecosystems.

After defining agroecosystems, we performed pattern, productivity and sustainability assessment. Pattern analysis is the identification of constraints and opportunities for the management of the system, while productivity and sustainability assessment focus on key questions about the functioning of the system, especially with respect to possible ways to overcome constraints to enhance productivity and sustainability to design research and development options. These analyses began with an objective productivity potential assessment based on soil and terrain conditions conducted using the FAO revised Framework for Land Evaluation [17]. Then, a full pattern, productivity and sustainability assessment was performed through a series of questionnaires and focus-group discussions, facilitated by local agriculture researchers and complemented by observations made by the researchers. The assessment includes physical and realizable productivity potentials and existing production constraints to suggest future adaptation intervention directions through participatory analysis.

3.2. Objective Landscape Classification

The local, expert-informed nature of AEA yields important information on decision making, perceived system characteristics, and social-ecological dynamics that are exceedingly difficult to capture using automated, fully objective classification methods. Nevertheless, automated objective classification that is informed by the results of a full AEA provides a number of useful capabilities that are complementary to the AEA itself. For one, automated classification can increase confidence in the interpolation and (moderate) extrapolation of agroecological systems maps to areas that had poor coverage in the participatory AEA process. Detailed social information may be incomplete in these areas, but the close association between landscape characteristics and farming ecology within many subsistence agriculture regions and the availability of satellite data to characterize land use and cropping systems can allow for reasonable estimation of system boundaries. Second, automated classification systems can be designed to provide information on variable importance in the definition of agroecological systems. A classification algorithm trained on data collected in traditional AEA, for example, may show that elevation is the most important predictive factor distinguishing between two agroecosystems, while human activities (e.g., widespread plantation forest) may distinguish a third agroecosystem. This information is very useful when evaluating management options and the physical—though not necessarily cultural—transferability of crops and conservation techniques between systems.

Insomuch as present-day agroecosystems are constrained by climate conditions, it is possible to project physically optimal migration of agroecosystems in an evolving climate. If, in addition to climate, soils or local topography are defining criteria for agroecosystems then we might anticipate changing productivity patterns as new combinations of quasistatic (soil type, slope) and evolving (precipitation, temperature) variables emerge. In cases where the present distribution of agroecosystems is primarily a function of farmer preference rather than physical constraints, physically-based objective agroecosystem classification will perform poorly and the agroecosystem may, in fact, not be the most appropriate unit for defining adaptation strategies.

In order to understand the relative contribution of climate and physical setting to the definition of agroecosystems, we performed an objective landscape classification using climatic and physiographic variables and information on soil type. Climatic variables included mean annual and mean seasonal precipitation and temperature estimates drawn from the WorldClim global gridded 1 km climatologies [20]. WorldClim grids are derived by interpolating mean monthly weather data from meteorological stations belonging to the Global Historical Climatology Network (GHCN), the FAO, the WMO, the International Center for Tropical Agriculture (CIAT), R-HydroNet, and minor additional networks. Interpolation is performed by applying the ANUSPLIN thin plate moving spline interpolation algorithm to these station data, with Shuttle Radar Topography Mission (SRTM) elevation data, latitude, and longitude included as independent variables. Climatological averages are calculated using 1960–1990 data, or in some cases 1950–2000 data.

Physiographic variables, including slope, elevation, aspect, and topographic moisture index were calculated using 90 m resolution SRTM data. Information on predominant soil type was drawn from the FAO global soil map database.

Classification was performed using the open-source decision tree (DT) classifier C4.5 modified to perform classifications on binary datasets. DTs are non-parametric, hierarchical classifiers that predict class membership by recursively partitioning original data sets into increasingly homogeneous, mutually exclusive subsets via a branched system of data splits [21]. Key components of DTs are internal nodes, terminal nodes, and branches. At each internal node, the optimal independent variable and threshold value are identified that result in the best possible data split based on statistical deviance [22]. Once the classification structure is established, each observation (pixel) from the dataset to which the DT is applied is passed through the tree and assigned to the class of the leaf node into which it falls.

A key feature of DTs is *pruning*, designed to mitigate overfitting and make the trees more parsimonious to improve predictive power across unseen samples. Pruning involves removing parts of the tree (splits) that are expected to have a relatively high error rate or contribute little to reducing the deviance in the training data.

Boosting is another feature of more modern DT modeling that generates multiple classifiers (decision trees) rather than a single classifier, in an effort to improve classification accuracy. Applied to C4.5, boosting optimizes multiple classifiers using a base classification algorithm in an iterative fashion while systematically varying the training sample to emphasize difficult-to-classify cases from previous iterations. The final classification output is produced by a weighted voting scheme across the multiple classifiers [23]. In this sense, the boosted classification can be understood as a consensus of multiple decision trees. While any number of iterations can be performed, traditionally 10 iterations have been used for most previous mapping efforts where boosting was employed [22–25].

To determine the importance variables that contribute to the definition of each agroecosystems (AES), we also used a numerical method called *Random Forests* (RF), which is related to the DTs described above. Random forests are a combination of tree predictors such that each tree depends on the values of a random vector sampled independently and with the same distribution for all trees in the forest [26]. The generalization error for forests converges to a limit as the number of trees in the forest becomes large. The generalization error of a forest of tree classifiers depends on the strength of the individual trees in the forest and the correlation between them. Using a random selection of features to split each node, yields error rates that compare favorably to existing boosting algorithms but are more robust with respect to noise. Internal estimates monitor error, strength, and correlation and these are used to show the response to increasing the number of features used in the splitting. Internal estimates are also used to measure variable importance, which is particularly important in determining the underlying environmental controls of each AES.

