Climate Change and New Markets: Multi-Factorial Drivers of Recent Land-Use Change in The Semi-Arid Trans-Himalaya, Nepal

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Abstract: The Nepalese Mustang District is subject to profound environmental change. In recent decades, rising temperatures have been apparent, accompanied by increasing precipitation variability and a reduction in glacier extent. In a semi-arid climate, this reduces water availability and threatens irrigation-based subsistence agriculture. In addition, the region is experiencing rapid socio-economic change due to a new road connecting the former periphery to new markets downstream. This enables a higher market orientation for agricultural products and improved accessibility for tourists. In recent decades, these changes have triggered severe transformations in the local land-use systems and settlements, which are investigated in this study. Detailed on-site re-mappings of the settlements of Marpha and Kagbeni were performed based on historical maps from the early 1990s. Additionally, land-use patterns and functionality of buildings in the district capital of Jomsom and in the settlement Ranipauwa/Muktinath were mapped. For all settlements, a profound increase in cash crop (apple) cultivation can be observed since the 1990s. Recently, new cultivation practices such as intercropping have been extensively introduced as an adaptation strategy to climate extremes. Demand for different crops from the new markets downstream is causing a significant decline in local, well-established cultivation of traditional crops such as buckwheat. This corroborates with an increasing demand for freshwater for the enhanced vegetable cultivation used for inter-cropping. Simultaneously, the freshwater demands from the tourism sector are steadily increasing. In a region where water quality is deteriorating and springs are already drying up due to climate change, this will probably lead to further challenges regarding the allocation of water in the future.

Keywords: Nepal; Mustang District; irrigation-based land use; Trans-Himalaya; climate change

1. Introduction

High mountain landscapes have complex topography with distinctive small-scale environmental gradients hosting diverse ecosystems with a huge repository of biodiversity [1,2]. Simultaneously, mountain ecosystems are recognized as being highly sensitive and vulnerable to variations in temperature and/or to changes in the hydrological cycle. This proven sensitivity characterizes them as important and valuable indicators of climate change [3–6] recent global warming trends in high mountain areas [7] are verifiably amplified with increasing elevation, commonly referred to as elevation-dependent warming (EDW) [8]. As a consequence, high mountain environments are, and will be in the future, more susceptible to rising temperatures in comparison to lower elevation ecosystems, e.g., threatening the niches and habitats of various floral species [9,10] and highly impacting the cryosphere [11–13] Moreover, mountain regions are prone to natural hazards, e.g., flooding, rock- and landslides, or debris flows, which are likely to occur more frequently and intensely due to the changing climate [14–17]. Due to their remoteness, high mountain communities are often not sufficiently integrated into, or even disconnected from, economic and political progress [14]. Simultaneously, the yield of subsistence farming is highly
limited due to adverse environmental conditions (harsh climate, degraded soils, or low nutrient availability). As a consequence, rural dwellers mostly live below the poverty line and food security is not ensured [18]. Poor households are especially highly vulnerable to a changing climate (crop failures and loss of livestock), and their social–ecological resilience and adaptive capacities are constrained [19].

Although traditional farming systems have been improved and adapted over generations, climate change poses unprecedented challenges to these well-established systems [18]. Particularly in dry mountain sites, absent or erratic precipitation accompanied by a temperature-induced increase in evapotranspiration can impair agricultural growth or rangeland productivity [20–22]. Higher water requirements can be partly compensated by increased precipitation or by an enhanced contribution of meltwaters from the cryosphere (if sufficiently available) [20,22].

The latter is decisive for the regional hydrological cycle, as ecosystem services such as a constant water supply are essential to high mountain systems. The annual precipitation amount of the adjacent lowlands is comparably lower to the high mountain areas, which dominantly receive orographic precipitation. The capacity of the cryosphere to retain and seasonally discharge water provides a critical buffer during dry seasons, thus gaining supra-regional importance with corresponding socio-economic repercussions. The human livelihoods downstream are strongly interlinked with high mountain “water towers” [23,24] or “cryosphere services” [25,26]. In a global context, Immerzeel et al. [27] emphasized the outstanding relevance of High Asia’s water towers for the whole of Asia. The Hindu Kush Himalaya (HKH) is, therefore, frequently referred to as the Third Pole since it hosts the largest source of freshwater outside the polar regions [28,29].

The cryosphere in the HKH area is currently undergoing a rapid and impressive transition. A substantial decrease in glacier volume and surface area has been recorded for almost all global mountain systems [30,31]. Demonstrably, for large parts of the extended HKH region (except parts of the western HKH, e.g., the Karakoram), a profound acceleration in ice loss has been observed in recent decades [13,32,33]. However, the livelihoods of mountain communities are highly dependent on a constant supply of fresh water, which is of utmost importance in areas with a semi-arid climate or regions with a pronounced seasonality in precipitation. For example, between 50 and 90% of the total discharge in monsoonal-dominated areas of Asia originates from cryosphere services during the dry season [34,35].

During northern hemispheric summer (June–September), the south and east Asian summer monsoon systems transport large quantities of moisture-saturated air masses towards the HKH region, resulting in an abundant supply of precipitation. In the winter season, the primary source for (occasional) precipitation events is generated by westerly wind disturbances [36,37]. This seasonal alternation of the climate regimes results in seasonally differing water availability [36]. During the dry pre-monsoon season (March/April to June) with rising temperatures, the meltwater supply is of major importance for all catchments within the Himalayan Arc [38], in particular to the widespread irrigation-fed agriculture [39]. In many regions of the western HKH and the Trans-Himalayan regions, subsistence agriculture would be inconceivable without pervasive irrigation [40–43].

The Nepalese Mustang District, generally subdivided into the Upper and the Lower Mustang, is mainly located north of the main Himalayan crest comprising the Annapurna (8091 m asl) and Dhaulagiri (8167 m asl) Himalaya (Figure 1A). The Kali Gandaki river cross-cuts the Himalayan Arc, forming the deepest river gorge in the world [44]. The main crests of the Dhaulagiri and Annapurna Himal serve as distinct topo-climatic barriers for the northward movement of humid air masses during the monsoon season. As a result, abundant orographic precipitation on the windward (southern) side of the Himalayan Arc is characteristic (Figure 1B). By traversing the main ridges, foehn effects result in a substantial reduction in precipitation by a factor of six [45], leading to the typical semi-arid climate of the Trans-Himalaya. Consequently, the settlements in the Mustang District north of the Himalayan main crest highly depend on the water supply delivered by the
cryosphere (glacier runoff, snow melt, and sparse occurrences of permafrost [46]). However, verifiable changes in the glacierized area [47,48] coupled with a variable and recently declining snow cover during winter and early spring [49–52] are causing seasonal water shortages in local communities that are highly threatening to traditional irrigated farming practices [53–57]. This development may become even more aggravated in future climate change scenarios [58,59]. With increasing deglaciation, river runoff temporarily increases to peak water, beyond which runoff steadily decreases due to the reduction in ice volume and, thus, meltwater availability [60]. In mountain regions dominated by primary small glaciers, peak water has presumably already been reached [30]. In our study area, this assumption is corroborated by a constant declining trend since 1995 in the Kali Gandaki mean annual river discharge at the gauging station in Jomsom [52,53].

