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Spatiotemporal Variation in the Land Use/Cover of Alluvial Fans in Lhasa River Basin, Qinghai–Tibet Plateau

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Abstract: Alluvial fans are an important land resource with agricultural potential in Qinghai–Tibet Plateau. The spatiotemporal variation in land use/cover is an important indicator to understand the value of alluvial fans and protect and make scientific use of such fans. In this study, the spatiotemporal characteristics of land use/cover are determined by analysing the land use/cover changes of alluvial fans in the Lhasa River Basin (LRB) at different times, counties/districts, altitudes, and gradients. Results show that the area of cultivated land and the artificial land provided by alluvial fans for LRB has continuously increased. In 2000, 2010, and 2020, 17.72%, 21.84%, and 24.17% of cultivated land and 7.89%, 7.51%, and 25.24% of artificial land in LRB were provided by alluvial fans, respectively. At all altitudes and slopes, cultivated land and artificial land are increasing but the increasing part is basically due to the massive loss of grassland. The spatiotemporal changes in all land use/cover types of alluvial fans were dominated by human activities, although they were also influenced by natural factors to some degree.

Keywords: alluvial fan; land use/cover changing; Lhasa River Basin; Qinghai–Tibet Plateau

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Citation: Chen, T.; Jiao, J.; Wei, W.; Li, J.; Zhang, Z.; Yang, H.; Ma, H. Spatiotemporal Variation in the Land Use/Cover of Alluvial Fans in Lhasa River Basin, Qinghai–Tibet Plateau. *Agriculture* **2023**, *13*, 312. https://doi.org/10.3390/agriculture13020312

Academic Editor: Alvyra Šlepetienė

Received: 2 December 2022
Revised: 20 January 2023
Accepted: 25 January 2023
Published: 28 January 2023

1. Introduction

Land use/cover is the direct manifestation of the effects of human activities on the surface ecological environment, and it connects and influences human society and the ecological environment [1]. In recent years, with the increase in population and the intensification of global land use/cover changes, ecological environment security has been threatened at different scales [2]. Different land use/cover types, such as grassland, woodland, and wetland, maintain various ecological services and play important roles in maintaining biodiversity, water conservation, and soil conservation [3,4]. Therefore, changes in land use/cover, especially when land use/cover is developing in an unsustainable direction, are likely to cause many ecological and environmental problems, such as regional climate change, land degradation, and water quality deterioration [5–8]. These eco-environmental problems will lead to damage to land ecological services, and damage to land ecological services will aggravate the eco-environmental problems and form a vicious circle [9]. Consequently, research on land use/cover change has increased rapidly in recent years, especially in ecologically fragile areas, national parks, and large cities where a serious contradiction exists between land supply and demand [10–13]. Related studies have made great contributions to land use/cover planning, ecological environment protection, and sustainable development in these areas.

Qinghai–Tibet Plateau (QTP) is a world-famous ecologically fragile area, and its land use/cover change has received extensive attention [14]. The grassland area increased by 96,397 km^2 from 2001 to 2016, and the increased area was mainly from the transformation of sandy land and forestland in QTP [15]. Permanent glacier snow decreased by 22.72%, and built-up areas increased by 106.38% from 1980 to 2015 in the Yarlung Tsangpo River Basin of QTP [16]. The land use/cover change from 1977 to 2004 in the Qinghai Lake Basin of QTP, especially the decrease in grassland and woodland, has aggravated the water quality of Qinghai Lake [17]. The fastest change in land use/cover occurred in urban or built-up land, which was increased by 2.32% in 1990–2000 and by more than 50% in 2000–2007 in the Lhasa River Basin of QTP [18]. These studies have shown that a serious contradiction still exists between the limited land resources and the increased human demand in some areas of QTP. The contradiction is due to the fragile ecological environment and complex landforms comprising the mountains and valleys of QTP, so the land suitable for human production and living is reduced [19]. The population is mainly concentrated on the relatively flat river terraces in river valleys [18], but river terraces are limited land resources where large-scale towns and even cities have been developed at present. The population of QTP is still increasing, and further land resources are needed to produce food or live in the area. Limited river terraces have difficulty meeting the human demand for land resources, so cultivated land, and residential areas are constantly developing into areas with high altitudes and high slopes, which are not the first choice of people in terms of residence [20,21].

Similar to river terraces, alluvial fans in river valleys are important to land resources. Alluvial fans are developed in all kinds of terrestrial environments around the world, such as humid tropical, humid mid-latitude, alpine, periglacial, and different paraglacial settings [22]. Alluvial fans arise in a variety of environments, but comparable causes impact their landform and substance. Alluvial fans are directly impacted by bedrock types, basin extent, slope gradient, and geological catchment characteristics [23,24]. Solid materials eroded from an upland catchment make up alluvial fans [25]. Alluvial fans developed into settlements or farmlands are typically found in areas with favorable hydrological conditions, good soil, and a generally level landscape [26–29]. Therefore, the alluvial fan is an important land resource in many mountain areas of the world [30].