In RF, the variable importance is measured in two ways: (1) Mean decrease in accuracy, which measures how much inclusion of a predictor in the model reduces classification error; and (2) Mean decrease in Gini coefficient—here used as a measure of "node impurity" in the tree-based classification. A low Gini (*i.e.*, larger decrease in Gini) means that a particular predictor variable plays a greater role in partitioning the data into the defined classes. In this application, we use both of these measures to define the importance of environmental variables with respect to defining each AES.

Using the climatic and physiographic inputs described above, the C4.5 DT algorithm with boosting was trained using 141 ground truth points identified by their location and their membership in one of the six agroecosystems defined in Table 1. We then applied the trained DT to the entire gridded dataset of predictor variables, producing an objective map of landscape categories.

3.3. Identification of Adaptation Options

Finally, specific adaptation strategies and development programs were formulated in consultation with local agricultural experts, informed by farmer interviews and discussion fora, to build climate resilient and sustainable agricultural development for each agroecosystem. Adaptation strategies specific to the different agroecosystems were evaluated for three objectives:

(1) *Address the problem of low livelihood assets*. Such activities generally aim to reduce poverty and other problems associated with a lack of capabilities, for example through improving livelihoods. Although these activities do not address specific climate change impacts, they do help buffer actors from climate trends and shocks [27] and therefore build resilience. This means that resilience is at the core of adaptation actions.
(2) *Build adaptive capacity*. These activities specifically address a household or community's ability to respond to climate changes (e.g., communicating climate change information, building awareness of potential impacts, investing in livelihood capital), which is a function of livelihood assets in combination with climate change awareness and understanding of potential impacts.
(3) *Transform adaptive capacity into action*. These activities focus on reducing the cumulative impacts of climate change, ensuring that no externalities occur from adaptation actions (e.g., adaptation by one actor does not adversely affect other actors), avoiding anticipated adverse impacts of climate change and ensuring that the distributional impacts of adaptations are minimized [28].

We also recognize that adaptation, for both ecosystems and human systems, is a process that requires the engagement of a wide range of stakeholders at multiple levels and in multiple sectors. It requires analysis of current exposure to climate shocks and stresses and model-based projections of future climate impacts. It demands an understanding of the existing vulnerability and adaptive capacity of households and communities within each agrosystem, as well as an appreciation for the specific development and policy choices available to the local government. The current study is limited to the adaptation objectives of participating stakeholders and the knowledge of agroecological systems, climate sensitivities, and policy options available to the researchers and stakeholders. No attempt is made in the current study to project future climate trends. Rather, adaptation options to a range of potential climate threats are considered.

In this context, the adaptation options presented in this study are a qualitative summary of the leading themes that emerged from community discussion fora and expert workshops. The discussion fora were transcribed by researchers and students participating in the project and subsequently analyzed to identify consistent themes. Output of expert workshops are summarized in formal reports [6].

4. Results and Discussion

4.1. AEA Definition of Agroecosystems

AEA identified six major agroecosystems (AES) in the study area (Figure 4A). These AES show a remarkable degree of differentiation in terms of constraints, opportunities, production orientation, and socio-economic characteristics of farmers (Table 2). This diversity offers both an opportunity and challenge for adaptation to climate change: diversity of current climate conditions suggests that multiple farming techniques, crops, and strategies are active within the region, providing a broad foundation for adaptive efforts, but that same diversity makes it difficult to establish climate change projections and adaptation strategies that are targeted to address to these highly localized conditions.

Figure 4. The six agroecosystems of the Choke Mountain watersheds. (**A**) As defined using standard agroecosystem analysis. (**B**) As defined using automated landscape analysis. Legend applies to both maps.

