

Article

Modeling Cultural Keystone Species for the Conservation of Biocultural Diversity in the Afroalpine

Shambel Alemu Chengere^{1,*} , Cara Steger², Kflay Gebrehiwot³ , Sileshi Nemomissa¹
and Bikila Warkineh Dullo¹ 

¹ Department of Plant Biology and Biodiversity Management, College of Natural and Computational Sciences, Addis Ababa University, Addis Ababa P.O. Box 3434, Ethiopia

² Department of Natural Resources and Environment, Cornell University, Ithaca, NY 14850, USA

³ Department of Biology, Samara University, Semera P.O. Box 132, Ethiopia

* Correspondence: shambel.alemu@aau.edu.et; Tel.: +251-91-216-5150

Abstract: Climate warming threatens the future sustainability of mountains, and tropical mountains are particularly threatened with loss of biodiversity and associated ecosystem services. Conservation biologists increasingly turn to habitat suitability models to guide the establishment and assessment of protected area networks to protect the highest number of species, yet this focus often neglects the values, attitudes, and beliefs of the people living around protected areas. If we consider protected areas as dynamic social–ecological systems, habitat suitability modeling for conservation planning must pay greater attention to the role of biocultural diversity, rather than biodiversity alone. Here, we describe a conservation assessment of the Afroalpine grassland ecosystem in the northern highlands of Ethiopia. We use a cultural keystone species known as guassa grass (*Festuca macrophylla*) to focus our modeling efforts and evaluate the potential distribution of this endemic species in relation to current national and community-based protected areas. Our model performed highly according to the area under the curve (AUC = 0.96), yet nearly 80% of highly suitable guassa habitat falls outside the range of our training data and thus must be interpreted conservatively. We found that guassa grass distribution is primarily limited by low mean temperature in the warmest quarter (BIO10, 36.7%), high precipitation in the wettest quarter (BIO16, 21%), and low precipitation in the driest quarter (BIO17, 15.6%). As climate change causes rapid warming at high elevations and alters rainfall patterns in the Ethiopian highlands, we urge managers to carefully monitor the changing populations of guassa grass to evaluate whether the species is experiencing an extinction debt. We also recommend four additional areas as potential community-based conservation areas, with government and NGO support for peer-to-peer communication networks. Spatially explicit modeling may be a valuable tool to determine whether these existing and proposed protected areas can sustain future populations of guassa grass.

Keywords: social–ecological systems; climate change; grassland; MaxEnt model; community-based conservation areas; extinction debt



Citation: Chengere, S.A.; Steger, C.; Gebrehiwot, K.; Nemomissa, S.; Dullo, B.W. Modeling Cultural Keystone Species for the Conservation of Biocultural Diversity in the Afroalpine. *Environments* **2022**, *9*, 156. <https://doi.org/10.3390/environments9120156>

Academic Editor: Christine Fürst

Received: 25 March 2022

Accepted: 1 May 2022

Published: 16 December 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Mountain systems provide essential ecosystem services to the world yet are disproportionately threatened by climate change [1–5]. Mountains occupy ~30% of the global land mass [6] and may contain up to 28% of the world's human population [7] yet support an astonishing 85% of the world's amphibian, bird, and mammal species [8]. Mountains contribute approximately twice as much total runoff to the world's freshwater supply than would be expected based on their share of surface area and serve as critical “water towers” in arid and semiarid climates [9]. Hydrological processes in mountains are already being altered by global environmental change, with continued changes expected in the timing, volume, and variability of water [4]. Climate warming threatens the future

sustainability of mountain systems as most species ranges continue to shift upward in elevation [10,11], increasing competitive pressures on mountain species with as-yet-unknown consequences [12–17]. Warming appears to be amplified at higher elevations, causing more rapid and disproportionately intense change for mountains compared to lowlands [18].

Tropical mountains are particularly threatened with loss of biodiversity due to their high baseline levels of diversity [8], endemism [19], and rarity [20,21]. In Africa, the Afroalpine ecosystem occurs over 3000 m above sea level and is confined to a mosaic of mountains and plateaus that form isolated “sky-islands” separated by extensive savannas, semi-deserts, agricultural areas, and other social–ecological barriers [22]. The highlands of Ethiopia occupy an estimated 658,551 km² (58.2% of the country), based on our calculations using the Albers equal area conic projection and a geospatial mountain delineation [7]. Nearly half of these highlands are “high mountains” that can support Afroalpine vegetation [23,24]. The highlands support the livelihoods of millions of Ethiopians and provide water to hundreds of millions of additional downstream users (e.g., by providing over 70% of the Nile River flow [25]). The Ethiopian highlands are severely threatened by climate and land use change [21]. Despite their ecological and economic importance, and the imminent threats they face from global environmental change, our calculations place only 15% of the high mountains of Ethiopia within protected areas.

Conservation biologists are increasingly turning to habitat suitability models, also known as species distribution models, to guide the establishment and assessment of protected area networks [26–30]. Referred to as systematic conservation planning [29] or regional conservation planning [31], this two-step process typically involves modeling distributions of large numbers of species (hundreds to thousands) or species assemblages and then using algorithms to select locations that maximize biodiversity representation with as little land as possible [27,30,32]. These conservation planning processes are often considered a more time- and cost-effective approach than modeling individual species [31]. However, this focus on protecting the highest level of biological diversity ignores the values, attitudes, and beliefs of the people living in or around protected areas. The failures of top-down “fortress conservation” are well-documented [33,34], and even efforts in community-based conservation have often fallen short of their people-oriented goals [35]. Despite these challenges, there is increasing agreement that we must consider protected areas as dynamic social–ecological systems [36–38].

We argue that habitat suitability modeling for conservation planning must pay greater attention to the role of biocultural diversity, rather than biodiversity alone, to realize the benefits of a social–ecological approach to protected area design and evaluation. Biocultural diversity has been defined as the “diversity of life in all its manifestations—biological, cultural and linguistic—which are interrelated within a complex socio-ecological adaptive system” [39]. It refers to the interconnectedness of human cultures and the biophysical environments in which they exist [39–41]. Early efforts to integrate biocultural diversity into conservation planning focused on standardization and measurement of cultural diversity (i.e., through language, ethnicity, or religion) for protected area conservation [42,43]. An analysis of the diversity of language and vascular plants found that mountains have some of the highest rates of biocultural diversity when examined at a global scale [44]. However, these indicators are less useful for examining biocultural diversity at a local scale; when cultural diversity might take the form of diverse social constructions of meaning that require qualitative inquiry and whose complexity cannot be adequately or ethically represented in a scientific model [45,46]. While ethnographic understanding of culture is therefore necessary to analyze biocultural diversity at a local scale, there is still a role for modeling to extend this understanding to broader scales.

The concept of cultural keystone species can be a useful proxy for integrating biocultural diversity into habitat suitability modeling. Cultural keystone species are “species whose existence and symbolic value are essential to the stability of a cultural group over time” [47]. Cultural keystone species are often used intensively and for multiple purposes [48]. For example, cocoa has been described as a cultural keystone species in the

Amazon for its roles in facilitating the transmission of cultural knowledge between generations and mediating communication with spiritual beings [47]. Some criteria for cultural keystone species may include the species having a central role in (a) community origin stories, narratives, or myths; (b) the transmission of cultural knowledge; (c) community rituals, songs, or dances; (d) supplying basic needs such as food or shelter; or (e) defining the biophysical landscape [47,48]. Cultural keystone species are often described as important to the community for either spiritual, symbolic, or physical reasons, and are often difficult or impossible to replace [47,48]. Crucially, cultural keystone species are often also ecologically valuable and have a disproportionate impact on the conservation of other species in the system [47]. Therefore, we propose that habitat suitability modeling might focus on the distributions of cultural keystone species as surrogates for broader scale biocultural diversity [31,47].

In this paper, we focus our efforts on a conservation assessment of the Afroalpine grassland ecosystem that uses a cultural keystone species to drive our modeling efforts and evaluate the potential distribution of this species in relation to current national and community-based protected areas. The endemic guassa grass (*Festuca macrophylla*) is thought to have evolved around 290–300 thousand years ago in the northern highlands of Ethiopia [22], during a time of rapid technological and cultural evolution amongst early humans [49,50]. Contrary to long-held beliefs that high elevations were inhospitable to early humans, stone tools dating to the same era have been found in the Ethiopian highlands [51,52]. This shared evolutionary heritage of humans and guassa grass is compelling, as the guassa grass has become a cultural keystone species for modern people living in the Ethiopian highlands—so much so that the first community conservation area in Ethiopia was named in its honor [53]. Previous research in this area has revealed the central role of guassa grass in the social, economic, and political lives of people [53,54]. The guassa grass is celebrated for its length and strength, and is used to thatch roofs, construct ropes, plaster walls, and craft a wide variety of other cultural items such as mattresses and parkas [54]. The presence of guassa grass is said to have inspired the original establishment of the conservation area, which has become a site of contested cultural and political control throughout its history [53,54]. Ecologically, the guassa grass shares functional traits with other tussock grasses in the tropical alpine zone, contributing to carbon sequestration, freshwater supply and regulation, and supporting highly diverse flora and fauna [55,56].

The purpose of this paper is to (a) model the habitat suitability of guassa grass across the Ethiopian highlands, and to (b) evaluate the current extent of suitable guassa habitat contained within protected areas as a measure of biocultural diversity protection in the Afroalpine. Below, we describe the study area and modeling process. We focus our results on the ecological and geospatial insights gained from modeling the habitat suitability of a cultural keystone species. We then discuss these results in relation to the potential future sustainability of the guassa grass and propose how additional ecological research and community-based initiatives can contribute to the continued conservation of this valuable social–ecological resource.