The good soil, hydrology, and terrain conditions of alluvial fans make them suitable areas for human life in mountain environments [27]. However, because alluvial fans are fan-shaped landforms formed by the continuous deposition of weathered materials from the catchment, their surface is vulnerable to the threat of flood disasters [31,32]. Although the surface of alluvial fans is threatened by floods, it still has many cultivated lands, orchards, and residential areas, which is a contradiction that can reflect the shortage of available land resources in mountainous areas [26]. With the increased population in mountainous areas, human beings have to consider using any relatively available land as much as possible. Therefore, in recent years, some scholars have paid attention to the land use/cover characteristics of alluvial fans. The area of towns on alluvial fans in the southern part of the desert in Israel is increased, leading to increased impermeable surfaces that are likely to trigger floods [33]. In recent years, the area of residential areas, roads, and artificial canals on the surface of two alluvial fans in southern Turkey has increased, making the landform of alluvial fans increasingly difficult to be influenced by natural factors but easily influenced by human activities [34]. The deposition and development process of alluvial fans in the loess Glubczyce Plateau (SW Poland) is related to the land use/cover change in the historical period (ca. 5.5 ka BC), and alluvial fans are likely to be eroded when the forest area is reduced [30]. Therefore, at present, the study of alluvial fans mainly focuses on the formation, development, sources, influencing factors, and surface disasters, but pays little attention to the land use of its surface. Few studies have focused on the impact of land use on the topography of alluvial fans. However, the main purpose of those studies is to analyse the influence of land use/cover on the geomorphology of alluvial fans. Studies on the spatiotemporal variations in land use/cover are few, although such variations are important indicators of the scientific protection and use of alluvial fans. Moreover, related studies in alpine areas are lacking. Therefore, the current study has two main objectives. The first one is to use the Lhasa River Basin (LRB) of QTP as an example to analyse the temporal changes in land use/cover in 2000, 2010, and 2020 and the spatial changes in land use/cover in different counties/districts, slopes, and altitudes. Secondly, through a discussion, we analyse the influencing factors of land use/cover distribution and its change in alluvial fans and propose scientific methods for the sustainable development of alluvial fans, which should provide a scientific basis for the protection and rational utilisation of alluvial fans in alpine regions.

2. Materials and Methods

2.1. Study Area

The Lhasa River is one of the first-class tributaries of Yarlung Zangbo River, and it originates from the south foot of Nyainqentanglha Mountain and is one of the highest rivers in the world. LRB is located in the south of QTP, with an area of 31,760 km^2. The area accounts for only 2.7% of the area of the Tibet Autonomous Region, but 15% of the cultivated land and population of the Tibet Autonomous Region are distributed, and it is the central area of politics, economy, and culture in Tibet. LRB has nine counties/districts, namely, Chen Guan, Tolung Dechen, Chushur, Taktse, Medro Gongkar, Lhundup, Damshung, Seni, and Chali (Figure 1). The upper reaches of the Lhasa River have a small population and mainly develop animal husbandry. The middle reaches have a large population and mainly develop agriculture. The downstream area is densely populated and mainly develops industries and agriculture and its services. The total area of cultivated land in LRB is 656.44 km^2 (as of 2011), which is mainly distributed in the lower reaches and gradually decreases to the upper reaches. At present, cultivated land is gradually advancing to areas with high slopes and altitudes [20].

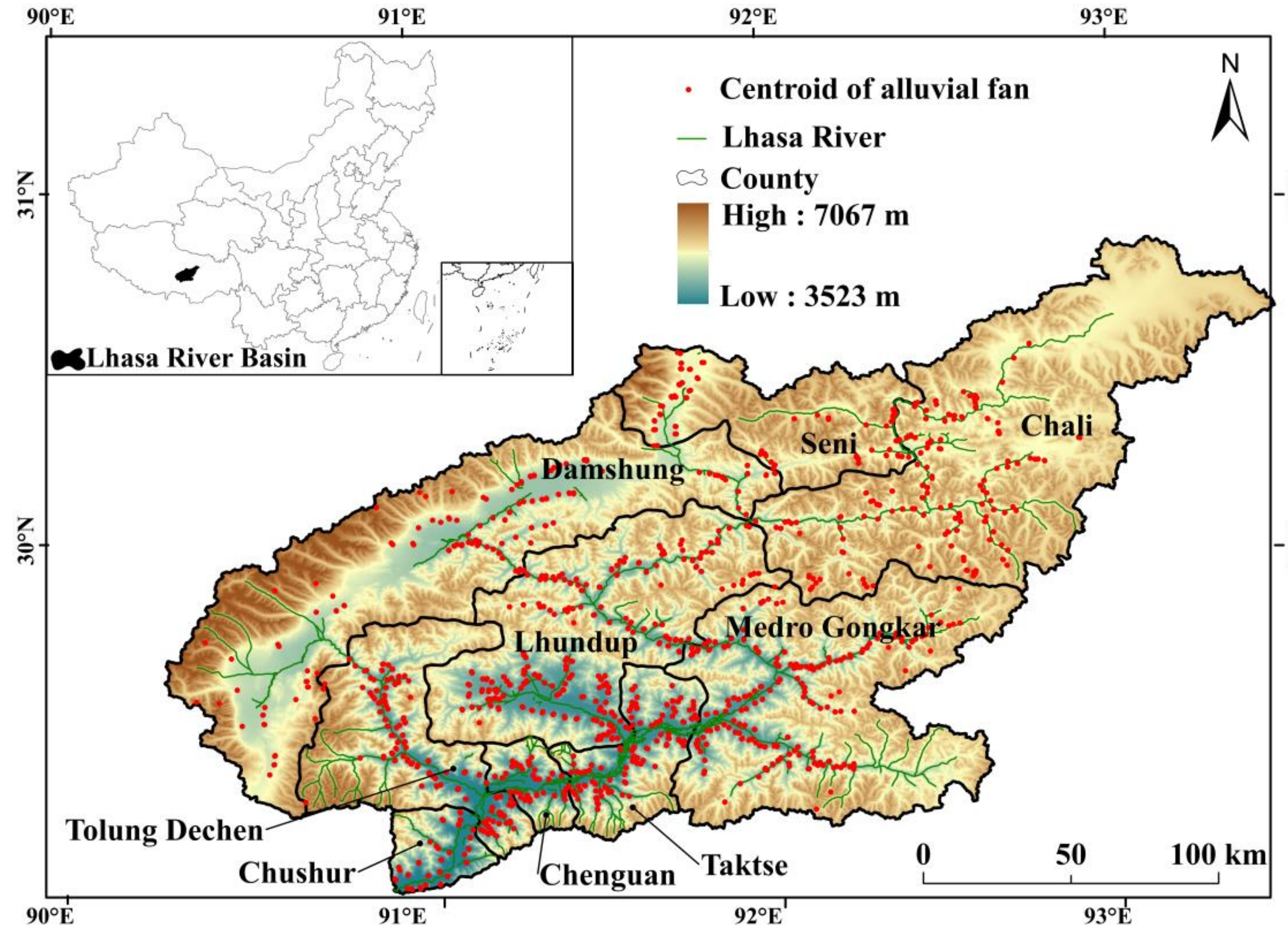


Figure 1. Administrative division of Lhasa River Basin.

