LETTER

Climate change creates opportunities to expand agriculture in the Hindu Kush Himalaya but will cause considerable ecosystem trade-offs

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Abstract

Theoretically, climate change will create warmer temperatures and greater precipitation in mountainous regions, making agriculture possible in areas that were once unsuitable for cropping. But the extent and the nature of these ‘agricultural frontiers’ is as yet unknown. Building upon recent research on Climate Change Driven Agricultural Frontiers [CCDAFs], this paper assesses the potential of agricultural expansion in the Hindukush Himalaya [HKH]. Using FAO crop suitability data, we estimated the extent of CCDAFs under three Representative Concentration Pathways for 13 crops as well as the potential impacts of developing these frontiers on ecosystem services. We show that under climate change projected by the IPSL- CM5A-LR climate model, 34,507 km² of agricultural frontiers may emerge in the HKH by 2100 under RCP 6.0. Additionally, results suggest that there will be new opportunities for crop diversification as individual crops will gain frontier area. However, developing these CCDAFs will impact supportive and regulating ecosystem services including carbon storage and sequestration, soil quality, biodiversity, and hydrological processes—with implications for regional water security. These impacts must be considered alongside the benefits of additional food production when evaluating the net benefits of developing CCDAFS.

Introduction

Climate change is expected to expand the range of land suitable for agriculture by increasing average temperature and precipitation in high-elevation regions, creating new areas that may become suitable for agriculture known as Climate Change Driven Agricultural Frontiers [CCDAFs] [1–5]. Globally, it is estimated that climate change will increase the enormous amount of potentially suitable cropland, predominantly in the Northern Hemisphere [4, 6]. King et al [2] advise that by 2099, roughly 76% of boreal regions might reach appropriate growing degree days sufficient for small cereal crops, with a 1200 km northward latitudinal shift of the leading edge. Some of these potential frontiers will be located in the Hindukush Himalayan region. Factors such as soil quality, terrain, infrastructure, and innovations in agricultural technology such as fast-maturing commodity crops that increase productivity in the marginal areas will be major determinants of which of these frontiers will actually be cultivated [5, 7].

Emerging literature focuses on identifying and evaluating what is known as Climate Change Driven Agricultural Frontiers [CCDAFs] — defined as areas that are not currently cultivated or suitable for agriculture presently, but that may become suitable for agriculture in the future due to changing climatic patterns [4, 5]. It is unclear if CCDAFs will yield a net positive or negative impact on the Hindukush Himalayan region’s economic development and ecosystem services. Therefore, further research is needed to understand the impacts of.
agricultural frontier expansion across various dimensions, including food security, ecosystem services, and regional economic development. For instance, cultivating crops in CCDAFs could substantially expand regional food production and potentially alleviate food insecurity in northern hilly poor communities while contributing to much-needed economic development [8, 9]. For example, producing fresh, locally grown, nutrient-rich food could create jobs and help address the high rate of food insecurity in the remote areas of the Hindu Kush Himalayan region [10].

Realizing the potential benefits of CCDAFs for provisioning services will require carefully exploring trade-offs between existing regulating and supportive ecosystem services such as climate regulation, water resource maintenance, and biodiversity support [1, 4, 11]. For instance, land-use changes that increase the provisioning of ecosystem services may result in a loss of biodiversity and increased greenhouse gas emissions from newly plowed carbon-rich land [12, 13]. With climate change already affecting soil organic carbon in areas of the HKH, landuse change to agriculture could further impact soil carbon dynamics through tilling the land [14, 15]. Research suggests that a complete global expansion into CCDAFs could generate a tremendous amount of carbon emissions to preclude limiting climate change to 1.5 °C of warming, threaten water resources for billions of people, and severely degrade ecosystems that support biodiversity hotspots [4, 16]. Consequently, managing trade-offs between expanding food production in the remote hilly region and the degradation or destruction of these ecosystem services will be a significant dilemma for federal, provincial, and regional policymakers within the Hindukush Himalayan region. More specifically, forest and water systems in the HKH play very significant roles and provide essential services to communities in the area. These are being negatively impacted by climate change as well as agricultural expansion in the region [17–19]. Agricultural expansion can impact forests through land clearing - resulting in decreased carbon stores and biodiversity due to forest loss [17, 18, 20]. As well, water availability and quality in the HKH is being negatively impacted by climate change and agricultural expansion may further affect water security in the region [19, 21]. In summary, all the literature discussed above suggests that CCDAFs could be utilized to intensify agricultural production to support food security. However, almost all of them warn that any such development should be cautiously approached due to potentially negative impacts on ecosystem services [1–6].