Figure 1. (A) Digital Elevation Model (m asl) of Nepal [61]. (B) Mean annual precipitation amounts (mma−1) across the Himalayan Arc [45]. (C) Location of the investigated settlements Marpha, Jomsom, Kagbeni and Ranipauwa, close to the pilgrimage site Muktinath. Light blue shadings indicate glacier-covered regions at higher elevations [47].

Along with these climatically induced challenges, an ongoing socio-economic transformation along the Kali Gandaki valley is straining the historically well-adapted rural livelihoods. The construction of a continuously passable road along the valley (the “Annapurna Highway”) within one of the most popular tourist regions in Nepal provides new market opportunities for local communities [62]. This is accompanied by the incorporation of more market-orientated field systems [63], increasingly replacing traditional subsistence farming. These external triggers and their multidimensional nature will certainly cause profound transformations in the livelihoods of mountain people. This, in turn, will be reflected in changes in farming practices or settlement structures, amongst others. Specific and well-tailored strategies need to be developed for sustainable development and livelihood security in a rapidly changing system. However, selecting the right adaptation strategy or evaluating its success requires both documentation and long-term observation or monitoring [14]. In the remote villages of Nepal’s Trans-Himalayas, the quantification of these data is challenging. Typical approaches in remote sensing, such as the use of long-term recording optical satellite imagery (e.g., Landsat Missions), are not readily applicable as the sensor resolution is too coarse compared to the small-scale agricultural fields. In addition, multiple crops are commonly cultivated on the same field, which further exacerbates the use of remote sensing and makes on-site mapping indispensable. Consequently, there is
little information about land use practices or the functionality of buildings and how they have changed over time. In this study, we used the unique opportunity to investigate these transformations through very detailed historical maps coupled with recently detailed re-mappings. In the early 1990s, the settlements of Kagbeni and Marpha (Figure 1C) were mapped in detail as part of an integrative Nepal–German research project [14,64–66]. The historic maps were carefully updated after almost 30 years within an on-site mapping in 2018. The older maps serve as a basis to quantify agricultural and socio-economic transitions during the recent decades. We assume that recent changes in climate coupled with the rapid socio-economic development of a formerly peripheral region force substantial transformations in cropping systems and result in economic adjustments within the respective settlements. Through the additional land-use mapping in the district capital of Jomsom and the functionality mapping of buildings at Ranipauwa/Muktinath, we additionally investigated whether the observed changes in Kagbeni and Marpha are comparable to developments in other irrigation-based land-use systems in the Mustang district.

2. Study Site and Methods

2.1. Geography of the Mustang District

The Hindu Kush Himalayan (HKH) region has been subject to a severe temperature increase during the last century [8,67]. As derived by CHELSA (Climatologies at High resolution for the Earth’s Land Surface Areas [45]) reanalysis data, such a profound warming trend is also traceable for Nepal [68–71] especially for the high elevation Mustang District. Annual mean temperatures in the Mustang District at elevations exceeding 4000 m asl have substantially increased since 1979 by more than one Kelvin [K] (Figure 2A). In comparison, the increase in temperature below 4000 m asl within the Kali Gandaki river gorge is less prominent (0.4–1.0 K) but still significant ($p < 0.01$) for larger parts of the lower Mustang District. For our investigation area, only one available long-term recording climate station, located in Jomsom, is available (Figure 2C). The significant ($p < 0.01$) warming trends since the early 1980s are apparent, being strongest during winter and the pre-monsoon season, according to an increase of +0.5 K per decade (mean temperature for December to April). However, in the semi-arid climate, this period is crucial to replenish the cryosphere’s water reservoirs (especially temporal snow events and their meltwaters) before the onset of the rainy season during the summer monsoon in July (Figure 2C). The replenishment of the water towers is further aggravated by the intense radiative climate accompanied by strong thermally induced diurnal winds of 15–25 ms$^{-1}$ [66–68]. Evaporation at the settlements above ~3000 m asl exceeds precipitation amounts during each month of the year [69].

Due to the EDW strongly evident above 4000 m asl, the cryosphere services for water supply in our study region are increasingly threatened (Figure 2A). Trans-Himalayan glaciers of the Mustang District exhibit marked recession since the Little Ice Age and have already lost 40% of their initial area [47]. Other water reservoirs, such as rock glaciers as the lower limit of discontinuous permafrost (Figure 3C), also represent a valuable long-term water source; however, the quantification and the response to climate change is challenging [46,72]. While the Jhong Khola and Thini Khola catchments (Figure 3A, Kagbeni [28°50′13″ N/83°47′00″ E, 2850 m asl] and Jomsom [28°46′55″ N/83°44′25″ E, 2750 m asl]) provide small cryosphere services at high elevations (e.g., debris-covered glaciers and creeping permafrost bodies, Figure 3B and C) the lower elevated Pongkyu Khola catchment (Marpha [28°45′10″ N/83°41′13″ E, 2680 m asl]) almost completely lacks such services. Dry conditions in the Nepalese Trans-Himalaya are particularly evident during the winter season when westerly disturbances are absent. During winter, the temporal snow line is situated well above 7000 m asl (Figure 3A).
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Figure 2. (A) Trends in mean annual temperature [in K] calculated from the CHELSA reanalysis data [45] for the period 1979–2013. Only significant trends (p < 0.01) are shown. (B) Satellite Imagery of the investigation area (Operational Land Imager band composites 6,5,4; acquisition date: October 16, 2020) with blue colors indicating snow and glacierized areas. (C) Climate diagram for Jomsom and (D) photograph towards the settlement of Kagbeni (6 April 2018). Green colors indicate fields with germinated winter barley on the irrigated fields.

The mean discharge of the Kali Gandaki during summer (July–August) exceeds that of spring (March–April) by a factor of 12 to 15 [73,74]. As a result, all settlements and irrigated fields are located on river terraces or alluvial fans to mitigate the threat of seasonal flooding and associated erosion during the rainy season (Figure 2D) [15]. Accordingly, not the Kali Gandaki but the perennial tributary streams represent the only easily accessible source of surface water for these settlements.