LRB has a plateau monsoon semi-arid climate. The plateau is able to characterized by high altitude, periglacial processes, and a cold and dry continental climate. The annual rainfall is between 340 and 600 mm, and its distribution is uneven, namely, concentrated from June to September [35]. The terrain of LRB is steep, ranging from 3523 m to 7067 m. The landforms mainly include mountains, river terraces, and alluvial fans [36]. River terraces, with many towns and cultivated land being distributed, are important land resources for the locals. However, due to the development of the social economy and population in recent years, the utilisation degree of river terraces is high.

Although the slope of alluvial fans is higher than that of river terraces, it is much smaller than that of mountains; research has proven that alluvial fans still have certain development potential because of their closeness to rivers, roads, and villages [19]. At present, they face many ecological and environmental risks, such as mass movements, boulder streams, creep/soil creeps, rockfalls, gully erosion, floods, debris flows, soil coarsening, and desertification [19,37]. There are a large number of alluvial fans in LRB. LRB has 826 alluvial fans with an area of 1166.03 km^2 (Figure 1, [19]). Due to the fact that the slope of the alluvial fan is relatively gentle and close to the Lhasa River, it has the potential for utilization.

The vegetation type of LRB is characterized by alpine meadows, alpine shrub shrubs, cushion vegetation, alpine steppe, etc. The vegetation species on the alluvial fans mainly includes crops such as brassica napus, hordeum vulgare, and pisum sativum, woody plants such as pyrus spp, populus szechuanica, and caragana sinica, and herbaceous plants such as leusine indica, agropyron cristatum, and gnaphalium affine [36].

There are seven soil types in this LRB: alpine steppe soil, alluvial soil, alpine meadow soil, meadow soil, subalpine meadow soil, subalpine steppe soil, and alpine frozen soil. The soil of the alluvial fan belongs to alluvial soil and contains more gravel.

2.2. Data Sources

The distribution data on alluvial fans were derived from previous research [19]. DEM data were obtained from the NASA EARTHDATA (ALOS, 12.5 m). Land use/cover data were obtained from the GlobeLand30 official website (http://www.globallandcover.com/, accessed on 15 November 2021). We obtain the land use data of the Lhasa River basin after Project, Mosaic, and Clip the raster data from the website in ArcGIS. Then, the land use data of alluvial fans can be obtained by using the distribution data of alluvial fans, the land use data of the Lhasa River basin, and the Spatial Analyst in ArcGIS. The land use/cover in this website is divided into 10 types, namely, cultivated land, forest, grassland, shrubland, wetland, water body, tundra, artificial surface, bare land, and permanent snow and ice (Table 1). The total accuracy of land use/cover can reach 85.72%, and the kappa coefficient can reach 0.82, as introduced by this website (http://www.globallandcover.com/; accessed on 15 November 2021).

Table 1. GlobeLand30 Classification System (http://www.globallandcover.com/).

Landcover Class	Content
Artificial Surfaces	It refers to the surfaces formed by man-built activities. All kinds of habitation in urban and rural areas, industrial and mining areas, transportation facilities, etc. are included in this category, while interior contiguous green land and water bodies in the construction land use.
Bare Land	It refers to natural covered lands with cover density lower than 10%. Desert, sand, gravel ground, bare rocks, saline, alkaline lands, etc. are included in this category.
Cultivated land	It refers to the lands used for cultivating crops. Paddy fields, irrigated upland, rainfed upland, vegetable land, cultivated pasture, greenhouse land, land mainly planted with crops rarely with fruit trees or other trees, tea garden, coffee garden, and other economic cropland and so on are included in this category.

Table 1. *Cont.*

Landcover Class	Content
Forest	It refers to the lands covered with trees, the top density of which occupies over 30%. Deciduous broadleaf forest, evergreen broadleaf forest, deciduous coniferous forest, evergreen coniferous forest, mixed forest, and sparse woodland the top density of which covers 10–30% are included in this category.
Grassland	It refers to the lands covered by natural grass with a cover density over 10%. The prairies, meadow steppes, alpine grasslands, desert steppes, and lawns, etc. are included in this category.
Permanent snow and ice	It refers to the lands covered by permanent snow, glacier, and icecap. Permanent snow, the glacier in the high-mountain region, and the icecap in the polar, etc. are included in this category.
Shrubland	It refers to the lands covered with shrubs and the cover density is over 30%. Mountain shrubs, deciduous and evergreen shrubs, and desert jungle in desert area with a cover density over 10% are included in this category.
Tundra	It refers to the lands covered by lichen, moss, hardy perennial herb, and shrubs in the cold and high mountain area. Shrub tundra, grass tundra, wet tundra, alpine tundra, and barren tundra, etc. are included in this category.
Water bodies	It refers to liquid water-covered region in the land area. River, lake, reservoir, pit-pond, etc. are included in this category.
Wetland	It refers to the junction lands of land and water area, which are constantly covered by biogas or hygrophyte plants and shallow water or wet soils. Inland marsh, lake marsh, river floodplain wetland, forest/shrub wetland, peat bogs, mangrove, salt marsh, etc. are included in this category.