2. Methods

2.1. Area of Study

Three protected areas currently serve as strongholds for the guassa grass and associated Afroalpine vegetation in the northern Ethiopian highlands (Figure 1), and all three are located in the Amhara Region of Ethiopia: Simien Mountains National Park, Guassa Community Conservation Area, and Abune Yosef Community Conservation Area. Extensive ethnographic work has been conducted in the Guassa Community Conservation Area, revealing the role of guassa grass as a cultural keystone species [53,54].

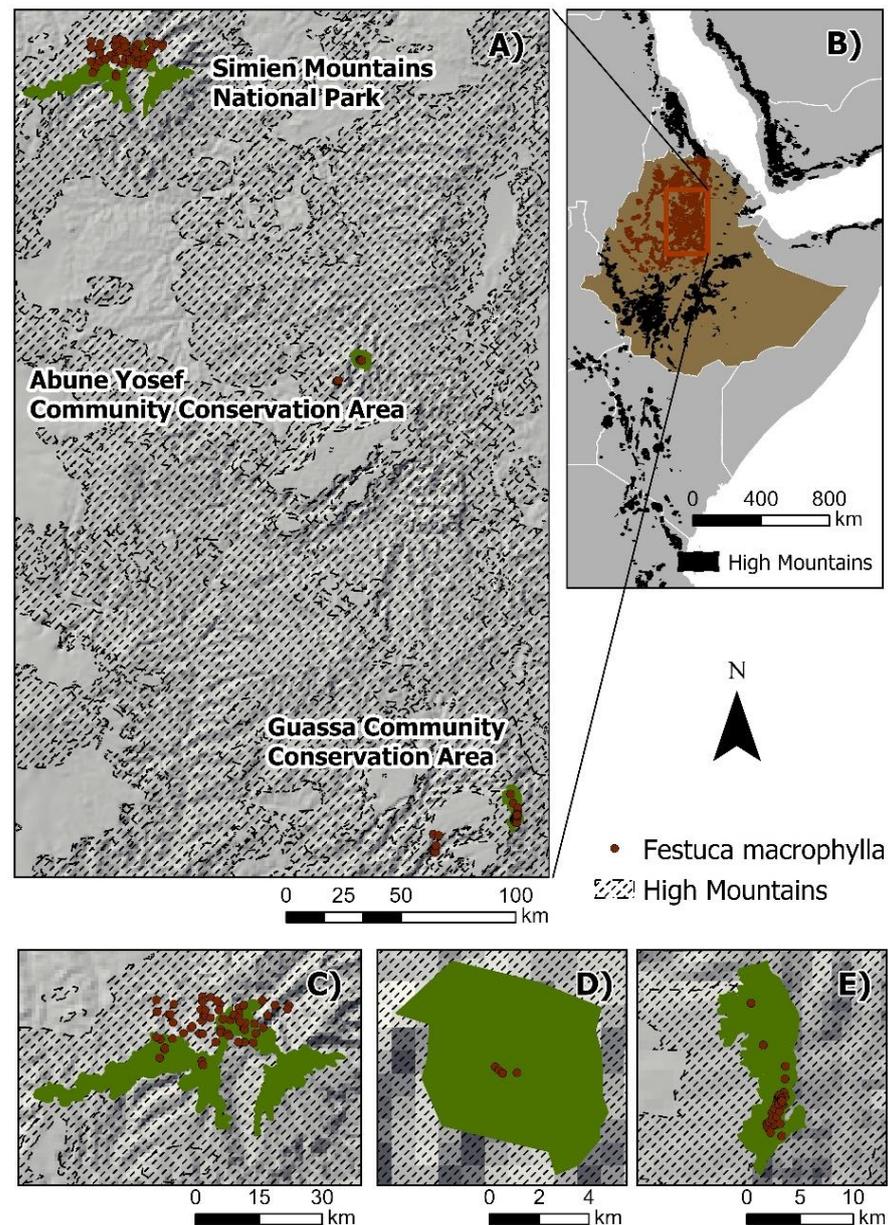


Figure 1. Map depicting (A) three protected areas where guassa grass (*F. macrophylla*) is currently found, (B) the location of these areas in the country of Ethiopia and the broader Horn of Africa context, (C) the distribution of guassa grass observations in Simien Mountains National Park, (D) the distribution of guassa grass observations in Abune Yosef Community Conservation Area, and (E) the distribution of guassa grass observations in Guassa Community Conservation Area.

Simien Mountains National Park (SMNP; 486 km²) was established in 1969 primarily to protect the endemic *Walia ibex* (*Capra walie*). The SMNP is home to Ethiopia's highest peak, Mount Ras Dejen (4540 m). The climate of SMNP is characterized by frequent frosts, occasional high-altitude snowfall, and frequent hailstorms [57]. The daily mean temperature varies between a minimum of 1.5 °C and a maximum of 14.6 °C [58]. Precipitation in SMNP follows a unimodal rainfall pattern with high average annual rainfall (around 1500 mm). In 1978, SMNP was listed as a World Heritage Site; however, it became a World Heritage Site in Danger in 1997 due to increased anthropogenic pressure and declines in iconic species such as the *Walia ibex*. The number of tourists to the SMNP has increased in recent years, which has enhanced conservation funding while also presenting new challenges for regulating tourist impacts on the environment [59].

The SMNP can be divided into three distinct vegetation belts: the montane forest belt, the transitional ericaceous belt, and the uppermost Afroalpine belt [60,61]. The montane forest belt is rich in species, with large trees such as *Prunus africana*, *Hagenia abyssinica*, and *Olea europaea* [62]. The transitional ericaceous belt includes the shrubs *Erica arborea* and *Hypericum revolutum* in low altitudes [63]. The Afroalpine zone contains Afroalpine grasslands scattered with giant lobelias (*Lobelia rynchopetalum*) and various types of low and tall grass steppes (*F. macrophylla*, *Carex monostachya*) and wetlands [58,64]. In addition to the Walia ibex, SMNP is home to several endemic species such as Ethiopian wolf (*Canis simensis*) and Gelada baboon (*Theropithecus gelada*), many of which are endangered due to habitat fragmentation and destruction due to anthropogenic impact [65,66].

The Guassa Community Conservation Area (GCCA; 79 km²) and the Abune Yosef Community Conservation Area (AYCCA; 46 km²) are both community conservation areas with rich histories of traditional environmental management [53,54,67]. GCCA was officially recognized by the Ethiopian government in 2012 and AYCCA in 2014. Both community conservation areas were created in collaboration with Frankfurt Zoological Society and were largely promoted as protected areas for the endemic and endangered Ethiopian wolf (*C. simensis*). Both areas have a bimodal precipitation regime, with short rains in the early spring (February to April) and long rains in (June to September) [68]. The mean monthly minimum temperature of GCCA was 5 °C, and the maximum was 20 °C, while at AYCCA they were 4 °C and 26 °C, respectively [69]. The vegetation of GCCA and AYCCA is characterized by high Afroalpine plant species such as the genera *Alchemilla*, *Helichrysum*, *Senecio*, *Carex*, *Festuca*, and the endemic giant Lobelia (*Lobelia rynchopetalum*) and *Kniphofia foliosa*. Both areas are also rich in biodiversity and contain several endemic species of fauna, including the Ethiopian wolf (*C. simensis*) and the Gelada baboon (*T. gelada*) [53,69].

The altitude of GCCA varies from 3200–3700 m a.s.l. The climate also varies widely due to the differences in elevation and size of mountain block [68]. Temperatures are characterized by mild days and cold nights. In the drier months (December to February), daytime temperatures can rise to 25 °C, while night-time temperatures can drop to −7 °C. The area receives its name from the “guassa grass” (*F. macrophylla*), which is highly valued by the local community. People often describe guassa as “our clothes, our food, our everything”, and recount the cultural responsibility they have to protect the area for future generations. The GCCA is currently managed by nine farmers’ associations, local institutions that were created throughout Ethiopia in 1975 for rural administration. However, the area has been managed according to a traditional management system known as Qero for at least 400 years [53]. The community protects the area through various regulations that control the access of natural resources by the communities [70].

Prolonged volcanic activity has led to the creation of high mountains in northern Ethiopia that include some of the highest peaks, such as Abune Yosef [71], which reaches 4284 m a.s.l. The soils are predominantly Andosols and Vertisols [69]. Elevations above 3500 m a.s.l are considered potential Afroalpine grasslands; however, because much of this land has been turned into agricultural land, these grasslands can only be found above 3700 m a.s.l. In the region around AYCCA, agricultural practices are not uncommon at an altitude of almost 3800 m a.s.l. [72].

2.2. Species Occurrence Data

We compiled a dataset of 119 occurrence points (Figure 1) from a range of sources. Data were collected during field visits to the Guassa Community Conservation Area in 2016, 2018, and 2020 ($n = 48$) and Abune Yosef Community Conservation Area in 2017 and 2018 ($n = 11$). Furthermore, occurrence data were retrieved from the Global Biodiversity Information Facility (GBIF) collected for the Natural History Museum of Oslo in 2007 ($n = 6$) and specimens of the National Herbarium of Ethiopia ($n = 19$), and various other published sources, including GBIF and JSTOR ($n = 35$). These data are available in Supplementary Materials.