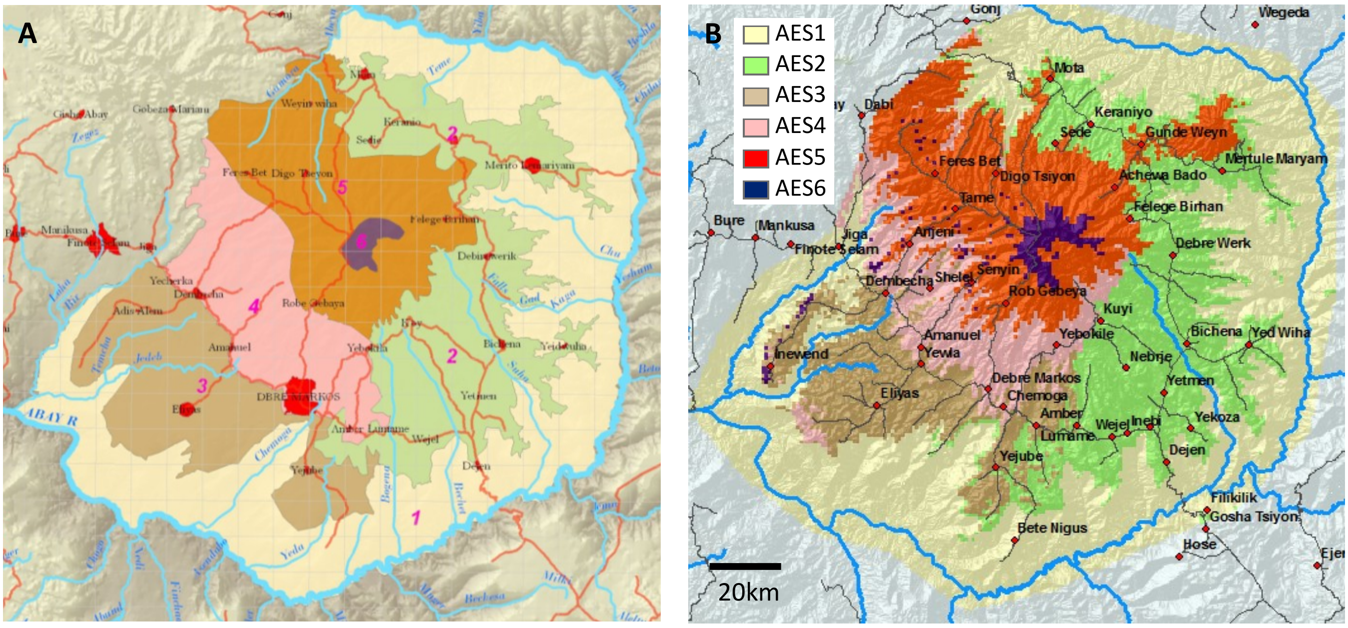


Table 2. Characteristics of AES in the Choke Mountains watersheds

Agroecosystem	Farming systems	Traditional Climatic Zone	Major soils	Major crops
AES 1: Lowlands and Abay Valley	Fragmented sorghum-based, extensive	Upper Kola	Leptosols Cambisols	Sorghum, tef Maize, haricot bean
AES 2: Midland plains with black soil (Dejen-Mota)	Intensive Tef-based	Lower Weyna Dega	Vertisols	Tef, durum wheat, barley, chickpea, grasspea
AES 3: Midland plains with brown soils (Baso-Elias)	Intensive Maize-Wheat based	Lower Weyna Dega	Nitosols Alisols	Maize, wheat, Tef
AES 4: Midland Slopping lands (Macha-Gozamin)	Semi-intensive Wheat/barley-based	Upper Weyna Dega- Lower Dega	Leptosols Nitosols Alisols	Wheat, tef, barley, engido (*Avena spp.*)
AES 5: Hilly and Mountainous highlands	Barley/potato-based	Upper Dega	Leptosols Luvisols	Barley, potato, Fava bean, engido
AES 6: Afro alpine	Choke protected area	Wurch	Cambisols Andosols Phaeozems	No major crops. Shrubs, grasses, and moorlands dominate

The six identified AES are:

Lowland and valley fragmented agroecosystems (AES 1; 7200 km^2): This agroecosystem includes the lowlands in the eastern part of the Choke Mountain watersheds and fragmented valleys along the Blue Nile gorge, with an altitude range of 800 to 1400 m. AES1 is characterized by relatively unfavorable agro-ecologic conditions: rugged terrain, lower and more sporadic rainfall than the other AES, and extensive land degradation. Production in this AES is constrained by shallow soil depth, low soil fertility, and sloping terrain. The annual temperature falls between 21 °C and 27.5 °C and the growing period ranges between 61 and 120 days. Dominant crops are sorghum, maize and tef, and soils include Leptisols and Cambisols. Even though these soils are fertile and are generally suitable for a wide range of agricultural uses, the prevalence of long, steep slopes leads to high rates of erosion. *Oxytenathera abysnica* and *Accacia spp.* are the dominant natural growing trees. The zone has potential for forest and agroforestry, sorghum and haricot bean production. Malaria is a major health related constraint in this area.

Midland plains with black soil (AES 2; 3200 km^2): AES 2 is found on the eastern toe of Choke Mountain, extending from the town of Dejen to the town of Mota. This agroecosystem represents midland plains with black soil with an elevation ranging from 1400 to 2300 m. The annual temperature varies between 11 and 15 °C. The growing period is between 121 and 180 days. Heavily textured Vertisols dominate the area. These soils have considerable agricultural potential, on account of their high fertility and their physiographic setting on extensive level plains amenable to mechanized cultivation, but adapted management is a precondition for sustained production. Because of the high content of shrink-swell clay in these soils, cultivation is difficult when they are dry and waterlogging is a problem when they are wet. There is no significant natural vegetation cover in this AES. *Prunus africana*, *Hagenia abyssinica*, *Erythrina brucei and Arundinaria alpina* species are vegetation types seen very sparsely. The zone is potential for input-intensive tef, durum wheat and chickpea production, provided appropriate Vertisol management practice is in place.

Midland plains with brown soils (AES 3; 1600 km^2): AES 3 is found on the western and southern toe of Choke Mountain toe. It is a midland plains area dominated by Nitosols, a brown soil very suitable for agriculture, and Alisols, with some Cambisols as well. Nitisols are deep, well-drained and are among the most productive soils of the humid tropics appropriate for a wide variety of crops. The good workability of Nitisols, their good internal drainage and fair water holding properties are complemented by their generally good chemical (fertility) properties. Alisols have similar properties, albeit with potential problems with Aluminum toxicity. The elevation of AES3 varies between 1400 and 2400 m. The annual temperature varies between 16 and 21 °C, and the growing period is between 121–180 days. Maize and wheat based farming systems dominate in the agroecosystem. It is also a potential area for pulses and oil crops. This system is potentially suitable for input-intensive, mechanized agriculture and irrigation that could contribute to rapid increases in productivity.