2.3. Statistical Analyses

To effectively reflect the spatial characteristics and differences in land use/cover change on alluvial fans, the study area was classified using the boundaries of the counties/districts in LRB. The land use/cover on alluvial fans in different altitudes and slope grades was analysed in ArcGIS. Altitude was classified in ArcGIS by the equidistant method and divided into four levels, namely, ≤4000, 4000–4500, 4500–5000, and 5000–5500 m. The slope data were obtained using the slope tool of ArcGIS, and they were classified into six grades of ≤5°, 5°–8°, 8°–15°, 15°–25°, 25°–35°, and ≥35° in accordance with the classification of slopes in the Standard for Classification and Grading of Soil Erosion (SL 190–2007) issued by the Ministry of Water Resources of the People's Republic of China. Different land use/cover distribution areas of alluvial fans with different counties/districts, altitudes, and slope grades were obtained using the Zonal Statistics function in ArcGIS.

3. Results

3.1. Temporal Changes in Land Use/Cover Change in Alluvial Fans

3.1.1. Area Changes in Land Use/Cover

The areas of cultivated land, shrubland, bare land, artificial surface, and water body on alluvial fans from 2000 to 2020 increased by 98.74%, 59.38%, 33.34%, 1023.13%, and 1169.43%, respectively, whereas the areas of grassland, woodland and wetland decreased by 16.39%, 62.20%, and 100%, respectively (Figure 2a). All types of land use/cover changed in 2000, 2010, and 2020. In the period 2000–2010, the order was grassland > cultivated land > shrubland > artificial surface > water body > woodland > bare land > wetland. In 2010–2020, only the surface area of artificial land exceeded that of shrubland, and the order of the other types was the same as that in 2000–2010.

Cultivated land and artificial surface on alluvial fans were closely related to human activities. Although the proportion of cultivated land and artificial surface to alluvial fans was small, their proportion to the corresponding area of LRB was high (Figure 2b). Cultivated land accounted for 17.72%, 21.84%, and 24.17% of the cultivated land of LRB in 2000, 2010, and 2020, respectively. Similarly, artificial surface accounted for 7.89%, 7.51%, and 25.24% of the artificial surface of LRB in 2000, 2010, and 2020, respectively. This result shows that alluvial fans provide important living and production spaces and are important land resources for LRB.

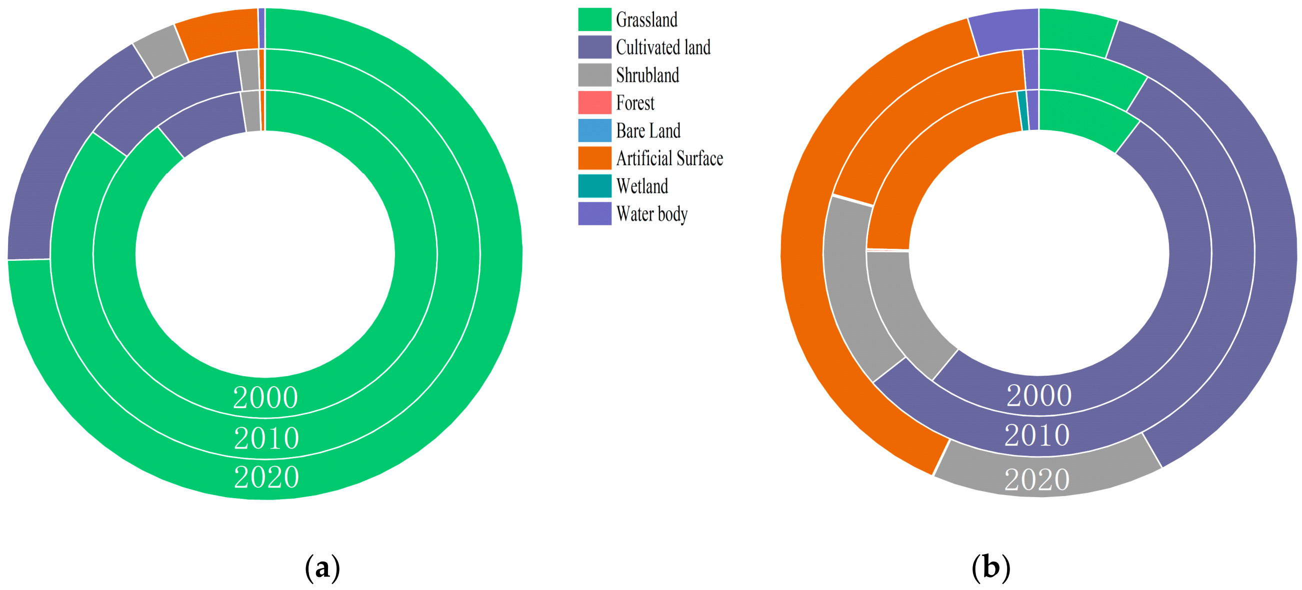


Figure 2. Ratio (%) of the area of land use/cover to the total area of alluvial fans or to the corresponding land use/cover in LRB. (**a**). Ratio to the total area of alluvial fans; (**b**). Ratio to the corresponding land use/cover in LRB.

3.1.2. Transfer Characteristics of Land Use/Cover on Alluvial Fans

Cultivated land and grassland were the two types of land use/cover with the greatest changes during 2000–2010 (Table 2). Cultivated land and grassland accounted for 62.90% and 31.77% of the total transfer-in areas and 27.25% and 65.58% of the total transfer-out areas, respectively, during 2000–2010. During 2000–2010, the transfer-in area of cultivated land was larger than the transfer-out area. Out of the total of 87.93 km^2 of transfer-in area of cultivated land, 97.23% was from grassland. A total of 38.09 km^2 of cultivated land was transformed into grassland (96.85%) and shrubland (3.15%). Conversely, the transfer-out area of grassland was larger than the transfer-in area. A total of 91.67 km^2 of grassland was transferred out, of which 93.26 was converted into cultivated land. A total of 44.42 km^2 of grassland was transferred in, of which 83.05% was transferred from cultivated land.