In this context, this study builds on foundations set by Hannah et al. 2020 [4] and K C et al. 2021 [5], focusing in the Hindukush Himalaya [HKH]. The HKH is projected to experience climate change at a greater pace and magnitude than much of the rest of the world [22]. The region is also highly vulnerable to food insecurity and supplies freshwater for over 1.3 billion people [22]. Therefore, this study seeks to answer how climate change will affect the distribution of suitable agricultural land in the HKH; and, secondly, how a shifted distribution in suitable agricultural land might affect ecosystem services in the region.

Materials and methods

This study used a three-step analysis to answer its two primary research questions. A diagram of the process is summarized in figure 1.

**Step One.** Determine areas suitable for agriculture in the present and future

The FAO Global Agro-Ecological Zones [GAEZ] database was used to evaluate the suitable extent for each crop at a 9 km resolution [23]. Suitability was defined by the share of land that contains land defined by GAEZ as moderately suitable, suitable, or very suitable. We conducted our analysis at five thresholds at least—1%, 5%, 10%, 25%, and 50%—of land within each cell classified as very suitable, suitable, or moderately suitable for agriculture [23]. We then conducted analysis of each scenario using RCP 2.6, 4.5, and 6.0 under the IPSL-CM5A-LR climate model [24]. 13 crops were included in this study: barley, buckwheat, chickpea, foxtail millet, gram, maize, rapeseed, dryland rice, wetland rice, soy, sugar cane, wheat, and white potato. Current cropland was identified using the ESRI 2020 Land Cover dataset [25]. We resampled to 1000m resolution using nearest neighbour analysis.

**Step two.** Determine current and climate change driven agricultural frontiers

Current frontiers were classified as areas suitable in the 2011–2041 period [23], unsuitable in the 2071–2100 period [23], and contained no areas classified as crops in 2020 [22]. Emerging CCDAFs were classified as areas unsuitable in the 2011–2041 period [23], suitable in the 2071–2100 period [23], and contained no areas classified as crops in 2020 [25]. Pure emerging CCDAFs were classified as any areas within the combined extent of all emerging CCDAFs that did not intersect with any of the combined extent of current frontiers for all 13 crops.

Step two was replicated across five ‘share of suitable land’ thresholds and three RCPs, creating 30 frontier profiles for each crop, and a total of 195 current agricultural frontier profiles and 195 CCDAF profiles.
Step Three. Assess potential ecosystem service impacts

Using pure emerging CCDAFs identified in Step Two using the 1% land suitability threshold, we evaluated potential ecosystem service impacts.

We used above and below ground carbon data [26] and intersected that with the resulting CCDAFs to determine the mass of above and below ground carbon [26] within emerging pure CCDAFs in the HKH. To determine the potential impact on biodiversity and supportive services, we evaluated the area of emerging pure CCDAFs intersecting protected areas [27] and determined the number of IUCN Red List species [28] which could be affected by developing CCDAFs. We determined the area of emerging pure CCDAFs intersecting areas with limited soil quality [29]. Provisioning services were evaluated through Vörösmarty et al.’s [30] assessment of global water security risk. We calculated the area of emerging pure CCDAFs intersecting areas experiencing water stress.

Limitations and Recommendations

Expanding this study’s methods to include additional methods, such as integrated sector assessment would help to understand which of the identified CCDAFs could be developed. Socio-economic scenarios have a greater impact on potential outcomes than climate change scenarios alone [31]. Our study does not account for limitations based agricultural frontiers, agricultural frontiers which exist due to restrictions such as a lack of capital or labour, political instability, or agricultural prices [32]. Further, low resolution of environmental spatial data causes analyses to exclude impacts of smallholder farmers [32]. As well, analysis on expanding agricultural production tends to focus on extensification rather than intensification [33]. Future research should therefore need to integrate factors such as socio-economic variables and productivity of various farming methods.