2.3. Environmental Predictors

We used 24 variables for predicting suitable habitats of guassa grass. The 19 bioclimatic variables and average annual solar radiation data were downloaded from WorldClim (www.worldclim.org, accessed on 29 July 2021) at $\sim 1 \text{ km}^2$ (30 arc second) resolution [73]. Furthermore, elevation, aspect (sine and cosine), slope, and topographic position index variables at 1 km^2 were derived from a 250 m GMTED digital elevation model [74]. We processed the variables to the spatial extent of the northern highlands of Ethiopia, and calculated correlations between variables using Band Statistics in ArcGIS Pro 2.8. We removed variables until there were no correlations >0.7 and retained 11 predictors ($r < 0.7$) with the highest ecological relevance to the guassa grasses [75,76]. We acknowledge that our focus on biophysical predictor variables overlooks the critical role of social drivers of change in determining species distributions. Unfortunately, we were unable to include social variables at the same scale and resolution of these environmental predictors.

2.4. Model Selection

We used the software MaxEnt [77,78] due to the opportunistic nature of our dataset, composed of presence-only locations. MaxEnt consistently performs well compared to other modeling approaches [79] and has been used in across a wide range of ecological conditions in global [80] to highly local [81] applications. For example, Maxent has shown promise as a conservation planning and management tool when predicting suitable habitat for threatened, endemic, and endangered species [82,83], anticipating the spread of invasive species [84,85], and forecasting potential impacts of climate change [86,87].

The background area of the model exerts a strong influence on the final predictions in MaxEnt [76,88]. It is recommend to [76,89] select a background sample that reflects only the environmental conditions where the species is equally likely to reach via dispersal. As the guassa grass is endemic to the northern highlands of Ethiopia, we restricted our background sample to only the high mountains in the Ethiopian massif, which, at $154,600 \text{ km}^2$, occupies roughly half the land in the northwest corner of the country (Figure 1). Furthermore, other Afroalpine areas may have been suitable habitats but the grass has been historically limited to the northern mountains. This restriction is not only more ecologically realistic, but it has the further benefit of focusing the model at a scale that is more relevant to managers [88].

We evaluated model performance using the area under the receiver–operating characteristic curve (AUC). We tested a range of regularization coefficients but found that the default of 1 yielded the highest AUC and most realistic prediction patterns [76]. The regularization parameter balances overfitting with generalizability in the model, and previous research has shown that the default value of 1 is not always optimal for all species [78,90,91]. We fitted each model on the full dataset using 10-fold cross-validation to estimate predictive performance on the withheld 10% of data [90]. We used a jackknife test to evaluate the relative contributions of each environmental predictor and to rank variable importance for guassa grass habitat suitability. As a result of this testing, we further refined our environmental variables to only the six that showed strong ($>5\%$) contribution to the predictions and useful ecological insight (Table 1). This additional reduction in predictor variables yielded the most parsimonious model without materially impacting the AUC. We selected the logistic output for the model, as it produced a more conservative estimate of probability of guassa grass occurrence than the default cloglog transformation at high values [92]. We classified the predicted output into five categories: unsuitable (0–0.2), low suitability (0.21–0.40), moderate suitability (0.41–0.6), suitable (0.61–0.8), and highly suitable (0.81–1.0) habitats.

Table 1. Six environmental predictors, their ecological significance for modeling suitable habitat for guassa grass (*F. macrophylla*), and their percent contribution to final model predictions.

Variable	Description	Ecological Significance	Percent Contribution
BIO10	Mean temperature of the warmest quarter	Afroalpine vegetation is found in cold climates [24]	36.7
BIO16	Total precipitation of wettest quarter	The wettest months are typically June through September. Afroalpine vegetation is found in wet conditions [93].	21
BIO17	Total precipitation of driest quarter	The driest months are typically December through February. Desiccation stress and fire occurrence during these months are thought to favor grasses over shrubs in the Afroalpine [94].	15.6
SLOPE	Rate of change of elevation in magnitude	Guassa grass is thought to prefer steep to moderately steep slopes [68].	9.9
BIO2	Mean diurnal range: mean of monthly (max temp – min temp)	Afroalpine vegetation has evolved under conditions of high daily temperature fluctuations, known as “summer every day and winter every night” [95,96]. Diurnal fluctuations are typically greater during the dry season.	9.4
BIO19	Total precipitation of coldest quarter	Afroalpine vegetation is thought to persist in areas of low temperature and high moisture [68,97].	7.4

3. Results

The average test AUC across the 10 replicate model runs was 0.96 (SD \pm 0.02). The most important predictor was BIO10 (mean temperature of the warmest quarter) with a contribution of 36.7%, followed by BIO16 (precipitation of wettest quarter) at 21%, BIO17 (precipitation of driest quarter) at 15.6%, slope at 9.9%, BIO2 (mean diurnal range) at 9.4%, and BIO19 (precipitation of the coldest quarter) at 7.4%. The marginal response curves illustrate the species–environment relationship defined by the model, where mean temperatures in the warmest quarter below 15 °C support higher probabilities of guassa grass presence (Figure 2a). A sharp distinction between wet and dry seasons appears to also be a critical ecological factor in suitable guassa grass habitat, as high precipitation in the wet season (>730 mm) and low precipitation in the dry season (<15 mm) were the next most influential variables (Figure 2b,c). Our results suggest that guassa grass is more suited to higher slopes (above 15%), and to a mean diurnal range of roughly 12–15 °C (Figure 2d,e). Finally, precipitation in the coldest quarter appears to exert a small influence on our predictions, with higher guassa grass habitat probability between 100–600 mm (Figure 2f).

Our results estimated 591 km² of highly suitable habitat for guassa grass, less than half of one percent of the total northern highlands land area. Only 53 km² (8.9%) of highly suitable guassa grass habitat and 170 km² (18.3%) of suitable guassa habitat currently fall within a protected area. Notably, 294 km² (49.7%) of the highly suitable habitat is in South Wollo, and 177 km² (30%) of the highly suitable habitat is located on Mount Choke (Table 2). These areas are the most dissimilar to our predictor variable training range, and Mount Choke, in particular, is completely outside the training range of one or more of our environmental predictor variables. Therefore, both of these estimates should be treated with

strong caution, and likely represent an overestimate of highly suitable guassa grass habitat. A total of 930 km² were identified as suitable habitat (0.6% of the northern highlands), and 1069 km² of moderately suitable habitat (0.7% of the northern highlands). The vast majority of the northern highlands are either low suitability (2040 km²) or unsuitable (149,629 km²) guassa grass habitat.

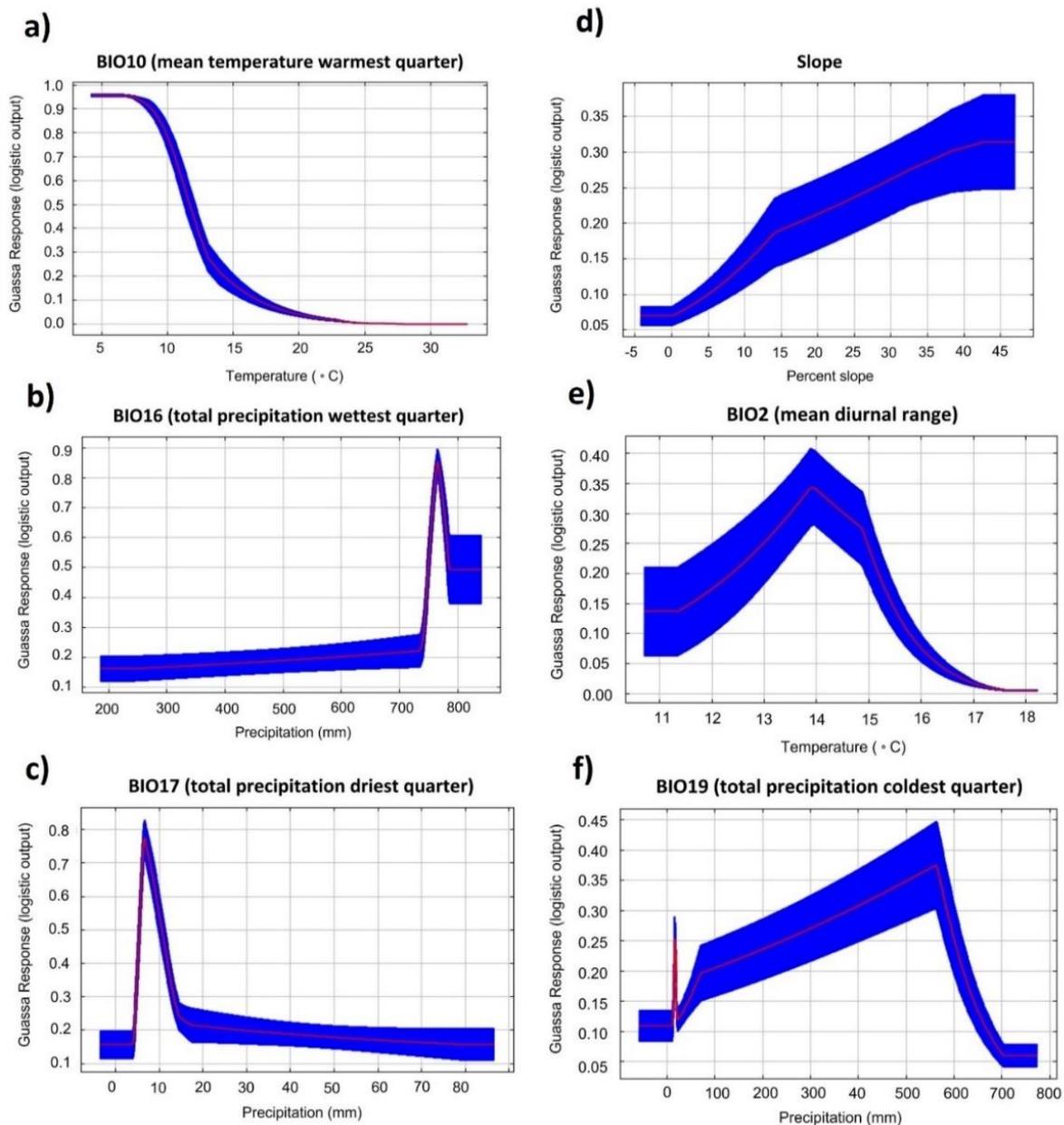


Figure 2. Marginal response curves showing how each environmental variable impacts the final model prediction for suitable guassa grass habitat. Each curve shows how the predicted probability of guassa presence changes as each variable increases (with all other variables held at their mean value). The variables include: (a) BIO10, the mean annual temperature of the warmest quarter, (b) BIO16, the total precipitation of the wettest quarter, (c) BIO17, the total precipitation of the driest quarter, (d) the slope (in percent), (e) BIO2, the mean diurnal temperature range, and (f) BIO19, the total precipitation of the coldest quarter.