The transformation relationship of land use/cover types in 2020–2010 was different from that in 2000–2010 (Table 3). Although cultivated land and grassland still accounted for the largest proportion of the transfer-in and transfer-out areas, only the transfer-out area of grassland was larger than the transfer-in area, and the other land use/cover types had a transfer-in area that was larger than the transfer-out area. In particular, cultivated land, artificial surfaces, and shrub- land accounted for 45.66%, 21.94%, and 8.21% of the sum of the total land use/cover transfer-in areas. A total of 179.81 km^2 of grassland was transferred out, of which 68.86% was converted into cultivated land and 23.37% into artificial surfaces. Cultivated land was transferred in 117.52 km^2, and 99.25% was from grassland. Cultivated land was transferred out of 70.65 km^2 and 73.26% was converted into grassland and 19.52 km^2 into artificial surfaces.

Table 2. Land use/cover conversion matrix of alluvial fans from 2000 to 2010.

Land Use/Cover/km^2		**2010**								
		Grassland	**Cultivated Land**	**Shrubland**	**Forest**	**Bare Land**	**Artificial Surfaces**	**Wetland**	**Water Body**	**Transfer-Out Area**
2000	**Grassland**	949.29	85.49	4.34	0.05	0.00	1.57	0.00	0.23	91.67
	Cultivated land	36.89	59.88	0.75	0.01	0.00	0.43	0.00	0.01	38.09
	Shrubland	5.69	1.76	13.40	0.01	0.00	0.02	0.00	0.00	7.47
	Forest	0.14	0.08	0.01	0.03	0.00	0.00	0.00	0.00	0.22
	Bare land	0.01	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.01
	Artificial surfaces	1.55	0.59	0.02	0.00	0.00	3.33	0.00	0.00	2.16
	Wetland	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.02
	Water body	0.14	0.00	0.00	0.00	0.00	0.00	0.00	0.28	0.14
	Transfer-in area	44.42	87.93	5.11	0.06	0.00	2.02	0.00	0.25	—

Table 3. Land use/cover conversion matrix of alluvial fans from 2010 to 2020.

Land Use/Cover/km^2		**2020**							
		Grassland	**Cultivated Land**	**Shrubland**	**Forest**	**Bare Land**	**Artificial Surfaces**	**Water Body**	**Transfer-Out Area**
2010	**Grassland**	813.90	116.64	17.30	0.05	0.04	42.03	3.76	179.81
	Cultivated land	51.76	77.15	3.84	0.04	0.00	13.79	1.22	70.65
	Shrubland	5.15	0.64	12.09	0.00	0.00	0.61	0.01	6.41
	Forest	0.04	0.03	0.00	0.01	0.00	0.01	0.00	0.09
	Bare land	0.01	0.00	0.00	0.00	0.03	0.00	0.00	0.01
	Artificial surfaces	0.04	0.18	0.00	0.00	0.00	5.12	0.00	0.23
	Water body	0.14	0.00	0.00	0.00	0.00	0.00	0.28	0.20
	Transfer-in area	57.13	117.52	21.14	0.09	0.04	56.48	4.99	—