Results

Depending on the scenario, results show that between 8,088 km² and 34,507 km² of land land that may not be currently suitable for farming may become suitable due to climate change between now and 2100 (figure 2). A crop-by-crop breakdown of emerging frontiers (figure 3) reveals that maize will have the largest total area of emerging frontiers. Our result shows a complex nature of CCDAF will emergence as some crops will gain larger frontiers areas with increasing RCP and some gain smaller frontiers areas with increasing RCPs. For example, in scenario A, frontier areas for maize, wheat, barley, and potato will gain a smaller frontier with increasing RCP whereas wetland rice gain larger frontier with increasing RCP (figure 3). In Scenario B, finger millet and barley
will get smaller frontiers area, while soy and wetland rice gain larger area. In Scenario C, barley will gain small frontier area while wetland rice, dryland rice, sugar cane, finger millet, soy, and gram will gain larger area. In Scenario D, all crops other than chickpea, maize, and buckwheat gain larger frontier area. In Scenario E, soy, dryland rice, and finger millet will gain larger frontier area. In all scenarios, except Scenario A, the mean frontier area for all 13 crops increases with increasing RCP.

Ecosystem service impact analysis revealed potential impacts of developing the full extent of CCDAFs (figure 4). In scenario A—the most liberal estimate of CCDAF impacts—0.23 GtC of 138 above and below ground carbon lie in CCDAFs, 2,447 km² of protected areas lie within CCDAFs, 139 and 39,140 km² of area classified as experiencing high and moderate threat to water security lie 140 within CCDAFs. Intersections between CCDAFs and IUCN Red List species reveal that 1,927 141 extant species may be impacted by utilizing CCDAFs.

**Discussion and conclusions**

The results of our analysis indicate two key findings. First, there is a small amount of new-frontiers will be emerged in the HKH relative to the total area of the HKH. While 10.3–24.1 million km² of CCDAFs may emerge globally [4] and 1.8 million km² of CCDAFs may emerge in Canada [5], only about 34,000 km² will be in the HKH. In comparison, new-to-world CCDAFs are relatively limited in the HKH. However, our analysis found that within these frontiers, the ways in which crop ranges may shift is quite significant as emergences of CCDAF show the complex nature. Some crops will gain larger frontiers areas with increasing RCP and some gain smaller
frontiers areas with increasing RCPs. For example, frontier areas for maize, wheat, barley, and potato will gain a smaller frontier with increasing RCP whereas wetland rice gain larger frontier with increasing RCP. This, therefore, indicates that while there may be some new land opened up to farming, the main impact will be that existing agricultural operations will need to adapt to a changing climate as ranges change. It is possible that limited new-to-world CCDAFs were identified because new land has already become suitable for agriculture and been developed in the region. This would align with literature that states that the HKH is experiencing climate change at a faster rate than the rest of the world [22].

Second, the ecosystem service analysis shows that carbon stores, water security, biodiversity, and supportive habitat will be impacted by developing CCDAFs in the HKH. Clearing land and tilling soils for agriculture has been identified as a significant source of future greenhouse gas emissions which will further contribute to climate change [12, 34]. Our findings suggest that developing all 34,507 km² of identified CCDAFs would result in 0.23 GtC emissions via clearing and tilling, this represents about 2.3% of global greenhouse emission from fossil fuels in 2014 [35]. However, CCDAF development will be limited by limited soil quality. Furthermore, agricultural expansion has been projected to threaten global biodiversity hotspots [36]. Our results agree that species and supportive services for biodiversity in the HKH may be at risk if CCDAFs are utilized in this region. With climate change driving upslope shifts in species ranges [37], the biodiversity impact of agricultural frontiers must be considered and researched further as endemic species in the HKH are particularly vulnerable to climate change [33]. Finally, the impact of climate change on water security has been a significant concern in the HKH [36]. Conversion of land to agriculture may pose further threats to water security in the region as cropland has higher rates of run-off and soil loss [38]. This is also a consequence of forest loss due to agriculture as loss of forests in the HKH provide important provisioning and regulating services through soil stability, nutrient cycling, and decreased run-off [39]. Our results indicate that
water security may be further negatively impacted by agricultural expansion as a large portion of CCDAFs lie within areas that are already experiencing water stress.

While the impact on these ecosystem services must be considered, it is also important to note the potential impact of CCDAFs on food security in the HKH. High mountain communities in the HKH are significantly more vulnerable to food insecurity as they face low productivity, climate and terrain limitations, natural hazards, poor infrastructure, difficulty accessing markets, high production and transportation costs, and experience higher rates of micronutrient deficiency relative to lowland communities [39]. Thus, the potential of new opportunities for agriculture in these areas could pose benefits to food security; however, the specific ways in which CCDAFs will impact local and regional food security need to be further researched.

In summary, this paper demonstrates that while climate change may create opportunities for agricultural expansion and crop diversification in the HKH, there will be considerable ecosystem service trade-offs that should be considered when developing these areas.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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