Table 2. Three existing protected areas and four proposed protected areas, describing the land area that falls within each class of suitable guassa grass habitat and what percent of the protected area that covers.

Name	Unsuitable	Low Suitability	Moderate Suitability	Suitable	Highly Suitable
Existing Protected Areas					
Simien Mountains National Park	81 km ² (16.5%)	113 km ² (23.0%)	132 km ² (26.9%)	134 km ² (27.3%)	31 km ² (6.3%)
Guassa Community Conservation Area	6 km ² (7.5%)	7 km ² (8.8%)	15 km ² (18.8%)	30 km ² (37.5%)	22 km ² (27.5%)
Abune Yosef Community Conservation Area	14 km ² (29.8%)	8 km ² (17.0%)	19 km ² (40.4%)	6 km ² (12.8%)	0 km ² (0%)
Potential Protected Areas					
Mount Choke	21 km ² (6.6%)	49 km ² (15.5%)	35 km ² (11.0%)	35 km ² (11.0%)	177 km ² (55.8%)
South Wollo	59 km ² (8.1%)	40 km ² (5.5%)	59 km ² (8.1%)	278 km ² (38.1%)	294 km ² (40.3%)
Mount Guna	6 km ² (6.7%)	6 km ² (6.7%)	33 km ² (37.1%)	34 km ² (38.2%)	10 km ² (11.2%)
Ankober	7 km ² (6.1%)	8 km ² (7.0%)	30 km ² (26.3%)	65 km ² (57.0%)	4 km ² (3.5%)

4. Discussion

This paper models the habitat suitability of a cultural keystone species, guassa grass (*Festuca macrophylla*), across the northern Ethiopian highlands. We summarize the biophysical conditions that appear to support the guassa grasses and evaluate the current extent of suitable habitat, outlining four additional areas that could be targeted for guassa grass conservation. Based on these results, we propose that additional ecological research is needed to understand whether the guassa grasses are facing extinction due to accelerated warming at high elevations. We also suggest that future conservation efforts should focus on community-centered initiatives, as biocultural diversity conservation must integrate both cultural and ecological values.

4.1. Evaluating the Extinction Debt of Guassa Grass

Climate change threatens the equilibrium of Afroalpine vegetation as warming temperatures at high elevations allow for new species to colonize and/or dominate [98,99], driving others to extinction [100]. The expansion of agriculture and rangelands to support additional human communities on what was once considered inhospitable lands further restricts available land for Afroalpine vegetation [68]. Our results indicate that guassa grass will be sensitive to these warming temperatures as the ideal habitat for the grasses lies in areas with average maximum temperatures under 15 °C. Our results also suggest that guassa grass distribution is attuned to seasonal precipitation patterns, and there is mounting evidence that early spring rains are declining or disappearing across the Ethiopian highlands [101–103].

These habitat modifications may already be causing an extinction debt for guassa grass, which is the idea that there is a time lag whereby extinctions can occur over a considerable amount of time following perturbation [104–106]. Extinction debt is thought to be “paid off” faster in landscapes such as the Afroalpine that have small, isolated patches [107]. In grasslands, it is estimated that extinction debt occurs when less than 10% of the original grassland area remains [108]. While we have qualitative knowledge of declining guassa grass habitat from local ecological knowledge in the GCCA [54], there are no quantitative historical datasets that would allow us to evaluate whether current guassa grass habitat has exceeded this 10% threshold or not.

Without access to historical data, one of the most promising ways to empirically assess extinction debt is through spatially explicit modeling for single species [107,109]. Data on population growth rates across reference sites can be integrated into metapopulation models, which often take the form of patch occupancy models, cellular automata, and individual- or agent-based models [110,111]. These models can then be used to inform protected area management. For example, these models can identify minimum viable metapopulation sizes based on the required habitat area for populations to persist over 95% of model simulations [111]. We propose that spatially-explicit modeling would be a valuable tool to determine whether existing and proposed protected area networks would sustain future populations of guassa grass. However, extensive habitat surveys and demographic data are still needed before such models can occur. A critical barrier to collecting this data is the lack of funding for basic vegetation monitoring.

4.2. A Community-Based Conservation Network for Afroalpine Biocultural Diversity

Our results indicate there is extremely limited suitable habitat for guassa grass, and even our estimates are likely slightly inflated. We therefore propose four additional areas that should be considered for establishment as protected areas. However, we recognize that many conservation activities in Ethiopia have fallen short of their goals [112], even when they were nominally community-based initiatives [68]. Therefore, we stress that the locations in Figure 3 are intended as starting points for community-centered investigations into their suitability as protected areas. In some places, such as the Choke Mountains, these conversations have already started [113,114]. Though the two community conservation areas in our study have only been officially recognized by the government for ~10 years, the Indigenous management of these areas has persisted for hundreds of years, particularly in GCCA. We therefore propose that establishing a series of community-based conservation areas with strong peer-to-peer networks of communication and resource exchange is preferable to the creation of government-administered national parks.

A persistent shortcoming of community-based conservation is the lack of motivation and empowerment of local communities to take ownership over the area [72,115]. Granting communities official land tenure plays a critical role in overcoming this barrier, as people hesitate to spend time managing an area that might be taken away from them [104,116]. However, community motivation has also been shown to lag when the conservation narrative focuses too strongly on wildlife protection and discounts or ignores cultural values [117,118]. Meanwhile, community-based conservation that celebrates cultural knowledge and values has been shown to promote joint social and ecological benefits [119,120]. The cultural relationship between the people in Amhara Regional State and the guassa grass is therefore a unique and valuable characteristic of this area that can be leveraged for greater community empowerment towards conservation.

Effective community-based conservation areas require nested levels of governance that connects institutions both laterally and vertically [121]. Nongovernmental organizations have a key role to play, largely through start-up funding, technical training, and institutional support for knowledge sharing across individual community-based conservation areas [122,123]. A study of community-based conservation areas in the Oromia region of Ethiopia demonstrated that local governments are also expected to be active participants in community-based conservation areas and are especially needed to support collective action over individual rights. This focus on collective action should also strive to overcome problems of unequal distribution of benefits and reduced social capital, which are widespread issues in African community-based conservation [123].

In community conservation areas, as in the case of guassa area, the ultimate goal of species distribution modeling (SDM) is to create future information about species distribution. The (SDM's) findings will encourage conservationists to develop and use coping mechanisms. The suitable region of the species' geographical range for guassa grass is limited, according to the current findings. Environmental plans must be based on research findings and recommendations. The government and stakeholders must focus on

conserving and planting rare and this endemic species on their native areas. Moreover, conservation area would have an effect on safeguarding other treated plants and facilitating the establishment of additional species from seed banks [124,125].