Midland Sloping Lands (AES4; 1300 km^2): AES 4 is located at the foot-slope of Choke Mountain with elevation ranging from 2400 to 2800 m. Soils are Leptosols, Alisols, and Nitosols, and the terrain is sloping. The annual temperature varies between 11°C—15°C and the growing period between 120–180 days. *There is no* dominant natural plant species. *Eucalyptus globulus* is extensively gown as a plantation, and some of the residents of the area have become dependent on it for their livelihood. AES 4 is constrained by low natural fertility due to leaching of base ions (Ca, Mg, and K) and high level of soil acidity. Sloping terrain is more difficult to cultivate than flatland, and is subject to higher rates of water runoff and soil erosion. The main crop types produced are wheat, maize, tef, and a range of pulses. The highly rugged landform, associated land degradation, and soil acidity present major constraints for crop production. This AES does have potential for more intensive production system, but soil and water conservation measures are critical.

Hilly and Mountainous highlands (AES5; 2400 km^2): These hilly and mountainous highlands are found on the back-slope of Choke Mountain. Soils are predominantly Leptosols and Luvisols, and altitude varies between 2800 and 3800 m. The shallowness of soils in this AES, combined with the rapid drainage characteristics of Leptisols, can result in drought stress even though precipitation rates are quite high. The annual temperature ranges from 7.5 °C to 10 °C and the growing period is between 61 and 120 days. The major crops grown in the area are potato, wheat, barley, endigo (*Avena spp.*) and pulses that are local varieties, and there is virtually no use of chemical fertilizer. The dominant plant tree species are the *Juniperus procera, Erica arborea, Hagenia abyssinica, Hypericum revolutum* and *Olea europae*. The major constraints on production in AES5 are low temperature, soil erosion, and deforestation leading to water management problems. Rangeland (grazing or pasture land) degradation is also common due to overstocking. AES5 is not appropriate for high intensity agriculture, but it does have high potential for traditional forestry, including bamboos, and potato and barley production with appropriate mountain agricultural land management.

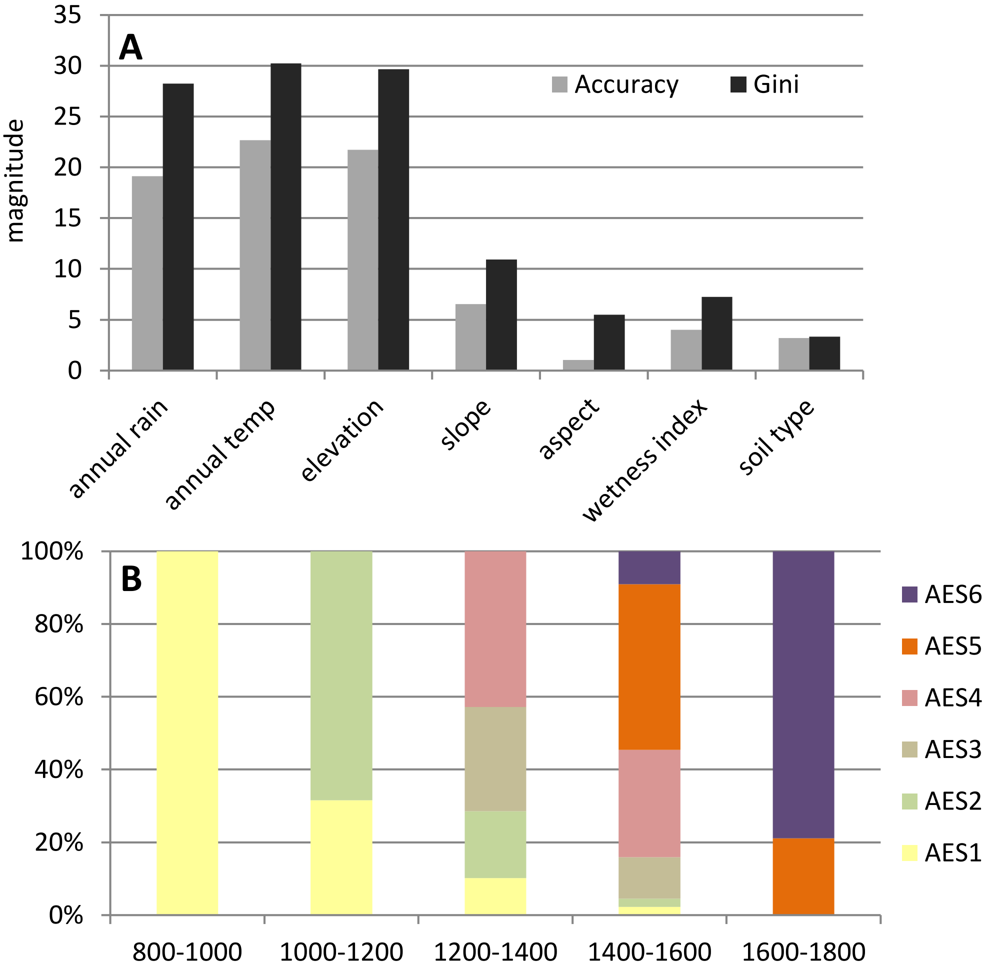
Afro Alpine (AES6; 250 km^2): The Afro Alpine is the Choke Mountain summit. Elevation ranges from 3800 to 4200, and soils are predominantly Cambisols, Andosols, and Phaozems, with some Luvisols (we note that Figure 2C, generated from FAO soils classifications, is highly simplified in this zone). The major natural habitats are moist moorland, sparsely covered with Giant Lobelia (*Lobelia synchopetala*), lady's mantle (*Alchemilla humania*), Guassa grass (*Festuca spp.*) and other grasses. The woody plant cover includes Asta (*Erica arborea*) and Amijja (*Hypericum revolutum*). Given the important functions of AES6 as a reservoir for biodiversity and a soil and water retention zone, combined with the area's relatively low agricultural potential due to low temperatures, the most appropriate use of AES6 is as a protected bioreserve. At present, ecological pressure due to grazing and fuel wood collection is reducing the proportion of AES6 that fulfills this role.