3.2. Spatial Changes in Land Use/Cover Change on Alluvial Fans

3.2.1. Land Use/Cover on Alluvial Fans in Different Counties/Districts

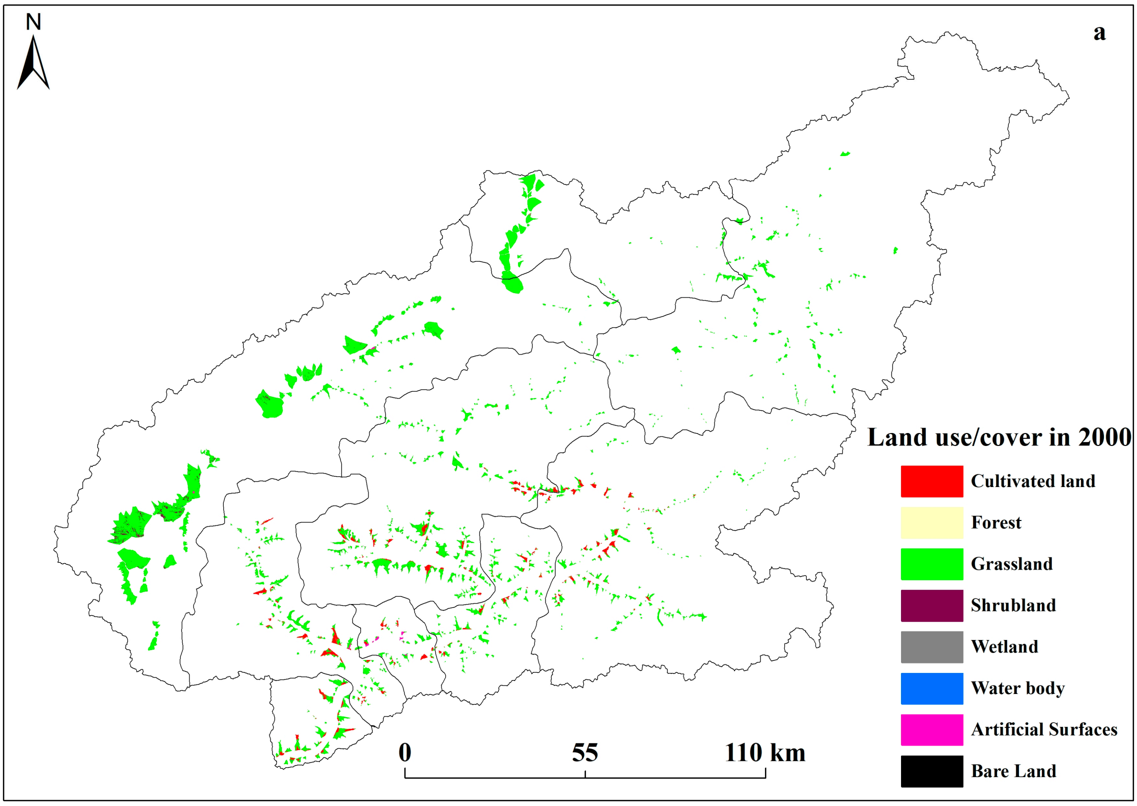
The cultivated land, artificial surfaces, shrubland, bare land, and water bodies on alluvial fans showed an upward trend in all counties/districts as a whole (Figure 3). In 2000, the cultivated land area on alluvial fans was 98.31 km^2, which was mainly distributed in the middle and lower reaches of the Lhasa River (Figure 3a), including Lhundup (26.56%), Medro Gongkar (23.02%), and Tolung Dechen (22.19%) counties/districts. The other counties had scarce cultivated land (Figure 4). In 2010 and 2020, the cultivated land area increased by 50.87% and 98.71%, respectively, compared with the percentages in 2000, and the main distribution counties/districts of cultivated land were unchanged (Figure 4b,c). In 2000, the artificial surface of alluvial fans was 5.50 km^2, which was mainly distributed in Chengguan District (Figure 3a). Compared with the situation in 2000, the area of artificial land remained unchanged in 2010, but by 2020, the area increased to 61.79 km^2, with a growth rate of 1023.13%, and the main distribution areas were Chengguan, Tolung Dechen, and Chushur counties/districts (Figure 3b,c). In 2000, the area of shrubland on alluvial fans was 20.90 km^2, accounting for 1.79% of the total area of the alluvial fans. It was mainly distributed in Damshung County (Figure 3a), with an area of 16.49 km^2 (Figure 4). Compared with the situation in 2000, the shrubland area decreased by 113.31% in 2010 and conversely increased by 59.38% in 2020. In 2000, the bare land and water body areas on the alluvial fans were small, accounting for only 0.05 km^2 and 0.42 km^2, respectively. By 2010 and 2020, the bare land area was unchanged, but the water body area increased dramatically with a growth rate of 1169.43%.

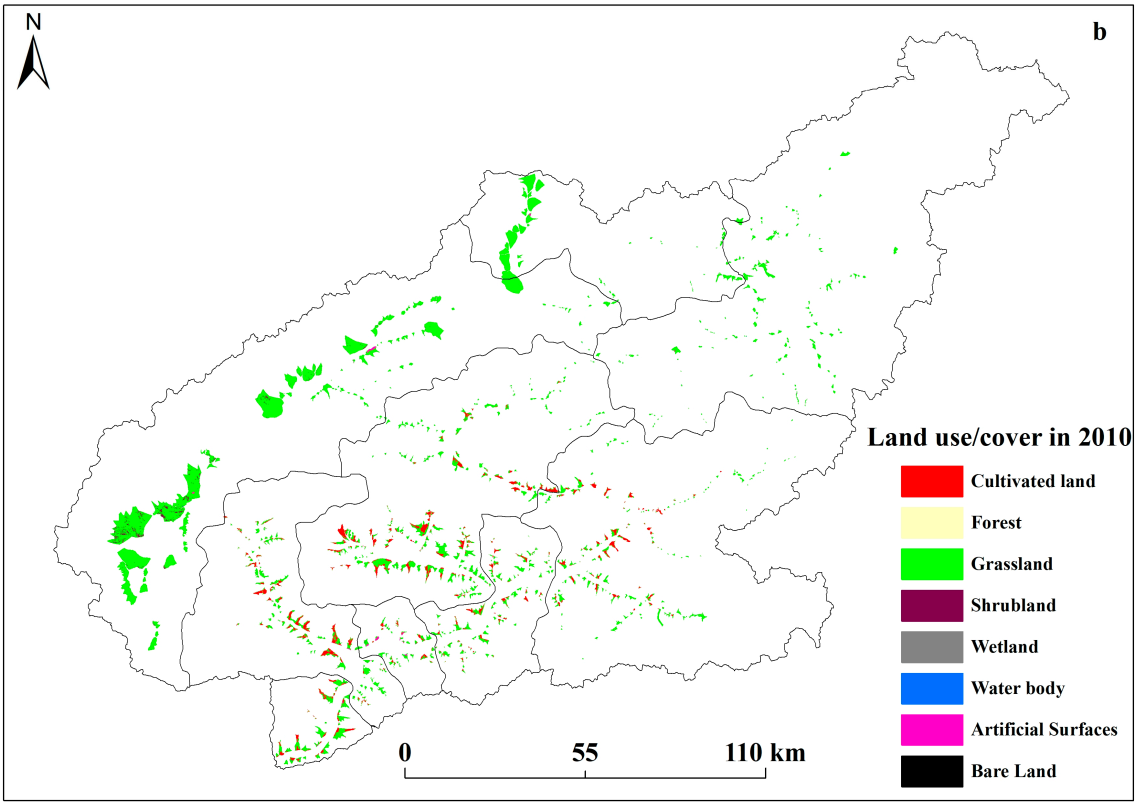
The total areas of grassland, woodland, and wetland on alluvial fans decreased in all counties/districts. Grassland was the most widely distributed land use/cover on alluvial fans. In 2000, its area was 1140.56 km^2, accounting for 89.27% of the total area of alluvial fans. It was also the largest distribution area of land use/cover in each county/district (Figure 3a), and it was mainly distributed in the counties/districts of Damshung (40.01%), Lhundup (14.34%), and Seni (9.05%) (Figure 4). By 2010 and 2020, the total area of grassland decreased (Figure 3), with Lhundup County being the main area of decline; however, the main distribution counties/districts of grassland did not change (Figure 3b,c). A few forestlands were present on the alluvial fans, with a total area of only 0.26 km^2 in 2000. The area decreased to 0.10 km^2 in 2010 and remained the same in 2020, and it was mainly distributed in Medro Gongkar and Taktse counties/districts. Wetland was the smallest area of land use/cover on alluvial fans, with a value of only 0.02 km^2 in 2000, and all of it was distributed in Chengguan District. By 2010 and 2020, no wetland was distributed on alluvial fans.