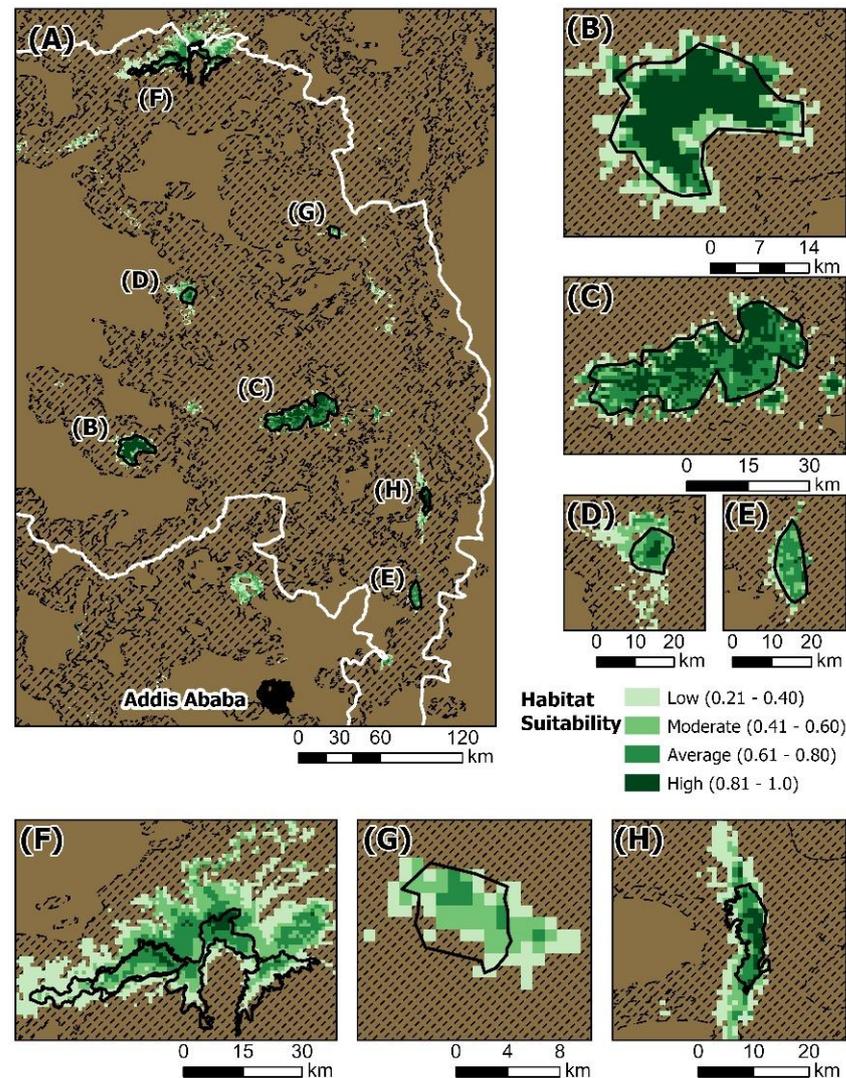


Figure 3. Map of predicted guassa grass habitat suitability, showing the distribution of habitat (A) throughout the state of Amhara (outlined in white), (B) on Mount Choke, (C) in South Wollo, (D) on Mount Guna, (E) around Ankober, (F) in and around Simien Mountains National Park, (G) in and around Abune Yosef Community Conservation Area, and (H) in and around Guassa Community Conservation Area. Boundaries for (B–E) indicate potential protected areas, while (F–H) represent existing protected areas.

5. Conclusions

In this paper, we sought to model the habitat suitability of guassa grass (*F. macrophylla*) across the northwestern Ethiopian highlands, evaluating the current extent of guassa grass habitat that is currently contained within protected areas. Our results indicate very limited areas of suitable habitat for guassa grass, leading us to define only four additional regions for consideration as protected areas. Thus, we discussed concerns over the future persistence of the guassa grass as continued habitat modification, climate change, and species invasion threatens these isolated sky-islands. The guassa grass is a cultural keystone species for certain areas within the Amhara Regional State, and we propose that building a network of community-based conservation areas with strong peer-to-peer

learning, open communication, and resource sharing may facilitate the future protection of the bioculturally diverse Afroalpine.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/environments9120156/s1>, Table S1: Occurrence data for *Festuca macrophylla*.

Author Contributions: Conceptualization, S.A.C., C.S., S.N. and B.W.D.; methodology, S.A.C., C.S., S.N. and B.W.D.; software, S.A.C., C.S., S.N. and B.W.D.; validation, C.S., K.G., S.N. and B.W.D.; formal analysis, S.A.C. and C.S.; investigation, S.A.C., C.S., K.G., S.N. and B.W.D.; resources, S.A.C., C.S. and B.W.D.; data curation, S.A.C., C.S. and K.G.; writing—original draft preparation, S.A.C. and C.S.; writing—review and editing, C.S., K.G., S.N. and B.W.D.; visualization, C.S., K.G., S.N. and B.W.D.; supervision, C.S., K.G., S.N. and B.W.D.; project administration, S.A.C. and C.S. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by funding from The Rufford Foundation (# 23171-2 and 27885-1) and the U.S. National Science Foundation through a Geography and Spatial Sciences Doctoral Dissertation Research Improvement Award (NSF # 1821288). The APC was funded by Cornell University.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data are included in Supplementary Materials.

Acknowledgments: The authors acknowledge the financial support from The Rufford Foundation (# 23171-2 and 27885-1). This work was also supported by funding from the U.S. National Science Foundation through a Geography and Spatial Sciences Doctoral Dissertation Research Improvement Award (NSF # 1821288). We are so grateful to Cornell University for funding the APC. We are sincerely thankful to the Department of Plant Biology and Biodiversity Management, Addis Ababa, Ethiopia, for the financial support from the Thematic Research fund throughout the work and for all the necessary research permissions. We thank the communities of Guassa Community Conservation Area and Abune Yosef Community Conservation Area for their assistance and permission in gathering the species location data.

Conflicts of Interest: The authors declare no conflict of interest.

References

- Grabherr, G.; Gottfried, M.; Pauli, H. Climate effects on mountain plants. *Nature* **1994**, *369*, 448. [[CrossRef](#)] [[PubMed](#)]
- IPCC. *Climate Change: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2007.
- Lenoir, J.; Gegout, J.C.; Marquet, P.A.; De Ruffray, P.; Brisse, H. A significant upward shift in plant species optimum elevation during the 20th century. *Science* **2008**, *320*, 1768–1771. [[CrossRef](#)] [[PubMed](#)]
- Loeffler, J.; Anschlag, K.; Baker, B.; Finch, O.D.; Diekkruieger, B.; Wundram, D.; Schroeder, B.; Pape, R.; Lundberg, A. Mountain ecosystem response to global change. *Erdkunde* **2011**, *65*, 189–213. [[CrossRef](#)]
- Klein, J.A.; Tucker, C.M.; Steger, C.E.; Nolin, A.; Reid, R.; Hopping, K.A.; Yeh, E.T.; Pradhan, M.S.; Taber, A.; Molden, D.; et al. An Integrated community and ecosystem-based approach to disaster risk reduction in mountain systems. *Environ. Sci. Policy* **2019**, *94*, 143–152. [[CrossRef](#)]
- Sayre, R.; Frye, C.; Karagulle, D.; Krauer, J.; Breyer, S.; Aniello, P.; Wright, D.J.; Payne, D.; Adler, C.; Warner, H.; et al. A new high-resolution map of world mountains and an online tool for visualizing and comparing characterizations of global mountain distributions. *Mt. Res. Dev.* **2018**, *38*, 240–249. [[CrossRef](#)]
- Karagulle, D.; Frye, C.; Sayre, R.; Breyer, S.; Aniello, P.; Vaughan, R.; Wright, D. Modeling global Hammond landform regions from 250-m elevation data. *Trans. GIS* **2017**, *21*, 1040–1060. [[CrossRef](#)]
- Rahbek, C.; Borregaard, M.K.; Colwell, R.K.; Dalsgaard, B.O.; Holt, B.G.; Morueta-Holme, N.; Nogues-Bravo, D.; Whittaker, R.J.; Fjelds , J. Humboldt’s enigma: What causes global patterns of mountain biodiversity? *Science* **2019**, *365*, 1108–1113. [[CrossRef](#)]
- Viviroli, D.; D rr, H.H.; Messerli, B.; Meybeck, M.; Weingartner, R. Mountains of the world 2019, water towers for humanity: Typology, mapping, and global significance. *Water Resour. Res.* **2007**, *43*, 7.
- Parmesan, C.; Yohe, G. A globally coherent fingerprint of climate change impacts across natural systems. *Nature* **2003**, *421*, 37–42. [[CrossRef](#)]
- Hickling, R.; Roy, D.B.; Hill, J.K.; Fox, R.; Thomas, C.D. The distributions of a wide range of taxonomic groups are expanding polewards. *Glob. Chang. Biol.* **2006**, *12*, 450–455. [[CrossRef](#)]