4.2. Objective Mapping of Agroecosystems

Results of the automated landscape mapping procedure are shown in Figure 4B. In general, there is close agreement between the distribution of agroecosystems defined using full AES analysis and those defined using objective mapping. Note that this general agreement should not to be interpreted as an independent confirmation of the AEA mapping, as the objective classification is trained on AEA ground control points and the AEA, in turn, takes physiographic and climatic information into account in defining agroecosystems. The agreement does, however, indicate that the distribution of farming systems in Choke Mountain watersheds is largely under climatic and physiographic control at this scale of analysis; we see no large or systematic disagreement between the participatory, farming-system oriented AEA and the physically based objective map. Areas of discrepancy between maps are in some cases a result of over-specificity in the automated algorithm—the edge effects seen at boundaries between AES in the automated classification, for example, are not observed on the landscape—and in other cases indicate areas where the full AEA, which did not include a comprehensive field survey, might have overgeneralized boundaries between agroecological zones—for example, the presence of several areas of AES5 along ridges and AES1 within valleys in the automated classification that are not noted in the standard AEA map.

The results of random forest (RF) analysis to determine variable importance are summarized in Figure 5. According to both measures of variable importance, climate information (mean annual precipitation and temperature) and elevation were by far the most influential variables driving the classification (Figure 5A). The importance of climate variables and elevation—which is in many ways a proxy for overall climate conditions—relative to soil type or slope suggests that the present distribution of AES is strongly influenced by prevailing climate conditions. Figure 5B emphasizes this point: there is a strong moisture gradient across Choke Mountain watershed AES, and in turn the AES segregate strongly according to prevailing precipitation patterns. Under a changing climate, in which both precipitation and temperature patterns across Choke Mountain watersheds are expected to evolve, the climatic zones that currently determine the distribution of AES are likely to migrate as the soil types that currently typify each AES remain static, and adaptive land management may be required.

Figure 5. (**A**)Variable importance determined by the RF method using accuracy and Gini criteria. (**B**) The relative distribution of AES across observed precipitation gradients.



4.3. Productivity Potential

Analysis of the suitability of soil characteristics and overall average suitability to agricultural production by AES is presented in Table 3. The relative suitability of land areas for agriculture includes climate, soil, and terrain conditions relevant to agricultural production (e.g., soil fertility and depth).

This purely physical evaluation of productivity is informative, and the relative suitability values for each AES are reflected in yields for low input and higher input agricultural systems that are observed today (Table 4). However, a full perspective on productivity potential requires examination of the ecological, cultural, and socioeconomic factors that determine the realizable productivity potential. Relevant management considerations that influence realizable productivity in each AES are listed in Table 5.

Table 3. Analysis of the suitability of soil characteristics and overall average conditions to agricultural production by AES.

	Depth*	**Natural Fertility***	**Drainage***	**Texture***	**Terrain***	**Average Suitability ****	**Dominant Constraints**
AES1	4	4	1	3	5	3	fragmentation, steep slopes, on-field erosion
AES 2	1	3	5	1	1	4	water logging
AES 3	1	3	1	1	1	5	soil acidity
AES 4	3	5	1	1	3	3	gully erosion, soil acidity
AES 5	4	5	2	2	5	2	long and steep slope erosion, gully erosion, acidity
AES 6	4	4	5	5	5	1	deforestation, overgrazing

For soil characteristics*: 1: not constrained; 2: slightly constrained; 3: moderately constrained; 4: constrained; 5: severely constrained. For average suitability**: 1: not suitable; 2: least suitable; 3: suitable; 4: more suitable 5: most suitable.

Table 4. Average yield (tones/hectare) standard deviation of yield (in parentheses) for major crops in Choke Mountain watershed agroecosystems, based on a 2009—2010 survey of 276 households evenly distributed across AES.

AES	**Tef**		**Wheat**		**Maize**	
	Local seed	Improved seed+Fert	Local seed	Improved seed+Fert	Local seed	Improved seed+Fert
AES 1	0.3 (0.5)	0.4 (0.6)	0.1 (0.5)	0.2 (0.7)	0.9 (1.1)	1.4 (1.7)
AES 2	1.5 (0.8)	2.0 (1.2)	1.7 (1.1)	2.1 (1.5)	1.3 (1.6)	3.4 (2.9)
AES 3	1.2 (0.6)	4.0 (0.8)	3.6 (1.2)	4.4 (1.4)	2.8 (1.5)	3.8 (2.0)
AES 4	1.0 (0.7)	1.6 (0.7)	2.1 (0.9)	2.2 (1.4)	2.4 (1.0)	3.1 (1.3)
AES 5	<0.1 (1.3)		0.9 (1.5)	1.1 (1.8)	0.1 (0.3)	0.2 (0.5)
Average	**1.4 (0.5)**	**1.9 (0.8)**	**2.8 (1.1)**	**3.6 (1.2)**	**2.6 (1.1)**	**3.7 (1.7)**

Table 5. Realizable potential for agroecosystems of the Choke Mountain watersheds. Assumed intensity of management reflects the level of agricultural investment deemed appropriate given the physical constraints on productivity and confirmed through participatory AEA. Key properties and production potentials were identified through AEA pattern and productivity analysis and are informed by previous work in the region as well as stakeholder perspectives.