3.2.2. Land Use/Cover on Alluvial Fans at Different Altitude Gradients

On the whole, the changes in land use/cover on alluvial fans at different altitude gradients were centralised in the area with altitude ≤4000 m, and the distribution area of each land use/cover in this altitude area was large. Grassland, woodland, and wetland showed a downward trend, whereas cultivated land, artificial surfaces, shrubland, and water bodies showed an upwards trend; bare land did not change (Figure 5). Particularly, the area of wetland was only 0.02 km^2, which was distributed only in areas with altitudes ≤4000 m.

Grassland was mainly distributed in the area with an altitude ≤4000 m. Relative to 2000, the grassland area at altitudes ≤4000 m, 4000–4500 m, and 4500–5000 m in 2010 and 2020 showed a downward trend. The grassland area at an altitude ≤4000 m decreased the most and accounted for 62.19% and 77.25% of the total reduced grassland area by 2010 and 2020, respectively.





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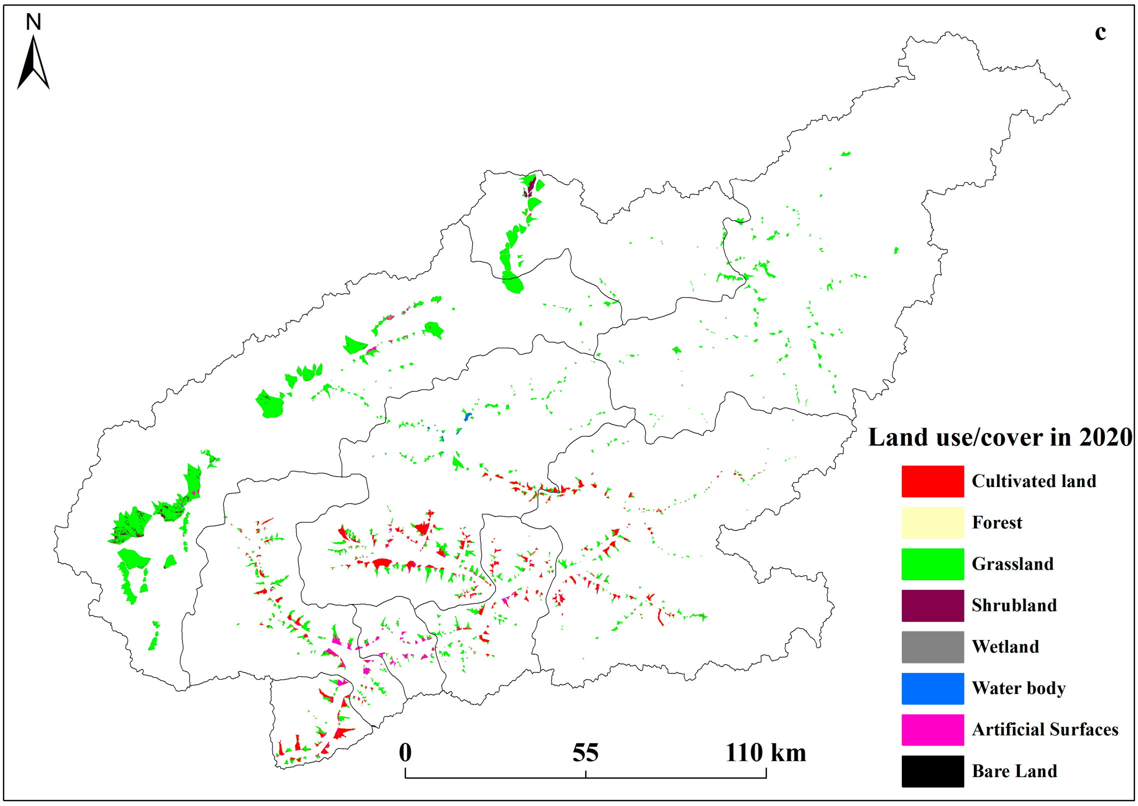

Figure 3. Spatial distribution of land use/cover in different years. (**a**). Land use/cover in 2000; (**b**). Land use/cover in 2010; (**c**) Land use/cover in 2020.