12. Thuiller, W. Patterns and uncertainties of species' range shifts under climate change. *Glob. Chang. Biol.* **2004**, *10*, 2020–2027. [[CrossRef](#)]
13. Thuiller, W.; Lavorel, S.; Araújo, M.B.; Sykes, M.T.; Prentice, I.C. Climate change threats to plant diversity in Europe. *Proc. Natl. Acad. Sci. USA* **2005**, *102*, 8245–8250. [[CrossRef](#)] [[PubMed](#)]
14. Thuiller, W.; Broennimann, O.; Hughes, G.; Alkemade, J.R.M.; Midgley, G.F.; Corsi, F. Vulnerability of African mammals to anthropogenic climate change under conservative land transformation assumptions. *Glob. Chang. Biol.* **2006**, *12*, 424–440. [[CrossRef](#)]
15. Bakkenes, M.; Alkemade, J.R.M.; Ihle, F.; Leemans, R.; Latour, J.B. Assessing effects of forecasted climate change on the diversity and distribution of European higher plants for 2050. *Glob. Chang. Biol.* **2002**, *8*, 390–407. [[CrossRef](#)]
16. Thomas, C.D.; Cameron, A.; Green, R.E.; Bakkenes, M.; Beaumont, L.J.; Collingham, Y.C.; Erasmus, B.F.; De Siqueira, M.F.; Grainger, A.; Hannah, L.; et al. Extinction risk from climate change. *Nature* **2004**, *427*, 145–148. [[CrossRef](#)]
17. Hagedorn, F.; Gavazov, K.; Alexander, J.M. Above-and belowground linkages shape responses of mountain vegetation to climate change. *Science* **2019**, *365*, 1119–1123. [[CrossRef](#)]
18. Pepin, N.; Bradley, R.S.; Diaz, H.F.; Baraer, M.; Caceres, E.B.; Forsythe, N.; Fowler, H.; Greenwood, G.; Hashmi, M.Z.; Liu, X.D.; et al. Elevation-dependent warming in mountain regions of the world. *Nat. Clim. Chang.* **2015**, *5*, 424–430. [[CrossRef](#)]
19. Gehrke, B.; Linder, H.P. Species richness, endemism and species composition in the tropical Afroalpine flora. *Alp. Bot.* **2014**, *124*, 165–177. [[CrossRef](#)]
20. Enquist, C.A.F. Predicted regional impacts of climate change on the geographical distribution and diversity of tropical forests in Costa Rica. *J. Biogeogr.* **2002**, *29*, 519–553. [[CrossRef](#)]
21. Stévant, T.; Dauby, G.; Lowry, P.P.; Blach-Overgaard, A.; Droissart, V.; Harris, D.J.; Mackinder, B.A.; Schatz, G.E.; Sonké, B.; Sosef, M.S.; et al. A third of the tropical African flora is potentially threatened with extinction. *Sci. Adv.* **2019**, *5*, eaax9444. [[CrossRef](#)]
22. Mairal, M.; Namaganda, M.; Gizaw, A.; Chala, D.; Brochmann, C.; Catalán, P. Multiple mountain-hopping colonization of sky-islands on the two sides of Tropical Africa during the Pleistocene: The afroalpine *Festuca* grasses. *J. Biogeogr.* **2021**, *48*, 1858–1874. [[CrossRef](#)]
23. Yalden, D.; Largen, M. The endemic mammals of Ethiopia. *Mammal Rev.* **1992**, *22*, 115–150. [[CrossRef](#)]
24. Brochmann, C.; Gizaw, A.; Chala, D.; Kandziora, M.; Eilu, G.; Popp, M.; Pirie, M.D.; Gehrke, B. History and evolution of the afroalpine flora: In the footsteps of Olov Hedberg. *Alp. Bot.* **2021**, *132*, 65–87. [[CrossRef](#)]
25. Conway, D. From headwater tributaries to international river: Observing and adapting to climate variability and change in the Nile basin. *Glob. Environ. Chang.* **2005**, *15*, 99–114. [[CrossRef](#)]
26. Anderson, R.P.; Martinez-Meyer, E. Modeling species' geographic distributions for preliminary conservation assessments: An implementation with the spiny pocket mice (*Heteromys*) of Ecuador. *Biol. Conserv.* **2004**, *116*, 167–179. [[CrossRef](#)]
27. Pauli, H.; Gottfried, M.; Reiter, K.; Klettner, C.; Grabherr, G. Signals of range expansions and contractions of vascular plants in the high Alps: Observations (1994–2004) at the GLORIA master site Schrankogel, Tyrol, Austria. *Glob. Chang. Biol.* **2007**, *13*, 147–156. [[CrossRef](#)]
28. Arcos, J.M.; Bécares, J.; Villero, D.; Brotons, L.; Rodríguez, B.; Ruiz, A. Assessing the location and stability of foraging hotspots for pelagic seabirds: An approach to identify marine Important Bird Areas (IBAs) in Spain. *Biol. Conserv.* **2012**, *156*, 30–42. [[CrossRef](#)]
29. Guisan, A.; Tingley, R.; Baumgartner, J.B.; Naujokaitis-Lewis, I.; Sutcliffe, P.R.; Tulloch, A.I.; Regan, T.J.; Brotons, L.; McDonald-Madden, E.; Mantyka-Pringle, C.; et al. Predicting species distributions for conservation decisions. *Ecol. Lett.* **2013**, *16*, 1424–1435. [[CrossRef](#)]
30. Fajardo, J.; Lessmann, J.; Bonaccorso, E.; Devenish, C.; Munoz, J. Combined use of systematic conservation planning, species distribution modelling, and connectivity analysis reveals severe conservation gaps in a megadiverse country (Peru). *PLoS ONE* **2014**, *9*, e114367. [[CrossRef](#)]
31. Ferrier, S.; Watson, G.; Pearce, J.; Drielsma, M. Extended statistical approaches to modeling spatial pattern in biodiversity: The north-east New South Wales experience I. Species-level modeling. *Biodiv. Conserv.* **2002**, *11*, 2275–2307. [[CrossRef](#)]
32. Kremen, C.; Cameron, A.; Moilanen, A.; Phillips, S.J.; Thomas, C.D.; Beentje, H.; Dransfield, J.; Fisher, B.L.; Glaw, F.; Good, T.C.; et al. Aligning conservation priorities across taxa in Madagascar with high-resolution planning tools. *Science* **2008**, *320*, 222–226. [[CrossRef](#)] [[PubMed](#)]
33. Brockington, D. *Fortress Conservation: The Preservation of the Mkomazi Game Reserve, Tanzania*; Indiana University Press: St. Bloomington, IN, USA, 2002.
34. West, P.; Igoe, J.; Brockington, D. Parks and peoples: The social impact of protected areas. *Annu. Rev. Anthropol.* **2006**, *35*, 251–277. [[CrossRef](#)]
35. Berkes, F. Community-based conservation in a globalized world. *Proc. Natl. Acad. Sci. USA* **2007**, *104*, 15188–15193. [[CrossRef](#)] [[PubMed](#)]
36. Palomo, I.; Montes, C.; Martin-Lopez, B.; González, J.A.; Garcia-Llorente, M.; Alcorlo, P.; Mora, M.R.G. Incorporating the social-ecological approach in protected areas in the Anthropocene. *BioScience* **2014**, *64*, 181–191. [[CrossRef](#)]
37. Cumming, G.S.; Allen, C.R.; Ban, N.C.; Biggs, D.; Biggs, H.C.; Cumming, D.H.; De Vos, A.; Epstein, G.; Etienne, M.; Maciejewski, K.; et al. Understanding protected area resilience: A multi-scale, social-ecological approach. *Ecol. Appl.* **2015**, *25*, 299–319. [[CrossRef](#)] [[PubMed](#)]