Common field cultivation in the irrigated oases of the Kali Gandaki valley commences in December by sowing winter barley [66]. After crop germination in early spring, fields are already verdant between March and April (Figure 2D). During this period, seedlings must be kept moist. Water requirements from February to April are, on average, almost seven times higher than the available precipitation amount [75]. With rising temperatures and increasing transpiration of the crops until the onset of the monsoon in July, water scarcity intensifies. Without the steady supply of meltwaters and a sophisticated water allocation
system, farming and the accessibility to drinking water in this climate would not be possible. Local people’s perception of environmental changes corroborates the increasing moisture constraints due to changed timing or extent of the snow cover [53,54,76–78].

Figure 3. (A) Alpine catchments (red) of the major tributaries (blue) Pongkyu, Thini, and Jhong Khola and location of irrigated fields in Marpha, Jomsom, and Kagbeni (light green; dark green represents irrigated fields of other settlements). Background imagery: Sentinel-2 [79] RGB-composite; acquisition date: 28 December 2015. (B) Thermokarst appearances at debris-covered glacier and (C) rock glacier in the Upper Jhong-Khola catchment indicating the presence of below surface ice below at an elevation of 5000 m asl.

2.2. Cultural Heritage and Recent Developments within the Mustang District

The Mustang District is famous for its role as a cultural and religious connecting area between the Tibetan-Buddhist culture in the north and Hindu culture in the south. Its unique socio-geographic setting within a periphery location results in it historically being one of the most important trading routes in Nepal, with a cultural exchange for 3000 years [66,80]. Historically, mountain dwellers were involved in trading activities between Tibet and India because mere subsistence farming did not ensure sufficient food supply throughout the year [66,81]. However, this exchange of products ended in 1959 with the forced closure of the border between Nepal and the now Tibet Autonomous Region by the new Chinese government [80,82,83]. To sustain local livelihoods, a third branch of economic income, animal husbandry, is a hallmark of the mixed economy of the Mustang population [84,85]. However, with the decreasing significance of trade caused by the closed border, tourism-related activities significantly increased during the past decades, especially in the Lower Mustang [62,86]. Since the Upper Mustang was not accessible for tourism until the early 1990s [87], the stream of visitors was historically more concentrated in the Lower Mustang areas. The investigated settlements of this study are located along the trail of the Annapurna Circuit Trek, which nowadays annually attracts several tens of thousands of Western visitors [88,89]. Additionally, the Hindu and Buddhist Pilgrimage site Muktinath attracts pilgrims, mostly from Nepal and India, to the sacred territory [90–92].

2.3. Cartographic Background

Prior to on-site mapping during a field campaign in 2018, base maps were generated based on optical satellite imagery. In the first step, we used georeferenced multispectral satellite imageries of WorldView-2 and 3 (WV-2, WV-3 DigitalGlobe™) that feature a hori-
horizontal resolution of 0.5 m and 0.4 m, respectively. The satellite imagery is implemented into the geographic information system of the Environmental Systems Research Institute (https://services.arcgisonline.com/ArcGIS/rest/services/World_Imagery/MapServer). The underlying satellite scenes were acquired between April and October (Figure 4; Kagbeni: WV-3 10 May 2015; Jomsom: WV-3 9 May 2015; Marpha: WV-2 9 April 2017; Ranipauwa/Muktinath: WV-2 10 October 2018).

Figure 4. Schematic view of methodological steps applied within this study.

Within the geographical information system, all images were projected to the local Universale Transversal Mercator projection zone (UTM 44N). Since the margins of the fields and edges of the irrigation channels are already vegetated in early spring, the manual digitization of the field boundaries can be a challenging process. Therefore, in a subsequent step, various satellite images from Google Earth Pro (GEP) were additionally acquired outside of the vegetation season. These GEP scenes were orthorectified in accordance with multiple control points to the WorldView satellite scenes (Figure 4). The lack of vegetation exposed the effective width of the irrigation channels and land tenure plots. Based on the orthorectified and georeferenced satellite images, the field margins and buildings were digitized manually, resulting in detailed equal-area projected blank base maps. Compared to the available historical maps, the level of detail is slightly higher in the newly generated satellite-based field boundaries and land tenure plots. Therefore, the cartographic information of Marpha and Kagbeni from the early 1990s was transferred to the new base maps (Figure 4). All field information of the historic maps could be assigned to those of the new maps, which confirms that there were no alterations in the land tenure over the last decades.

Due to the temperate climate within the Lower Mustang (Figure 2C), the investigated settlements are capable of two harvests a year despite elevations of almost 3000 m asl [41,42,75,93]. The historical maps of Marpha (October 1993) and Kagbeni (October 1991) are based on the autumn growing season. Therefore, our field campaign and the on-site mappings of Marpha, Kagbeni (and the additional settlements of Jomsom and Ranipauwa/Muktinath) were conducted during the same season (October 2018). Considering the underlying same investigation season and available historical mapping data, change detection in the crop-

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**Diagram Description:**

1. **Acquisition of high-resolution optical satellite imagery**
2. **Georeferenced World View 2-3 (DigitalGlobe™) Projection to UTM 44 N**
   - Jomsom: WV-3 May 9th, 2015
   - Marpha: WV-2 April 9th, 2017
   - Kagbeni: WV-3 May 10th, 2015
   - Ranipauwa: WV-2, October 10th, 2018
3. **Manual digitisation of field margins & buildings**
4. **Base maps**
5. **Orthorectification**
6. **Various Google Earth™ imagery (different seasons)**
7. **Visual validation of current apple trees (Jomsom) and buildings (Ranipauwa)**
8. **On-sit: mapping in 2018 (land use & functionality of buildings)**
9. **Historical Maps**
10. **Transfer cartographic material from the 1990s**
11. **Maps 2002**
12. **Maps 2018**
13. **Maps 1990s**
14. **Changes 2002 - 2018**
15. **Changes 1990s - 2018**
16. **Jomsom, Ranipauwa**
17. **Ranipauwa, Jomsom, Marpha, Kagbeni**
18. **Marpha, Kagbeni**
ping pattern and the functionality of the buildings in Marpha and Kagbeni can be well assessed (Figure 4).

Notably, no historic mapping data was available for the district capital of Jomsom and Ranipauwa/Muktinath [65]. However, Jomsom is located in the middle of the south–north transect between Marpha and Kagbeni and is of analytical importance as it constitutes the largest agricultural area in the district. The irrigated fields are centered between the main settlement of Jomsom in the north and the village of Thini in the southeast, close to the Thini Kola tributary. It is not feasible to distinguish which land tenure plots belong to Jomsom or Thini. Therefore, these irrigated fields are simply attributed to Jomsom hereinafter. High-resolution GEP satellite images covering Jomsom date back to 2002. However, these earlier satellite images were acquired in spring, when cropping patterns (grains, fruits) differ from the autumn season (e.g., mainly barley instead of buckwheat). Therefore, a direct comparison with our recent land-use mapping in Jomsom is not feasible. Nevertheless, fruit trees within the agricultural areas are clearly visible and distinguishable in the GEP imagery from 2002 (May 10), which covers 95% of the overall agricultural area in Jomsom. Additionally, a GEP scene from 2008 (May 10) covers the remaining fields. We used these two satellite scenes to visually validate the changes in apple cultivation between 2002 (2008) and 2018 (Figure 4). Naturally, this approach merely enables a classification into two categories: fields cultivated with apples and fields not cultivated with apples.