	Assumed intensity of management	**Key properties and production potentials**
AES1	Low level of inputs/traditional management (rainfed)	Largely subsistence based and not necessarily, market oriented. Production is based on the use of traditional cultivars (if improved cultivars are used, they are treated in the same way as local cultivars), labor-intensive techniques, and no application of nutrients, no use of chemicals for pest and disease control and minimum conservation measures.
AES 2	High level of inputs/advanced management (rainfed or irrigated)	Mainly market oriented. Commercial production is a management objective. Production is based on improved high yielding varieties, is fully mechanized with low labor intensity, and uses optimum applications of nutrients and chemical pest, disease and weed control
AES 3	High level of inputs/advanced management (rainfed or irrigated)	Mainly market oriented. Commercial production is a management objective. Production is based on improved high yielding varieties, is fully mechanized with low labor intensity, and uses optimum applications of nutrients and chemical pest, disease and weed control
AES 4	Intermediate level of inputs/improved management (rainfed or irrigated)	Partly market oriented. Production for subsistence plus commercial sale is a management objective. Production is based on improved varieties, on manual labor with hand tools and/or animal traction and some mechanization, is medium labor intensive, uses some fertilizer application and chemical pest disease and weed control, adequate fallows and some conservation measures.
AES 5	Low level of inputs/traditional management (rainfed)	Largely subsistence based and not necessarily, market oriented. Production is based on the use of traditional cultivars (if improved cultivars are used, they are treated in the same way as local cultivars), labor-intensive techniques, and no application of nutrients, no use of chemicals for pest and disease control and minimum conservation measures.
AES 6	Protected area	Because of their extreme cold temperature, shallowness and, usually, steepness and consequent high erosion hazard, the summit of the mountain (>3800 masl) are not suitable for arable farming. If its geographical area is clearly defined, recognized by the community and managed through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values, this AES could be a potential for climate change mitigation and adaptation (e.g., watershed protection) activities.

4.4. Constraints

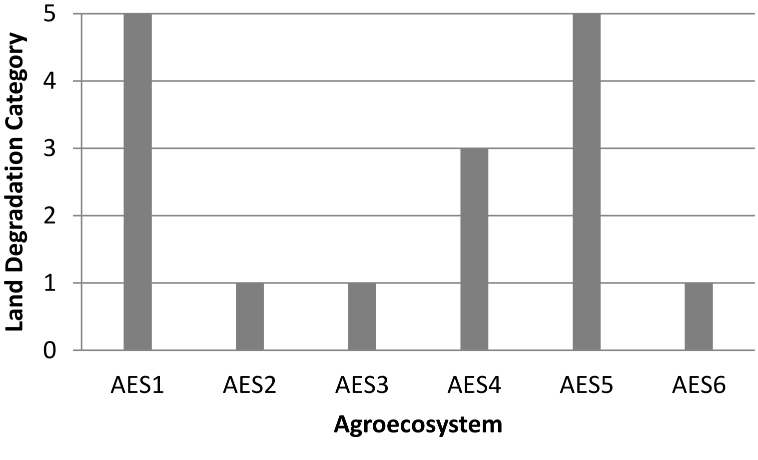
At the production level, agricultural productivity measures the value of output for a given level of inputs. To increase agricultural productivity, the value of output must increase faster than the value of inputs. Gains in overall agricultural productivity can therefore come from changes in production process that produce more output per unit of land or labor, or from changes in production and market costs and hence the increased profitability for farmers. Thus, increasing agricultural productivity not only relies on improved production efficiencies, such as through adoption of modern or improved technologies and practices, but also critically relies on many other factors such as adequate access to productive resources, well-functioning markets and infrastructure, and policy promoting economic and social stability.

A number of constraints on agricultural productivity have been identified in expert workshops, as reported previously [6]. Here we consider these constraints in the context of the AES described and mapped in this study, and as they were reported during participatory agroecosystem analysis. Identified constraints include a number of biophysical factors that are specific to particular agroecosystems as well as systemic constraints that affect farmers across the Choke Mountain watersheds.

A partial list of agroecosystem-specific constraints includes:

Land degradation: Soil erosion in Choke Mountain watersheds is a well-recognized problem, identified as a priority by the local community members. Steep slopes, traditional crisscross ox-drawn tillage systems that promote rapid erosion as well as limited agricultural land use characterize the Choke environment. The severity of human-induced land degradation (classified into five major classes of degradation, following the Land Evaluation method of [17]) differs dramatically across the six agroecosystems identified in this study (Figure 6). AES 1 and 5 are characterized by fragmented and steep slopes with the highest degradation rate. AES 2 and 3 have minimal soil erosion and other degradation problems, as they are in the mountain toes. AES 4 is prone to moderate soil erosion and associated degradiation. Nevertheless, there are still significant soil resources in the Choke Mountain watersheds, and experience indicates that productivity can be maintained and enhanced through effective field scale and landscape scale sustainable land management practices [5].

Figure 6. Human-induced land degradation of Choke Mountain watersheds by agroecosystems.



Deforestation: Forests, other woody/perennial biomass, and protected areas form an integral part of mountain farming economies and provide extensive environmental services to society. However, natural forests, shrub lands, and riparian woodlands are in decline across Choke Mountain watersheds [29], with the greatest impacts occurring in areas of expanded cultivation in AES 1, AES 5 and, where cultivation and fuel gathering have encroached, AES 6. Due to the landscape-scale benefits that forests have for soil and water retention, impacts of deforestation have both local and regional impacts on land degradation. Wetland loss is also occurring on Choke Mountain [4], with the greatest losses reported in AES 2, 3 and 4.