38. Brueckner-Irwin, I.; Armitage, D.; Courtenay, S. Applying a social-ecological well-being approach to enhance opportunities for marine protected area governance. *Ecol. Soc.* **2019**, *24*, 3. [[CrossRef](#)]
39. Maffi, L. Linguistic, cultural, and biological diversity. *Annu. Rev. Anthropol.* **2005**, *34*, 599–617. [[CrossRef](#)]
40. Kassam, K.A. Diversity as if nature and culture matter: Bio-cultural diversity and Indigenous peoples. *Int. J. Divers. Organ. Commun. Nations Annu. Rev.* **2008**, *8*, 87–95. [[CrossRef](#)]
41. Hanspach, J.; Haider, L.J.; Oteros-Rozas, E.; Olafsson, A.S.; Gulsrud, N.M.; Raymond, C.M.; Torralba, M.; Martín-López, B.; Bieling, C.; Garcia-Martin, M.; et al. Biocultural approaches to sustainability: A systematic review of the scientific literature. *People Nat.* **2020**, *2*, 643–659. [[CrossRef](#)]
42. Harmon, D. Indicators of the world's cultural diversity. In Proceedings of the Fourth World Congress on National Parks and Protected Areas, Caracas, Venezuela, 10–21 February 1992; pp. 1–33.
43. Loh, J.; Harmon, D. A global index of biocultural diversity. *Ecol. Indic.* **2005**, *5*, 231–241. [[CrossRef](#)]
44. Stepp, J.R.; Castaneda, H.; Cervone, S. Mountains and biocultural diversity. *Mt. Res. Dev.* **2005**, *25*, 223–227. [[CrossRef](#)]
45. Taylor, P.J. *Unruly Complexity*; University of Chicago Press: Chicago, IL, USA, 2005.
46. Crane, T.A. Of models and meanings: Cultural resilience in social-ecological. *Ecol. Soc.* **2010**, *15*, 4. [[CrossRef](#)]
47. Cristancho, S.; Vining, J. Culturally defined keystone species. *Hum. Ecol. Rev.* **2004**, *11*, 153–164.
48. Garibaldi, A.; Turner, N. Cultural keystone species: Implications for ecological conservation and restoration. *Ecol. Soc.* **2004**, *9*, 1. [[CrossRef](#)]
49. McBrearty, S.; Brooks, A.S. The revolution that wasn't: A new interpretation of the origin of modern human behavior. *J. Hum. Evol.* **2000**, *39*, 453–563. [[CrossRef](#)]
50. Ambrose, S.H. Paleolithic technology and human evolution. *Science* **2001**, *291*, 1748–1753. [[CrossRef](#)]
51. Vogelsang, R.; Bubenzer, O.; Kehl, M.; Meyer, S.; Richter, J.; Zinaye, B. When hominins conquered highlands—An acheulean site at 3000 m asl on mount dendi/Ethiopia. *J. Paleolit. Archaeol.* **2018**, *1*, 302–313. [[CrossRef](#)]
52. Ossendorf, G.; Groos, A.R.; Bromm, T.; Tekelemariam, M.G.; Glaser, B.; Lesur, J.; Schmidt, J.; Akçar, N.; Bekele, T.; Beldados, A.; et al. Middle Stone Age foragers resided in high elevations of the glaciated Bale Mountains, Ethiopia. *Science* **2019**, *365*, 583–587. [[CrossRef](#)]
53. Ashenafi, Z.T.; Leader-Williams, N. Indigenous common property resource management in the central highlands of Ethiopia. *Hum. Ecol.* **2005**, *33*, 539–563. [[CrossRef](#)]
54. Steger, C.; Nigussie, G.; Alonzo, M.; Warkineh, B.; Van Den Hoek, J.; Fekadu, M.; Evangelista, P.H.; Klein, J.A. Knowledge coproduction improves understanding of environmental change in the Ethiopian highlands. *Ecol. Soc.* **2020**, *25*, 2. [[CrossRef](#)]
55. Myers, N.; Mittermeier, R.A.; Mittermeier, C.G.; Da Fonseca, G.A.; Kent, J. Biodiversity hotspots for conservation priorities. *Nature* **2000**, *403*, 853–858. [[CrossRef](#)] [[PubMed](#)]
56. Mosquera, G.M.; Lazo, P.X.; Célleri, R.; Wilcox, B.P.; Crespo, P. Runoff from tropical alpine grasslands increases with areal extent of wetlands. *Catena* **2015**, *125*, 120–128. [[CrossRef](#)]
57. Hurni, H. Degradation and conservation of the resources in the Ethiopian highlands. *Mt. Res. Dev.* **1988**, *8*, 123–130. [[CrossRef](#)]
58. Hurni, H.; Stahl, P. *Simen Mountains, Ethiopia Vol II: Climate and the Dynamics of Altitudinal Belts from the Last Cold Period to the Present Day*; Geographische Gesellschaft Bern und Geographica Bernensia: Bern, Switzerland, 1982.
59. EWCA. *State of Conservation Report of the World Natural Heritage Site, Simen Mountains National Park (Ethiopia)*; Ethiopian Wildlife Conservation Authority: Addis Ababa, Ethiopia, 2015.
60. Nemomissa, S.; Puff, C. Flora and vegetation of the Simen Mountains National Park, Ethiopia. *Biol. Skr.* **2001**, *54*, 335–348.
61. Puff, C.; Nemomissa, S. *Plants of the Simen: A Flora of the Simen Mountains and Surroundings, Northern Ethiopia*; National Botanic Garden: Meise, Belgium, 2005; Volume 37.
62. Jacob, M.; Frankl, A.; Hurni, H.; Lanckriet, S.; Ridder, M.; Guyassa, E.; Beeckman, H.; Nyssen, J. Land cover dynamics in the Simien Mountains (Ethiopia), half a century after establishment of the National Park. *Reg. Environ. Chang.* **2016**, *17*, 777–787. [[CrossRef](#)]
63. Nievergelt, B.; Good, T.; Guttinger, R. A survey of the flora and fauna of the Simen Mountains National Park, Ethiopia. Special Issue of Walia. *J. Ethiop. Wildl. Nat. Hist. Soc.* **1998**.
64. Gebremedhin, B.; Flagstad, O.; Bekele, A.; Chala, D.; Bakkestuen, V.; Boessenkool, S.; Popp, M.; Gussarova, G.; Schröder-Nielsen, A.; Nemomissa, S.; et al. DNA Metabarcoding Reveals Diet Overlap between the Endangered Walia Ibex and Domestic Goats—Implications for Conservation. *PLoS ONE* **2016**, *11*, e0159133. [[CrossRef](#)]
65. Yihune, M.; Bekele, A.; Tefera, Z. Human-wildlife conflict in and around the Simen Mountains National Park, Ethiopia. *Ethiop. J. Sci.* **2009**, *32*, 57–64.
66. Alemayehu, K.; Dessie, T.; Gizaw, S.; Haile, A.; Mekasha, Y. Population dynamics of Walia ibex (*Capra walie*) at Simen Mountains National Park, Ethiopia. *Afr. J. Ecol.* **2011**, *49*, 292–300. [[CrossRef](#)]
67. Girma, E.; Tesfay, G.; Bauer, H.; Ashenafi, Z.T.; de Jongh, H.; Marino, J. Community Resource Uses and Ethiopian Wolf Conservation in Mount Abune Yosef. *Environ. Manag.* **2015**, *56*, 684–694.
68. Ashenafi, Z.T. Common Property Resource Management of an Afroalpine Habitat: Supporting a Population of the Critically Endangered Ethiopian wolf (*Canis simensis*). Ph.D. Thesis, University of Kent, Canterbury, UK, 2001.
69. Gebrehiwot, K.; Dessalegn, T.; Woldu, Z.; Demissew, S.; Teferi, E. Soil organic carbon stock in Abune Yosef afroalpine and sub-afroalpine vegetation, northern Ethiopia. *Ecol. Process.* **2018**, *7*, 6. [[CrossRef](#)]

70. Fischer, A.; Wakjira, D.T.; Weldesemaet, Y.T.; Ashenafi, Z.T. On the interplay of actors in the co-management of natural resources—A dynamic perspective. *World Dev.* **2014**, *64*, 158–168. [[CrossRef](#)]
71. Billi, P. Geomorphological landscapes of Ethiopia. In *Landscapes and Landforms of Ethiopia, World Geomorphological Landscapes*; Billi, P., Ed.; Springer Science + Business Media: Dordrecht, The Netherlands, 2015.
72. Gebrehiwot, K.; Teferi, E.; Woldu, Z.; Fekadu, M.; Desalegn, T.; Demissew, S. Dynamics and drivers of land cover change in the Afroalpine vegetation belt: Abune Yosef mountain range, Northern Ethiopia. *Environ. Dev. Sustain.* **2020**, *23*, 10679–10701. [[CrossRef](#)]
73. Hijmans, R.J.; Cameron, S.E.; Parra, J.L.; Jones, P.G.; Jarvis, A. Very high resolution interpolated climate surfaces for global land areas. *Int. J. Climatol.* **2005**, *25*, 1965–1978. [[CrossRef](#)]
74. Amatulli, G.; Domisch, S.; Tuanmu, M.N.; Parmentier, B.; Ranipeta, A.; Malczyk, J.; Jetz, W. A suite of global, cross-scale topographic variables for environmental and biodiversity modeling. *Sci. Data* **2018**, *5*, 180040. [[CrossRef](#)] [[PubMed](#)]
75. Elith, J.; Leathwick, J.R. Species distribution models: Ecological explanation and prediction across space and time. *Annu. Rev. Ecol. Evol. Syst.* **2009**, *40*, 677–697. [[CrossRef](#)]
76. Merow, C.; Smith, M.J.; Silander, J.A., Jr. A practical guide to MaxEnt for modeling species' distributions: What it does, and why inputs and settings matter. *Ecography* **2013**, *36*, 1058–1069. [[CrossRef](#)]
77. Phillips, S.J.; Anderson, R.P.; Schapire, R.E. Maximum entropy modeling of species geographic distributions. *Ecol. Model.* **2006**, *190*, 231–259. [[CrossRef](#)]
78. Phillips, S.J.; Dudík, M. Modeling of species distributions with Maxent: New extensions and a comprehensive evaluation. *Ecography* **2008**, *31*, 161–175. [[CrossRef](#)]
79. Elith, J.; Graham, C.H.; Anderson, R.P.; Dudík, M.; Ferrier, S.; Guisan, A.; Hijmans, R.J.; Huettmann, F.; Leathwick, J.R.; Lehmann, A.; et al. Novel methods improve prediction of species' distributions from occurrence data. *Ecography* **2006**, *29*, 129–151. [[CrossRef](#)]
80. Tittensor, D.P.; Baco, A.R.; Brewin, P.E.; Clark, M.R.; Consalvey, M.; Hall-Spencer, J.; Rowden, A.A.; Schlacher, T.; Stocks, K.I.; Rogers, A.D. Predicting global habitat suitability for stony corals on seamounts. *J. Biogeogr.* **2009**, *36*, 1111–1128. [[CrossRef](#)]
81. Williams, J.N.; Seo, C.W.; Thorne, J.; Nelson, J.K.; Erwin, S.; O'Brien, J.M.; Schwartz, M.W. Using species distribution models to predict new occurrences for rare plants. *Divers. Distrib.* **2009**, *15*, 565–576. [[CrossRef](#)]
82. Kumar, S.; Stohlgren, T.J. Maxent modeling for predicting suitable habitat for threatened and endangered tree *Canacomyrica monticola* in New Caledonia. *J. Ecol. Nat. Environ.* **2009**, *1*, 94–98.
83. Abdelaal, M.; Fois, M.; Fenu, G.; Bacchetta, G. Using MaxEnt modeling to predict the potential distribution of the endemic plant *Rosa arabica* Crép. in Egypt. *Ecol. Inform.* **2019**, *50*, 68–75. [[CrossRef](#)]
84. Evangelista, P.H.; Kumar, S.; Stohlgren, T.J.; Jarnevich, C.S.; Crall, A.W.; Norman, J.B., III; Barnett, D.T. Modelling invasion for a habitat generalist and a specialist plant species. *Divers. Distrib.* **2008**, *14*, 808–817. [[CrossRef](#)]
85. Wakie, T.T.; Evangelista, P.H.; Jarnevich, C.S.; Laituri, M. Mapping current and potential distribution of non-native *Prosopis juliflora* in the Afar region of Ethiopia. *PLoS ONE* **2014**, *9*, e112854. [[CrossRef](#)]
86. Davis, A.P.; Gole, T.W.; Baena, S.; Moat, J. The impact of climate change on indigenous arabica coffee (*Coffea arabica*): Predicting future trends and identifying priorities. *PLoS ONE* **2012**, *7*, e47981. [[CrossRef](#)]
87. Evangelista, P.; Young, N.; Burnett, J. How will climate change spatially affect agriculture production in Ethiopia? Case studies of important cereal crops. *Clim. Chang.* **2013**, *119*, 855–873. [[CrossRef](#)]
88. Elith, J.; Phillips, S.J.; Hastie, T.; Dudík, M.; Chee, Y.E.; Yates, C.J. A statistical explanation of MaxEnt for ecologists. *Divers. Distrib.* **2011**, *17*, 43–57. [[CrossRef](#)]
89. Saupe, E.E.; Barve, V.; Myers, C.E.; Soberón, J.; Barve, N.; Hensz, C.M.; Peterson, A.T.; Owens, H.L.; Lira-Noriega, A. Variation in niche and distribution model performance: The need for a priori assessment of key causal factors. *Ecol. Model.* **2012**, *237*, 11–22. [[CrossRef](#)]
90. Elith, J.; Kearney, M.; Phillips, S.J. The art of modeling range-shifting species. *Methods Ecol. Evol.* **2010**, *1*, 330–342. [[CrossRef](#)]
91. Anderson, R.P.; Gonzalez, I. Species-specific tuning increases robustness to sampling bias in models of species distributions: An implementation with MaxEnt. *Ecol. Model.* **2011**, *222*, 2796–2811. [[CrossRef](#)]
92. Phillips, S.J.; Anderson, R.P.; Dudík, M.; Schapire, R.E.; Blair, M.E. Opening the black box: An open-source release of Maxent. *Ecography* **2017**, *40*, 887–893. [[CrossRef](#)]
93. Ashenafi, Z.T.; Leader-Williams, N.; Coulson, T. Consequences of human land use for an Afroalpineecological community in Ethiopia. *Conserv. Soc.* **2012**, *10*, 209–216.
94. Wesche, K. The importance of occasional droughts for afroalpine landscape ecology. *J. Trop. Ecol.* **2003**, *19*, 197–208. [[CrossRef](#)]
95. Hedberg, O. *Features of Afroalpine Plant Ecology*; Almqvist & Wiksells Boktryckeri: Uppsala, Sweden, 1964.
96. Phillips, S. Poaceae (Gramineae). In *Flora of Ethiopia and Eritrea*; Hedberg, I., Edwards, S., Eds.; The National Herbarium, Addis Ababa University: Addis Ababa, Ethiopia; Uppsala, Sweden, 1995; Volume 7, pp. 3–6.
97. Buytaert, W.; Cuesta Camacho, F.; Tobón, C. Potential impacts of climate change on the environmental services of humid tropical alpine regions. *Glob. Ecol. Biogeogr.* **2011**, *20*, 19–33. [[CrossRef](#)]
98. Rahbek, C. The elevational gradient of species richness: A uniform pattern? *Ecography* **1995**, *18*, 200–205. [[CrossRef](#)]
99. Kidane, Y.; Stahlman, R.; Beierkuhnlein, C. Dead end for endemic plant species? A biodiversity hotspot under pressure. *Glob. Ecol. Conserv.* **2019**, *19*, e00670. [[CrossRef](#)]