The utilization of buildings in Ranipauwa near the pilgrimage destination of Muktinath (hereafter referred to as Ranipauwa/Muktinath) was additionally mapped during the survey in 2018. Land use was not considered for this settlement, as it is located 1000 m higher than the other three settlements and therefore has a harsher climate. Furthermore, the settlement is located directly at the pilgrimage site of Muktinath, which attracts thousands of tourists every year, making the transformation of the settlement structure a priority. Therefore, we used the same high-resolution imagery from GEP of 2002 (May 10) that was applied for the analysis in Jomsom. The comparison of the mapping from 2018 and the satellite imagery from 2002 enables us to at least perform a visual evaluation of the number of new buildings constructed in the last 16 years and how many of them are related to tourism services.

Methodological Advantages and Limitations

The manual digitization of the field boundaries and houses based on the high-resolution optical satellite images results in a high level of detail. Even though satellite missions, such as the Landsat Missions, have been gathering data for several decades, the spatial resolution of 30 m is too coarse for our studied settlements. On the one hand, false color composites or the calculation of the Normalized Difference Vegetation Index are able to capture fairly well the irrigated area, e.g., of Kagbeni (Figure 5A,B). On the other hand, the individual small-sized irrigated fields and the cropping patterns are not visible from these data (Figure 5C). This can only be accomplished by on-site mappings supported by detailed base maps. However, this methodology also has some shortcomings. The manual digitization of more than 3000 individual fields is very laborious and, due to the nature of the methodology, not readily reproducible. Digitization is a subjective process and is thus prone to variations. One possibility for addressing this uncertainty is to digitize the same fields multiple times [94]. Within this study, we digitized 35 fields of different sizes and complex shapes 10 times and calculated the relative area deviation (Figure 5D).

It is evident that the digitization provides accurate results with an area deviation well below 5%, even for the common small land tenure plots. This uncertainty decreases with increasing field size and accounts for less than 3% for fields around 500 m² (this corresponds to the averaged field size of the studied settlements, Table 1). Consequently, this methodological approach is highly suitable for complex and small-scale agricultural areas in a rugged mountain environment. However, due to considerable manual effort and on-site mapping, this approach is time-consuming and, therefore, impractical for investigating numerous settlements or the entire Mustang District. Therefore, the insights
gained in this study, e.g., on the transformation of cultivation practices or the tourism sector, are not necessarily transferable to the whole district or to other mountain regions. A generalization of these results is only possible if the ecological and socio-economic settings are comparable. In high mountain regions, however, these settings can greatly diverge within short distances; therefore, individual studies are advisable.

3. Results

The three investigated settlements of Kagbeni, Marpha, and Jomsom comprise a total of more than 3000 individual irrigated fields with a total field area of 148 ha. The individual land tenure plots are small in size, with edge lengths ranging between 20 and 30 m (Table 1).

| Settlement | Number of Fields in 1993 | Summed Area [ha] | Mean Area of the Fields [m²] | Buckwheat Area [%] | Apple Area [%] | Vegetables Area [%] |
|------------|-------------------------|------------------|----------------------------|------------------|----------------|-------------------|
| Marpha     | 889                     | 37.4             | 442.2                      | 1993: 42%        | 1993: 32%      | 1993: 4%          |
|            |                         |                  |                            | 2018: 1%         | 2018: 87%      | 2018: 3%          |
| Kagbeni    | 799                     | 33.8             | 416.5                      | 1991: 62%        | 1991: 17%      | 1991: 2%          |
|            |                         |                  |                            | 2018: 29%        | 2018: 36%      | 2018: 12%         |
| Jomsom     | 1316                    | 76.9             | 582.2                      | 2018: 17%        | 2002: 9%       | 2018: 2%          |
|            |                         |                  |                            | 2018: 17%        | 2018: 58%      | 2018: 2%          |

Figure 5. Comparison of Landsat OLI scenes with the mapping approach performed in this study: (A) False color composite (band 5-4-3) and (B) Normalized Difference Vegetation Index (NDVI) of Kagbeni settlement. (C) Manually digitized field boundaries (background image NDVI). The zoomed area of (C) is displayed as yellow box in (B). (Source: Landsat OLI available from the U.S. Geological Survey; acquisition date 14 October 2021). (D) Mean area deviation and standard deviations of 35 multiple digitized fields.
An elaborate network of irrigation channels, mostly composed of stone and sealed with clay (Figure 6A), traverses the fields. Over 42 km of irrigation channels are supplied by the three main perennial tributary streams, Jhong, Thini, and Pongkyo Kola (Figures 3 and 6A). In the past, some of the larger irrigation channels were cemented or covered with stones to reduce transpiration and to serve as footpaths. However, the majority of the irrigation channels and water reservoirs can be considered quite rudimentary (Figure 6A,C), with new technologies incorporating pumping stations encountered very occasionally. The edges of the alluvial fans and terrace rims are prone to recent erosion, e.g., seepage erosion at the outlet of the irrigation channels or undercutting by branches of the highly mobile braided-river system of the Kali Gandaki (Figure 6D). In recent years, erosion has been counteracted by the installation of gabions or concrete walls. However, these erected structures eroded shortly after their establishment (Figure 6E). To support the gabions, willows have been planted (Salix spp., Figure 6E). In combination with the stabilization of the ground, a side benefit of the willows is to harvest litter, fodder, and firewood. Nevertheless, some fields have completely eroded since the mapping in the early 1990s.

3.1. Changing Land Use Pattern in Marpha, Kagbeni, and Jomsom during the Last Decades

Field cultivation was analyzed according to the classification used in the historical mapping of the early 1990s [42]. Mature apple trees are frequently cultivated in conjunction with vegetables, classified as “fruit and vegetable garden” (Figure 6F). Common vegetables planted in this stratification are beans, cabbage, radish, onion, and spinach. A favored innovation is intercropping, or mixed cultivation, of apples and crops (“apple and crops”). The latter did not exist at all at the beginning of the 1990s at any of the settlements but now accounts for almost 30% of the total cultivated area. Intercropping with younger apple crops.