Water logging: AES 2 of the Choke Mountain watersheds is characterized by extensive areas of Vertisols, which are prone to severe water logging during the rainy season. Appropriate technologies do exist to improve drainage and prevent water logging, and in demonstrations these technologies have been demonstrated to triple wheat yields in AES 2. However, at present only 0.5% of farmers working in AES 2 Vertisol terrain make use of these technologies [6]. We note that unless the whole watershed is treated, localized drainage projects can lead to enhanced gully erosion downstream

Soil Acidity: At present, soil acidity is a major constraint on production, particularly for areas with Nitosols and Acrisols (AES 3 and AES 4), and acidity is increasing due to cultivation practices. In some areas acidity has forced farmers to switch to lower value, acid tolerant crops, and some land has been abandoned altogether. In order to improve the productivity of acid soils, the local government has initiated a liming program, but participation is low [6]. The AES analysis performed here suggests that a targeted focus on the communities located in AES 3 and AES 4 may allow for a more efficient and ultimately effective use of resources to address soil acidity.

Broader constraints affecting vulnerable households in all agroecosystems include:

Limited local-level capacity to design and implement resilience building measures: The majority of development interventions in the region have promoted some generic package of productivity enhancing practices and technologies. These interventions have had limited staying power, as farmers retreat from recommended practices that are inappropriate or inconsistent with the local agroecosystem or traditional practices and priorities. Participatory development of adaptation technologies is required in order to ensure that recommended interventions are appropriate to local conditions and to build human capacity for action within Choke Mountain communities. Participatory agroecosystem analysis conducted for this study indicates that the problem of generic, externally designed agricultural development interventions exists in all defined AES [5].

Limited access to life-improving technologies: In Choke Mountain watersheds, poverty and rough terrain conspire to limit the availability of services and technologies that could ease the burden of subsistence tasks, freeing labor for resilience building activities, and could allow communities to use their natural resource base in a more efficient manner. Women and girls fetch water and fuel wood from distant sources, men plow fields with single blade, oxen-drawn plows, and access to electricity is extremely limited. Relatively simple, development-appropriate technologies ranging from improved cookstoves to household-level renewable energy sources to water purifiers have been identified as viable options for communities in Choke Mountain watersheds [6].

Climate Change: Choke Mountain watershed agricultural systems are highly vulnerable to negative impacts of climate variability [15]. As patterns of variability and precipitation intensity alter under anthropogenic climate change, there is concern that this vulnerability will increase, threatening economic development and food security in the region. A trend towards higher mean annual temperature has already been observed [5]. Agronomic studies of predicted future changes suggest that continued temperature increases on the order of 2.5 to 5.0 °C over the 21st century will have a significant negative impact on average crop net revenue per hectare across Choke Mountain watersheds. Participatory agroecosystem analysis indicates that sensitivity to climate variability and change is a major concern in all defined AES. Objective AES classification further demonstrates that prevailing climate conditions—and, presumably, changes in prevailing climate under climate change—play a strong role in defining the distribution of agroecosystems, such that climate change is likely to influence productivity in all agriculturally active AES.

4.5. Adaptation Strategies

AEA provides a lens for adaptation analysis that takes into account the geographical differentiation (climate, topography, soils, farming systems) as well as the socio-economic stratification of the agricultural sector of the study area. In addition to the prevailing climate change impacts, livelihoods in farming communities face severe constraints related to intensive cultivation, overgrazing and deforestation, soil erosion and soil fertility decline, water scarcity, livestock feed, and fuel wood. Through AEA, the productive potential and adaptive capacity of the each agroecosystem were characterized, and appropriate climate resilience building strategies have been identified. These proposed strategies are not intended to be conclusive, but they represent a reasonable starting point from which communities can continue to develop resilience building activities and adaptation plans. For the Choke Mountain watersheds, it is understood that climate resilient strategies must address both the challenge of present day climate variability and the potential for shifting agroecological conditions in a changing climate.

AES-specific strategies for climate resilient development in Choke Mountain watersheds, as informed by AES analysis and developed at a stakeholder workshop [5,6] were identified as:

AES 1 and AES 5: Biofarm system: This is a system of establishing permanent agriculture (Permaculture) that draws from several disciplines including organic farming, agroforestry, integrated farming, sustainable development, and applied ecology. It is an applicable strategy for AES 1 and AES 5, but with different technology packages in each. The main objective of bio-farming is to optimize agricultural outputs (vegetables, dairy products, honey, *etc.*) for use by the local community, while minimizing external inputs (like excessive water or chemically based fertilizers). Specific techniques include use of drought-tolerant, nitrogen-fixing trees such as Acacia species to rebuild the soil, fruit trees, vegetables and high value herbal crops as intercrops within cultivated fields, and improved water harvesting and retention (such as pools, dams, pits, retaining ridges, *etc.*) and water-use efficiency (irrigation systems) to increase production and address increasing irregularity of rainfall patterns (particularly in AES1, where water stress is a major concern). As climate change brings warmer conditions and potential shifts in precipitation, the water retaining properties of biofarm systems will be particularly valuable.

AES 2: Sustainable intensification by adopting vertisol management technologies: Vertisols cover close to 0.4 million hectares, continuously distributed in 4 major Woredas within AES 2. A proven suite of techniques that includes drainage, water harvesting for a second cropping season, crop rotation of wheat—chickpea—tef, soil fertility management, and targeted use of improved seed and chemical fertilizers has the potential to increase yields significantly in this fertile zone. Should climate change lead to hotter temperatures and more frequent drought stress in this region, robust water infrastructure for the proposed second cropping season will be required. Drainage will become even more important should predictions of intensified precipitation events be realized.