100. Chala, D.; Brochmann, C.; Psomas, A.; Ehrich, D.; Gizaw, A.; Masao, C.A.; Bakkestuen, V.; Zimmermann, N.E. Good-bye to tropical alpine plant giants under warmer climates? Loss of range and genetic diversity in *Lobelia rhynchopetalum*. *Ecol. Evol.* **2016**, *6*, 8931–8941. [[CrossRef](#)]
101. Rosell, S. Regional perspective on rainfall change and variability in the central highlands of Ethiopia, 1978–2007. *Appl. Geogr.* **2011**, *31*, 329–338. [[CrossRef](#)]
102. Fashing, P.J.; Nguyen, N.; Venkataraman, V.V.; Kerby, J.T. Gelada feeding ecology in an intact ecosystem at Guassa, Ethiopia: Variability over time and implications for theropit and hominin dietary evolution. *Am. J. Phys. Anthropol.* **2014**, *155*, 1–16. [[CrossRef](#)] [[PubMed](#)]
103. Groth, J.; Ide, T.; Sakdapolrak, P.; Kassa, E.; Hermans, K. Deciphering interwoven drivers of environment-related migration—A multisite case study from the Ethiopian highlands. *Glob. Environ. Chang.* **2020**, *63*, 102094. [[CrossRef](#)]
104. Tilman, D.; May, R.M.; Lehman, C.L.; Nowak, M.A. Habitat destruction and the extinction debt. *Nature* **1994**, *371*, 65–66. [[CrossRef](#)]
105. Brooks, T.M.; Pimm, S.L.; Oyugi, J.O. Time lag between deforestation and bird extinction in tropical forest fragments. *Conserv. Biol.* **1999**, *13*, 1140–1150. [[CrossRef](#)]
106. Ferraz, G.; Russell, G.J.; Stouffer, P.C.; Bierregaard, R.O.; Pimm, S.L.; Lovejoy, T.E. Rates of species loss from Amazonian forest fragments. *Proc. Natl. Acad. Sci. USA* **2003**, *100*, 14069–14073. [[CrossRef](#)]
107. Kuussaari, M.; Bommarco, R.; Heikkinen, R.K.; Helm, A.; Krauss, J.; Lindborg, R.; Öckinger, E.; Pärtel, M.; Pino, J.; Rodà, F.; et al. Extinction debt: A challenge for biodiversity conservation. *Trends Ecol. Evol.* **2009**, *24*, 564–571. [[CrossRef](#)]
108. Cousins, S.A. Extinction debt in fragmented grasslands: Paid or not? *J. Veg. Sci.* **2009**, *20*, 3–7. [[CrossRef](#)]
109. DeAngelis, D.L.; Yurek, S. Spatially explicit modeling in ecology: A review. *Ecosystems* **2017**, *20*, 284–300. [[CrossRef](#)]
110. Carroll, C.; Noss, R.F.; Paquet, P.C.; Schumaker, N.H. Extinction debt of protected areas in developing landscapes. *Conserv. Biol.* **2004**, *18*, 1110–1120. [[CrossRef](#)]
111. Bulman, C.R.; Wilson, R.J.; Holt, A.R.; Bravo, L.G.; Early, R.I.; Warren, M.S.; Thomas, C.D. Minimum viable metapopulation size, extinction debt, and the conservation of a declining species. *Ecol. Appl.* **2007**, *17*, 1460–1473. [[CrossRef](#)]
112. Admassie, Y. *Twenty Years to Nowhere. Property Rights, Land Management and Conservation in Ethiopia*; Red Sea Press: Trenton, NJ, USA, 2000.
113. UNDP. Community and Regional Leadership Dialogue on Protecting Choke Mountain. 2019. Available online: <https://www.et.undp.org/content/ethiopia/en/home/presscenter/articles/2019/community-and-regional-leadership-dialogue-on-protecting-choke-m0.html> (accessed on 21 December 2021).
114. UNEP-WCMC; I.U.C.N. Protected Planet: The World Database on Protected Areas (WDPA). 2021. Available online: www.protectedplanet.net (accessed on 21 December 2021).
115. DeCaro, D.; Stokes, M. Social psychological principles of community based conservation and conservancy motivation: Attaining goals within an autonomy supportive environment. *Conserv. Biol.* **2008**, *22*, 1443–1451. [[CrossRef](#)] [[PubMed](#)]
116. Lapeyre, R. Community-based tourism as a sustainable solution to maximise impacts locally? The Tsiseb Conservancy case, Namibia. *Dev. South. Afr.* **2010**, *27*, 757–772. [[CrossRef](#)]
117. Marks, S.A. Back to the future: Some unintended consequences of Zambia’s community-based wildlife program (ADMAD). *Afr. Today* **2001**, *48*, 121–141. [[CrossRef](#)]
118. Silva, J.A.; Mosimane, A. “How could I live here and not be a member?”: Economic versus social drivers of participation in Namibian conservation programs. *Hum. Ecol.* **2014**, *42*, 183–197. [[CrossRef](#)]
119. Sheppard, D.J.; Moehrenschrager, A.; McPherson, J.M.; Mason, J.J. Ten years of adaptive community-governed conservation: Evaluating biodiversity protection and poverty alleviation in a West African hippopotamus reserve. *Environ. Conserv.* **2010**, *37*, 270–282. [[CrossRef](#)]
120. Dyer, J.; Stringer, L.; Dougill, A.; Leventon, J.; Nshimbi, M.; Chama, F.; Kafwifwi, A.; Muledi, J.; Kaumbu, J.-M.; Falcao, M.; et al. Assessing participatory practices in community-based natural resource management: Experiences in community engagement from southern Africa. *J. Environ. Manag.* **2014**, *137*, 137–145. [[CrossRef](#)]
121. Ostrom, E.; Dietz, T.; Dolšak, N.; Stern, P.C.; Stonich, S.; Weber, E.U. *The Drama of the Commons*; National Academy Press: Washington, DC, USA, 2002.
122. Seixas, S.C.; Berkes, F. Community-based enterprises: The significance of partnerships and institutional linkages. *Int. J. Commons* **2009**, *4*, 183–212. [[CrossRef](#)]
123. Galvin, K.A.; Beeton, T.A.; Luizza, M.W. African community-based conservation. *Ecol. Soc.* **2018**, *23*, 3. [[CrossRef](#)]
124. Janowiak, M.K.; Iverson, L.R.; Fosgitt, J.; Handler, S.D.; Dallman, M.; Thomas, S.; Hutnik, B.; Swanston, C.W. Assessing stand-level climate change risk using forest inventory data and species distribution models. *J. For.* **2017**, *115*, 222–229. [[CrossRef](#)]
125. Pecchi, M.; Marchi, M.; Burton, V.; Giannetti, F.; Moriondo, M.; Bernetti, I.; Bindi, M.; Chirici, G. Species distribution modelling to support forest management. A literature review. *Ecol. Model.* **2019**, *411*, 108817. [[CrossRef](#)]