Figure 6. (A) Irrigation channel branching off from the Jhong Khola tributary. (B) Small cascading water reservoirs (blue arrows) and sediment sinks used for irrigation or (C) for water supply to the households (pipelines: green arrows). (D) Undercutting and erosion of the terrace rims at Kagbeni. (E) Gabions and Salix spp. were installed to prevent ongoing erosion. (F) Fruit and vegetable garden. (G) Irrigated fields planted with buckwheat, maize, and intercropping with apple trees (Photos taken by the authors between 2015 and 2018).
trees is found in combination with maize, buckwheat, and potatoes (“apple and crops” Figure 6G). Fields cultivated only with fruit trees, such as pure apple orchards, are simply classified as "Fruits". Although the various apple varieties are most common, apricots, peaches, and walnuts are also occasionally found in the investigated area. The land use patterns and the respective changes in Marpha, Kagbeni, and Jomsom are depicted in Figures 7–9.

(a) Changing Land Use in Marpha

Our results revealed that a striking intensification in apple cultivation is evident in all three settlements. In Marpha, the percentage of cultivated area with apples, whether as “mono cultivation”, as “fruit and vegetable garden”, or as “intercropping”, has demonstrably increased during the last 25 years from 32% to 87% (Table 1 and Figure 7). In addition, new apple orchards (2 ha) were established on the alluvial fan of the Pongkyu Khola river north of Marpha (not displayed in Figure 7). The seasonally highly varying water masses of the streams must be channelized in its riverbed with great technical effort (e.g., gabions and concrete walls) to avoid avulsion and erosion of the new arable land. Two hectares of fruit orchards have already been established, while six hectares of recently constructed (since 2015) terraces are not yet cultivated.

It is noticeable that almost half of the “fruit and vegetable gardens” from the 1990s have been transformed into pure apple orchards (e.g., in the northeastern part of Marpha, Figure 7). Consequently, the percentage of apple monocultures also increased (from 10% to 31%). This is assumably a quasi-natural process triggered by increasing light competition: with increasing maturity and size of the fruit trees, intercropping with maize and buckwheat is replaced by vegetables, and finally, the sequence is completed in pure apple cultivation. The percentage of “fruit and vegetable garden” has remained stable in recent decades (22% of the total arable land in 1993 and 2018, respectively, pie chart in Figure 7). This constant value masks the underlying dynamics of the evolving field patterns: the fields that were formerly “fruit and vegetable gardens” and are now considered pure apple cultivation must have been substituted elsewhere.

This transition is particularly evident in buckwheat cultivation, which covered 42% of the total area in the 1990s. Today, buckwheat has almost completely disappeared and accounts only for 1% of the total cultivated area (pie charts in Figure 7, Table 1). Four-fifths of the fields formerly cultivated with buckwheat are now substituted with apple cultivation. The remaining fifth of the fields were either overbuilt or cleared and rendered barren by the construction of the Annapurna Highway (refer to next paragraph).

A similarly severe decline can be observed for mixed cropping (maize and beans) and potatoes, which formerly accounted for 10% and 6% of the total area. Both cultivations decreased to less than 1% in favor of apple (inter)cropping (Figure 7). The major agricultural products used for intercropping in Marpha are maize, buckwheat, and potatoes, accounting for 21%, 7%, and 6%, respectively. Overall, Marpha accounts for the lowest percentage of arable land that has fallen barren or was abandoned (less than 0.5%). Compared to Jomsom and Kagbeni, the percentage of fallow fields rose considerably, to 3% and 10%, respectively.

A decisive regional development in recent years was the finalization of the Annapurna Highway. Due to space constraints, the road cannot pass through or along the historic village (steep slopes towards the west, dense development, and mature apple orchards to the east of the village center). Therefore, the Annapurna Highway cross-cuts the main agricultural area in the northern parts of Marpha in a straight line. The remnants of dissected fields (about 30 fields are affected) are mainly left barren or used for new building sites. Since the historic village center of Marpha is characterized by a dense housing area, the only options for settlement expansion are outside or along the Annapurna Highway.
Figure 7. Land use at Marpha settlement during the autumn season in 1993 and 2018. Pie charts represent the relative area of the various crops in relation to the total arable land. The intercropping of apples with buckwheat, maize, and potatoes are grouped as cyan within the pie chart. The underlying detailed on-site mappings were performed in Oct. 1993 and Oct. 2018, respectively. Projection WGS 1984 UTM Zone 44N (scale 1:11,600).
(b) Changing Land Use in Kagbeni

In Kagbeni, the total area cultivated with apples (monocultures, fruit gardens, intercropping) has more than doubled since 1991. Noticeably, the percentage of apples is smaller in Kagbeni than in Marpha, amounting to 36% and 87%, respectively (Table 1). Approximately 40% of the “fruit and vegetable gardens” in Kagbeni have been converted into pure apple orchards during recent decades. However, the cultivated area of “fruit and vegetable gardens” was scarce in Kagbeni in 1991 and 2018 (3% and 5%, respectively; Figure 6; pie charts), which contrasts with the high proportion in Marpha (constant 22%). This transformation is, therefore, not decisive for the observed increase in apple cultivation. Indeed, new apple orchards were mostly established on formerly barren or abandoned fields in the southernmost areas or on the isolated fields along the Jhong Khola in the northeastern part of the settlement (Figure 8). These two regions alone account for 85% of the newly cultivated apple orchards.

During the last three decades, Kagbeni has revealed quite contrasting transformations to Marpha in terms of the cultivation of vegetables and intercropping. The pronounced increase in intercropping on the total cultivated area as observed in Marpha (+34%) and Jomsom (+33%) is lacking in Kagbeni (+2%). An opposing pattern is evident for vegetable cultivation, which is increasing in Kagbeni (from 2% to 12%) and decreasing in Marpha (from 4% to 3%) (Pie charts in Figure 7, Figure 8, and Figure 9). An analogous tendency can also be found in the cultivation of potatoes in the two settlements, with an increasing proportion in Kagbeni (from 4% to 9%) and decreasing proportion in Marpha (6% to 1%).

Similar to the development in Marpha, the decline in pure buckwheat cultivation is a very striking phenomenon in Kagbeni. The former buckwheat proportion of 62% of the total arable land has shrunk to 29% today (Table 1). This decline is favored by increasing cultivation of various crops (e.g., vegetables, potatoes, intercropping, or pure apple orchards, Figure 8).

The number of barren or abandoned fields is fairly stable at Kagbeni. However, the location changed (Figure 8). In the southern part of Kagbeni, formerly non-cultivated barren areas were converted into apple orchards, while several irrigated fields at the threatened terrace rims in the southwestern part along the Kali Gandaki have now been abandoned or left barren. Overall, approximately 10% of the arable land was left barren or abandoned between 1993 and 2018.