AES 3: Sustainable intensification using conservation agriculture technologies: Conservation Agriculture (CA) is an approach to managing agro-ecosystems for improved and sustained productivity, increased profits and food security while preserving and enhancing the resource base and the environment. CA is characterized by three linked principles, namely: continuous minimum mechanical soil disturbance, permanent organic soil cover and diversification of crop species grown in sequences and/or associations [30]. CA facilitates good agronomy, such as timely operations, and improves overall land husbandry for rainfed and irrigated production. Complemented by other known productivity enhancing practices, including the use of quality seeds, and integrated pest, nutrient, weed and water management, *etc.*, CA is a base for sustainable agricultural production intensification.

AES 4: Sustainable intensification by applying sloping land management technologies: In AES 4, an agroforestry based production system is recommended to sustain agricultural production on sloping lands. The goal of this strategy is to stimulate economic growth by developing new market opportunities for products, increasing utilization, and consumption of value-added products, and enhancing productivity and quality of crops through new technologies. Hedgerows are planted along contours of sloping land at intervals of four to six meters and various cereal crops and perennial cash plants are cultivated in the alleys. Hedgerows also act as effective barriers to soil erosion. Hedgerows can also be pruned several times a year, and the pruned leaves can be used as green manure or for composting. Crop rotation, tillage along contours, and use of compost and liming in addition to chemical fertilizers are also important components of sustainable management in this system.

AES 6: Bioreserve (protected area): The major focus of this strategy in the afroalpine zone is to develop a management plan to conserve biodiversity resources while providing some benefit sharing with the local communities. According to IUCN protected area categories, the Choke Mountains protected area would be "Category VI," *i.e.*, protected area managed mainly for the sustainable use of natural ecosystems.

In addition, there are a number of sustainable production systems that are recommended across AES 1–5. The home garden is the primary example of such a system. Though home gardens have existed since very early in Ethiopian agricultural history, they are in decline in Choke Mountain watersheds. This trend should be reversed, as the home garden provides an array of food sources, spices, and condiments, as well as medicinal plants, perfumes, and aromatic plants that play a role in traditional life. Home gardens can also be hotspots of biodiversity on the landscape.

The AES-specific land management strategies listed above are intended to build climate resilience under current patterns of climate variability, and with recognition for the fact that perceived increases and changes in the character of variability in recent years demand robust but flexible agricultural techniques. As agroecosystems migrate under climate change, a number of these resilience-building strategies can migrate with them. While techniques specific to particular soils or landforms will remain relevant within static geographies, those that are geared towards addressing rainfall variability or higher temperatures, for example through water management or crop and seed selection, can be adopted by new communities as climate conditions evolve.

5. Conclusions

An agroecosystem analysis (AEA) of Choke Mountain watersheds demonstrates the significant challenges associated with climate change adaptation in tropical highland environments. The great diversity of climate zones, physiographic settings, farming systems, and socioeconomic circumstances within this relatively small area require similarly diverse interventions to improve agricultural productivity and ensure sustainability in a changing climate. At the same time, AEA provides a tool for classifying the landscape into functionally similar systems, for characterizing potential and constraints within each system, and for developing adaptation strategies that are informed by local-scale analysis and community priorities. In this application, AEA also provided the foundation for an automated landscape classification trained using AEA field survey. This automated algorithm provides more limited information, but it offers a tool for mapping and projecting the physical aspects of each agroecosystem across the study area and over changing climate conditions.

A critical challenge that cuts across agroecosystems in Choke Mountain watersheds is the need to achieve realizable production potentials to the extent possible. Improving agricultural productivity is the key for ecological sustainability in Choke Mountain watersheds because productivity growth is the most sustainable mechanism to maintain the ecosystem goods and services of the mountain watersheds. It is potentially possible to increase agricultural production by putting natural forest, grazing and wetlands into cultivation, but the sustainability of systems that continue to encroach on these natural lands is questionable. Agricultural technologies such as improved seeds, fertilizer application, irrigation and soil and water conservation have a central place in enhancing agricultural productivity where utilized appropriately and efficiently.

The sustainable intensification of agricultural production, considering the challenges and opportunities of the different agroecosystems, can ensure food security and contribute to climate change adaptation by reducing deforestation and the encroachment of agriculture into natural ecosystems. The overall efficiency, resilience, adaptive capacity, and mitigation potential of the production systems can be enhanced through sustainable land management.

AEA offers a method for classifying the landscape and for identifying agroecosystem-specific constraints and opportunities for climate change adaptation. The analysis reported in this paper yielded a classification of six different agroecosystems in Choke Mountain watersheds. Adaptation strategies specific to each have been developed in consultation with local communities: bioreserve (protected area) for AES 6, permacalture (biofarm system) for AES 1 and 5, sustainable intensification by applying sloping land management technologies for AES 4, sustainable intensification by adopting Vertisol management technologies for AES 2 and sustainable intensification using conservation agriculture technologies for AES 3. In each case, the proposed land management techniques have been selected with consideration for present day climate resilience and robustness to changing conditions.

These resilience building strategies are processes that require time, investment and the engagement of a wide range of stakeholders at multiple levels and in multiple sectors, and there is certainly much work ahead. Participatory agroecosystem analysis has, however, provided communities of Choke Mountain watersheds and relevant development agencies with a robust foundation for this work. In this respect, adaptation planning in Choke Mountain watersheds already provides a model for other regions in Ethiopia and, potentially, subsistence agriculture communities contending with climate change in other countries and regions.

Conflict of Interest

The authors declare no conflicts of interest.

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