(c) Changing Land Use in Jomsom

The highest number of individual fields is located within the district capital of Jomsom. More than 1300 individual land tenure plots cover an area of almost 77 ha (Table 1). The agricultural area is thus more than twice as large as that of Kagbeni or Marpha. The average area of the fields in Jomsom is also more than 100 m² higher than that of the other two settlements. As no historical maps are available, a direct comparison across the decades is not possible. Therefore, only the recent cropping system can be displayed in detail. However, by using optical satellite imagery (Section 2.3), it was possible to detect the dynamics in apple cultivation between 2002 and 2018.
Figure 8. Land use at Kagbeni settlement during the autumn season in 1991 and 2018. Pie charts represent the relative area of the various crops in relation to the total arable land. The intercropping of apples with buckwheat, maize, and potatoes are grouped as cyan within the pie chart. The underlying detailed on-site mappings were performed in Oct. 1991 and Oct. 2018, respectively. Projection WGS 1984 UTM Zone 44N (scale 1:12,500).
Figure 9. Land use at Jomsom settlement during the autumn season in 2018 (upper graph) and historical development of apple cultivation (lower graph). Pie charts represent the relative area of the various crops in relation to the total arable land. The intercropping of apples with buckwheat, maize, and potatoes are grouped as cyan within the pie chart. The underlying detailed on-site mapping was performed in October 2018. Projection WGS 1984 UTM Zone 44N (scale 1:12,000).
In 2018, 58% of the total arable land was cultivated with any apple, with intercropping accounting for the largest proportion, with 33% of the total cultivated area, followed by pure apple orchards (19%) and “fruit and vegetable gardens” (6%) (Figure 9). The dominant crops for intercropping were maize and buckwheat, with 15% and 16%, respectively. Compared to Marpha, where the intercropping and the pure apple orchards are well balanced (34% and 31%, respectively), Jomsom demonstrates an imbalance in favor of intercropping. The small amount of old-growth apple orchards or fruit and vegetable gardens can be attributed to the high percentage of young apple trees observed during our mapping. The satellite imagery corroborates that merely 9% of the total area was cultivated with apples prior to 2002 (Figure 9). It was only afterward that apple cultivation increased rapidly so that within 15 years, almost half of the entire arable land was cultivated with apples. Similar to Marpha, predominantly maize and buckwheat are used for intercropping (15% and 16% of the total arable land, respectively). The simultaneous cultivation of potato and apple is of marginal importance (2%).

Jomsom is not only geographically located on the south–north transect between Marpha and Kagbeni. As revealed in Table 1, Jomsom also represents an intermediate in terms of apple cultivation (58%) between Marpha (87%) and Kagbeni (36%). The same applies to the percentage of buckwheat fields, which account for 17% of the total arable land, while Marpha and Kagbeni account for 1% and 29%, respectively. However, a unique characteristic of Jomsom is the comparatively high percentage of cultivated maize (16%), which is four times higher than in Marpha and Kagbeni.

3.2. Development of Touristic Facilities

In addition to the observed modification in land use, the investigated settlements have additionally undergone a considerable socio-economic change. The unequivocal focus on tourism as a main economic branch in the Mustang District is particularly reflected in the functionality of the buildings mapped in Ranipauwa/Muktinath. In 2018, almost half of the buildings (49%) can be considered tourist facilities. During the last 15 years, the number of houses in Ranipauwa/Muktinath increased from 46 to 114. Of all these buildings, 25% are classified as hotels, lodges, or shelters for pilgrims (in total, 29 lodges, Table 2). The accommodations for tourists commonly comprise a restaurant and a small shop selling souvenirs or food (accounts for all investigated villages within this study region). Additionally, to the hotel shops, 16 independent shops and 4 restaurants were present in 2018 (Table 2). Since the satellite images from 2002 only provide information as to whether the houses already exist or not, their historical functionality cannot be assured. Therefore, the number of buildings for tourism facilities in 2002 is considered to be the maximum possible number in Ranipauwa/Muktinath. However, in recent decades there has been a significant increase in tourist facilities, at least doubling the number of hotels, shops, and restaurants (Table 2). Of the newly established buildings, 12 are still under construction, making their functionality during the mapping in 2018 uncertain (not listed in Table 2). However, several of these buildings have more than three to four floors, which is very uncommon for domestic residences and suggests that they rather have tourist purposes, e.g., as hotel estates.

A similar development is apparent for Kagbeni. Of 72 newly constructed buildings since 1991, 51 (70%) can be assigned to tourist facilities. The ancient village center of Kagbeni is characterized by high-density housing, featuring a small-scale and contorted nature of traditional buildings positioned adjacent to each other. In consequence, due to space constraints, the recently constructed buildings are located outside the historical village center along the fluvial terraces of the Jhong Khola on formerly stable or threshing places and irrigated/abandoned fields (Figure 8). Since 1991, the number of hotels and lodges has more than quadrupled to 28 buildings. Besides hotels and lodges with compulsory restaurants and souvenir shops, the number of stand-alone restaurants/tea houses increased from 0 to 11. The number of shops has increased five-fold to date (Table 2). It is
noteworthy that besides several new souvenir and handicraft shops, two meat stores and a small supermarket recently opened.

Table 2. Development of touristic facilities in Marpha and Kagbeni derived from historical mapping [64,66] and recent remapping. For the Ranipauwa/Muktinath settlement, the functionality of the buildings is only assured in 2018. For 2002, only the presence or absence of the buildings is certain (italic).

| Settlement            | Total Number of All Touristic Facilities | Number of Hotels, Lodges, and Shelters for Pilgrims | Number of Shops | Number of Restaurants |
|-----------------------|-----------------------------------------|------------------------------------------------------|-----------------|-----------------------|
| Marpha                | 31/57 (1993/2018)                        | 14/22 (1993/2018)                                     | 14/29 (1993/2018) | 3/4 (1993/2018)       |
| Kagbeni               | 10/61 (1991/2018)                        | 7/28 (1991/2018)                                      | 3/15 (1991/2018) | 0/11 (1991/2018)      |
| Ranipauwa/Muktinath   | 23/54 (2002/2018)                        | 13/29 (2002/2018)                                     | 8/16 (2002/2018) | 2/4 (2002/2018)       |

As observed in Kagbeni, the historic village center of Marpha is characterized by a dense housing area, resulting in the erection of new buildings being possible only outside and along the Annapurna Highway. An increase in tourism facilities in Marpha is evident as the number of tourism-related facilities has almost doubled since 1993. The number of buildings for accommodation increased from 14 to 22, and the number of shops increased from 14 to 29. The shops are mostly to be found in the historic village center and, among other things, offer handicrafts or souvenirs. In Kagbeni and Ranipauwa/Muktinath, new lodges and hotels have been predominantly constructed outside the village center. In Marpha, however, the extension of pre-existing infrastructures instead of new construction is frequently observed. For instance, all the lodges that were surveyed in the 1990s are still present but enlarged.

4. Discussion

The Mustang District has undergone profound eco-climatological as well as socio-economic changes over the past decades, creating a distinct Trans-Himalaya mountain landscape in transition. However, the illustrated changes cannot be simply attributed to a single forcing such as climate change. It is more the result of a complex array of interdependent environmental and socio-economic drivers.

One of the driving triggers, the realization of the Annapurna Highway, lead to regional fundamental socio-economic repercussions [62,95]. The traditional trading by means of yaks, mules, or horses was replaced with less time-consuming and more efficient use of trucks and buses. Due to the direct connection to the marketplaces of large cities such as Beni, Pokhara, or even Kathmandu, agricultural products can now be transported conveniently and cost-effectively from this formerly peripheral region [62,96,97]. Moreover, the new transport options have also significantly reduced the proportion of jostled and bruised apples making the apple business much more lucrative even for households with small areas of arable land [98,99]. This means that the subsistence economy in the Mustang District has been superseded by a market-oriented economy in which fruit and vegetables are transported to supra-regional markets [62,97,100,101].

The settlement of Marpha, where apples were first introduced in the 1960s and where an Agricultural Research Centre (apple horticulture) is located, is traditionally closely associated with the cultivation of fruit trees [93]. Thus, it is plausible that Marpha nowadays accounts for the largest proportion of apples, with apples growing on 87% of the total arable land, giving rise to the name of “apple capital of Nepal” [76]. A declining percentage of apples from Marpha (87%), Jomsom (58%), and Kagbeni (36%) is evident. This decline in the favored cash crop might also be attributable to the different construction phases of the Annapurna Highway from south to north. The first construction phase was realized in 2007 and ended in Jomsom. The section north of Jomsom was addressed during the
subsequent construction phase [62]. Even in 2018, during the remapping, a significant extension of the road between Jomsom and Kagbeni was still in progress. The rapid expansion of apple cultivation is evident in Marpha and Jomsom, with a huge amount of young trees being inserted into the fields (resulting in a high percentage of intercropping; see Figures 6G, 7 and 9). In Jomsom, before 2002, only 9% of the arable land was cultivated with apple. To date, the proportion has risen to 58%. Additionally, apple cultivation is being expanded outside the traditional fields in new orchards along the Pongkyu Khola and on its alluvial fan north of Marpha. The new establishment of fruit plantations along the tributary streams is not a unique feature of the Marpha region. As observed during multiple field surveys by the authors in recent years, an apple orchard of 2.7 ha (derived from satellite scene WV-2 9 April 2017) was established within the tributary stream Syan Khola (located between Marpha and Jomsom). Even in a sheltered location within the stream bed of the Kali Gandaki at Tiri (neighboring village north to Kagbeni), approximately 2.4 ha were recently established. The new apple plantations, set up in riverbeds or alluvial fans, must be protected from erosion with great technical effort. The constructional measures are accompanied by a high financial burden, which is only worthwhile if a long-term yield is anticipated, which points to the high economic suitability of apple cultivation in Marpha and its surrounding settlements [97].

In contradiction to the creation of additional arable land for fruit trees is the observation and perception of the communities that increasing water scarcity is a worsening concern [54,75,102]. The underlying process of environmental change is the second main trigger explaining the observed agricultural changes in Mustang. The rising temperatures, decreasing snow cover duration, and the changing seasonality of solid precipitation reduce infiltration and, therefore, soil moisture. Even late winter and early spring snow events melt at an accelerated rate and shortly increase surface runoff, while a prolonged increase in soil moisture is absent. The diminished replenishing of the water resources during the dry season is causing springs to dry up in some regions within the study area [54,76,102–105]. This implies that the peak water supply due to reduced snow cover, deglaciation, or melting permafrost bodies has already been exceeded. For a tributary watershed of the Kali Gandaki between Kagbeni and Jomsom, one-fourth of the arable land is left barren due to water scarcity, which further causes tensions among the settlements regarding water allocation [103]. This is also reflected in the increasing proportion of barren and abandoned land within the south–north transect between Marpha and Kagbeni, which increased from less than 1% to 10%. However, caution must be taken when ascribing abandoned fields exclusively to a changing climate and insufficient irrigation water, as multiple causes can be present or promote those transitions such as emigration, natural hazards, conflicts in land ownerships, or focus on the new economic branch of tourism [63,66,105]. These abandoned fields are well preserved due to high aridity and are evidence of the long-standing settlement history, representing a striking feature of the cultural landscape in Mustang [53,63,106,107]. In recent decades, however, the fallow area has increased considerably due to water scarcity, leading, in extreme cases, to the resettlement of entire communities in the Trans-Himalayan Mustang [53,63,104,108].

A possible adaption or coping strategy in the farming system to a changing climate and reduced water availability is to implement crop diversification or a changed cropping pattern [109–111]. The incorporation of fruit trees into traditional farming techniques yields several benefits. (I) Trees are very robust even in disadvantageous climatic conditions and are certain to flower again the following year [111]. In contrast, traditional annual crops and their seeds can be completely forfeited under adverse climates resulting in a high financial loss in the current and subsequent seasons. (II) The trees are creating favorable microclimate conditions within the highly evaporative Mustang climate with its high wind speed and insolation. Moreover, the water consumption of fruit trees is lower than that of crops. Regmi et al. 2019 [102] estimated that the monthly irrigation water requirement of buckwheat and potato is higher than that of apples by a factor of 3.6 and 2.7, respectively. (III) Monocultures and the one-sided removal of nutrients are
From the point of increasing water scarcity, the introduction and expansion of apple cultivation are appropriate [109,112], accompanied by a reduction in intense water cultivation such as buckwheat. However, the associated labor input and benefits are also decisive for the prevalence of apple trees within the Mustang District. Labor requirements for the cultivation of crops such as buckwheat or barley are approximately three to six times higher than for fruit and vegetable gardens or pure apple orchards [97]. The high labor requirements for grain cultivation, accompanied by a decrease in population (especially permanent/seasonal out-migration of young people) in the high mountain valleys of Nepal [63,96,110,113], favor the transition from labor-intensive subsidence to easier accomplishable cash crop cultivation [96]. The working capacity for agriculture (grain cultivation) is also constrained by other time-consuming tasks such as collecting firewood, which requires a day each week [78,110], collecting fodder and litter for animal housing, or by pastoralism [114]. Moreover, the major proportion of labor for fruit tree cultivation is required only once a year during the harvesting period. During this period, migrant laborers are frequently employed, who in turn benefit from the easy accessibility of the Annapurna Highway.

In contrast to apple cultivation, buckwheat production in Marpha and Kagbeni has declined significantly during the past 25 years (−98% and −53%, respectively), although market prices have increased [63]. On the one hand, it can be presumed that the one-third reduction in the price of rice due to the Annapurna Highway [96] is contributing to the replacement of buckwheat as the predominant grain. On the other hand, the high labor requirement for buckwheat cultivation [97], combined with a general shift of agricultural products in touristic regions towards intensified vegetable production [115,116], results in decreasing production of traditional crops such as buckwheat. Furthermore, climatic constraints (the emergence of various pests and a concomitant decline in productivity due to a changing climate [84,117]) result in decreased productivity. In the southern parts of the Mustang District, in the more humid locations 15 km south of Marpha, rising temperatures favor the appearance of insect outbreaks and crop diseases affecting fruit trees [76,116,118,119]. Therefore, apple cultivation of formerly advantageous sites is gradually shifting towards higher elevations and drier sites in the north, with irrigation simultaneously increasing in relevance.

High amounts of irrigation water are wasted applying traditional irrigation systems (e.g., flood irrigation [110]) and to high losses in transportation [75]), making the maintenance and upgrading of water reservoirs or irrigation channels mandatory [103]. Nevertheless, the irrigation channels and water reservoirs within the three investigated settlements lack adequate construction technologies (cemented or polyethylene pipes), so the seepage rate remains high. For several regions of the Annapurna- and Dhaulagiri-Trans-Himalaya, water scarcity and accompanying conflicts are attributable to insufficient runoff in general but also to inefficient irrigation techniques [53,103,110,115]. This is further exacerbated by the steady increase within the tourism sector and the excessive demand for freshwater resources. Lama and Job [62] interviewed hoteliers who had already expressed concern about reduced water availability 10 years before this present study. Considering the increasing number of tourist facilities at Ranipauwa/Muktinath, Marpha, and Kagbeni during the last decades, water allocation will certainly be even more controversial among various stakeholders. Not only the continuous supply of water but also its quality is of great concern. The lack of basic infrastructures and management of sewerage and waste results in progressive contamination of the tributaries and threatens the potable water supply. Approximately 80% of the households in Kagbeni report insufficient access to drinking water [120]. Therefore, a new water source was tapped at the opposing western slope and piped across the Kali Gandaki to Kagbeni.

One additional adaption possibility to reduce water wastage due to irrigation is to subdivide larger fields into multiple ones [103]. However, such an approach was
not detectable for Marpha and Kagbeni by our remapping. This might be attributed to the historically small sizes of the fields, as the average size of the irrigated fields is 0.04 ha (Table 1). Moreover, the generally small cultivated area per household is not sufficient to feed the local population; e.g., for Kagbeni, less than 1 ha is available per household [42]. Therefore, livelihoods are secured by diverse branches of income, e.g., livestock and tourism.

The number of annual tourists within the ACA has risen sharply from the 1990s to 2019, from 40,000 to 180,000 [89]. In the most recent decade, pilgrimage tourism (in particular from India) has increased considerably at the Hindu and Buddhist pilgrimage site Muktinath [90,92,121,122]. The increase in pilgrim tourism is attributable to the construction of the passable road and the easier accessibility of the formerly isolated periphery [62,100,101]. Tourist and pilgrimage arrivals are particularly focused on the drier spring and autumn seasons (Mar–Apr and Oct–Nov) [86]. This inevitably results in increased freshwater consumption and demand for water-intensive crops (vegetables and pulses) [123,124]. Our remapping in Kagbeni indicates that despite increasing water scarcity, enhanced vegetable cultivation (from 2 to 12% of the total arable land). The same principle applies to Marpha; even though there are no fields with pure vegetable production, the vegetables are mainly cultivated in conjunction with apples in fruit gardens. At the same time, the sharp decline in buckwheat cultivation in Marpha and Kagbeni can also be attributed to tourists’ preference for rice [123].

Furthermore, the demand for meat paralleled the steady rise in the number of tourists and hotels within Marpha and Kagbeni. As a consequence, villagers intensified their livestock production in the 1990s, especially goats, which used to be considered more of a pet [123,124]. Each household in Jomsom and Kagbeni owns an average of 17 animals (cattle, yak and cross breeds, goats, etc.) in a mixed feeding system composed of grazing and feeding of agricultural by-products [84]. Maize is often used for supplemental feeding. Therefore, in Jomsom and Marpha, the percentage of maize (intercropped with apple) has a high proportion of 21% and 15% of the total arable land, respectively. However, livestock production is endangered by a changing climate, too. Increasing temperatures and extreme events (e.g., snow storms, droughts) and an increased snow cover variability result in an overall decline in rangeland productivity. In addition, reduced availability of forage and enhanced occurrence of livestock diseases is apparent, which result in an overall decline in livestock productivity [49,50,84,110,125].

5. Conclusions

The effects of climate change are exacerbated in the high-altitude regions of the semi-arid Trans-Himalayas in Nepal. Rising temperatures have a detrimental impact on regional cryosphere services since glaciers are melting at an accelerated rate, snow cover is decreasing, and seasonality in snowfall is changing. In addition, precipitation patterns outside the monsoon season are irregular, so water availability is highly variable. Parallel to the rapid climatic changes, socio-economic transformations such as the new Annapurna Highway or increasing tourist numbers exert pressure on subsistence-oriented and traditional agropastoralism. Our study revealed profound changes in irrigation-based land use systems and tourism facilities over the past three decades. A common adaptation strategy would be diversification in cultivation practices or even economic branches. For the settlements of Marpha, Jomsom, and Kagbeni, an excessive increase in cash crops (apple) was observed. The cultivation of apples has more than doubled in all three settlements since the 1990s. Especially, intercropping with apple and field crops has increased. At the beginning of the 1990s, this cultivation practice did not yet exist, and today it accounts for almost 30% of the total arable land. On the one hand, this type of farming yields several benefits towards the extreme evaporative climate compared to traditional farming practices. On the other hand, there is a great demand for apple products among the tourists who annually visit the Mustang District, as well as in the supra-regional markets in Pokhara, Kathmandu, and even India. Both the commercialization of fruits and the number of
tourists/pilgrims are closely related to the accessibility of the mountain region. With the new Annapurna Highway, the transport of apples was facilitated, and tourists could access the region much faster. This is corroborated by the significant increase in tourist facilities, which have all at least doubled in number. The high numbers of tourists and their requests for products such as vegetables and meat are resulting in a pervasive change in field cultivation with high water requirements. Simultaneously, the freshwater demand of the tourism sector in hotels and lodges is steadily increasing. This competes in a region where water quality is deteriorating due to the (seasonally) high population and where springs are already drying up due to climate change. With ongoing climatic trends, the conflict over the allocation of water will grow. Therefore, thorough water management is essential to reconcile the divergent concerns of agriculture, local communities, and tourism for the purpose of sustainable livelihoods. However, in this region, where the observed changes are occurring so rapidly, it remains uncertain whether all the interests of the various stakeholders are being addressed in a sustainable and appropriate manner.

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