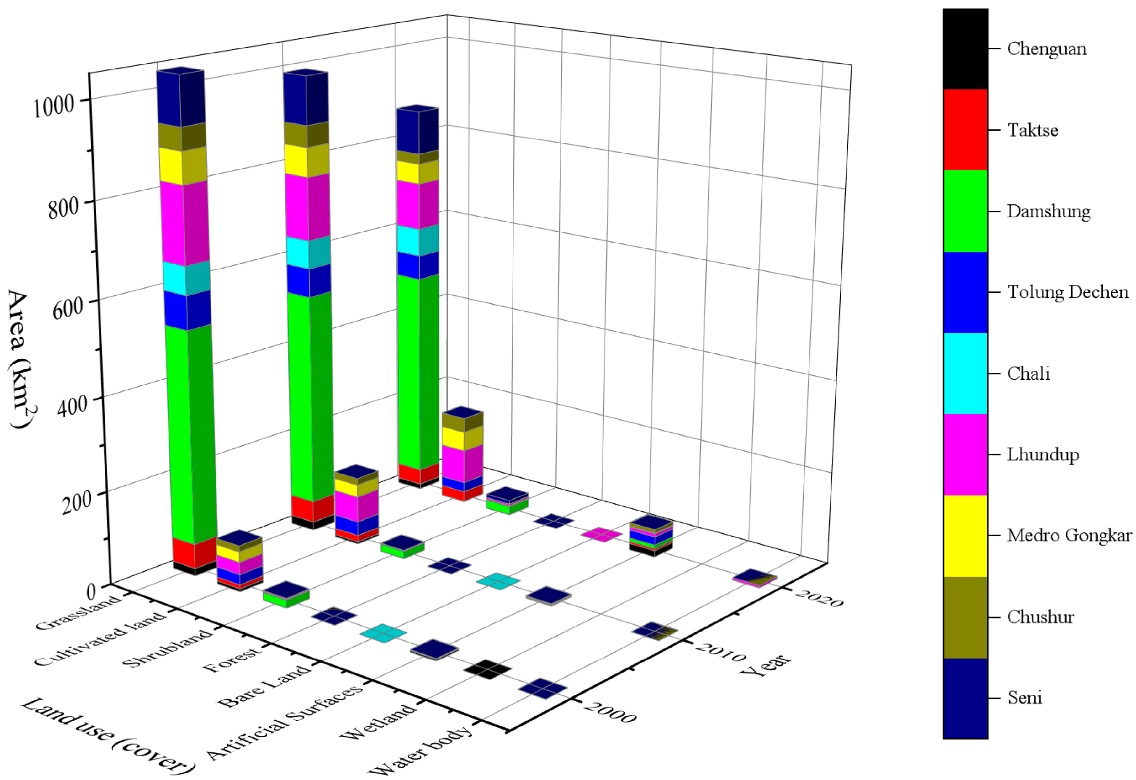

Figure 4. Land use/cover area of different counties/districts in different years (km^2).

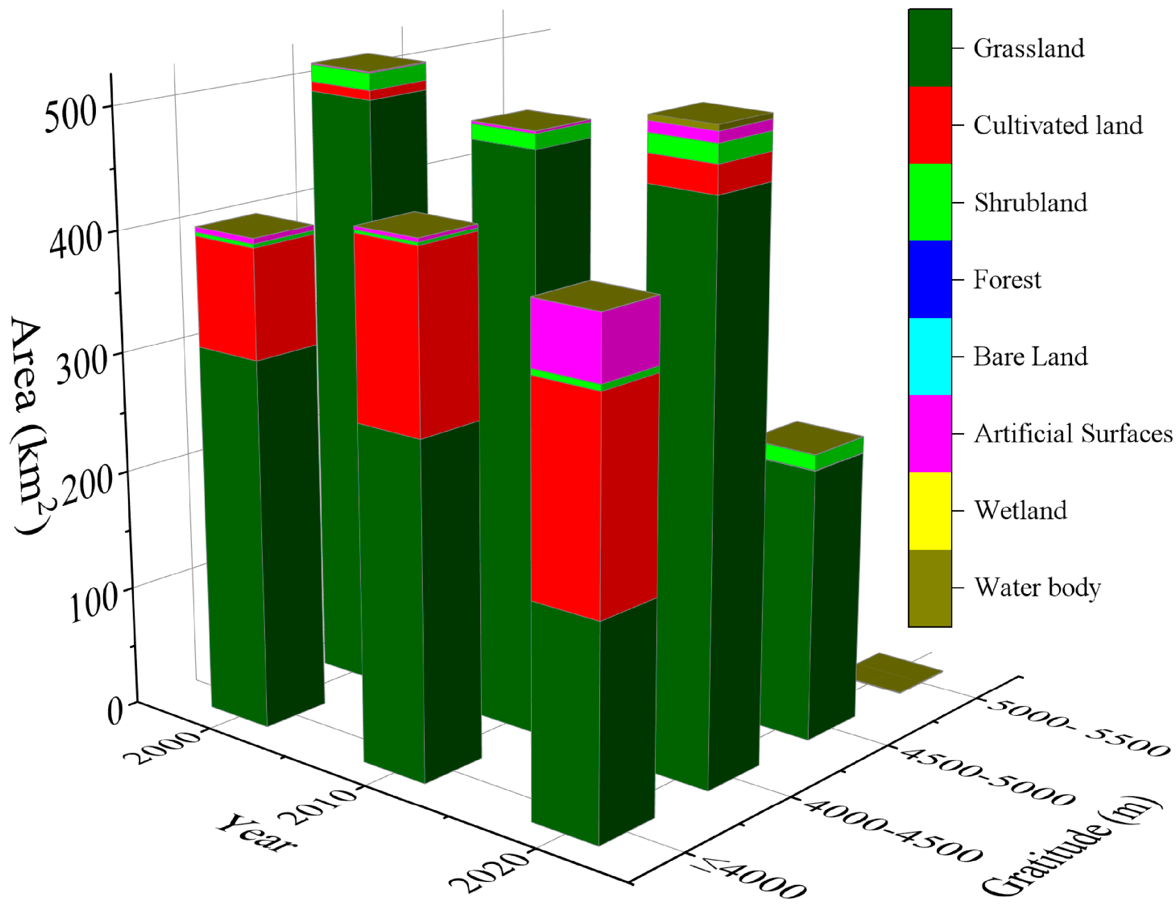

Figure 5. Area of land use/cover of alluvial fans at different altitude grades(km^2).

Cultivated land was mainly distributed at an altitude ≤4000 m. Compared with 2000, the increased area of cultivated land at this altitude accounted for 115.56% and 83.92% of the total increased area in 2010 and 2020, respectively. In the areas at an altitude of 4000–4500 m, the distribution of cultivated land was only 7.78 km2 in 2000. By 2010, no cultivated land existed at this altitude, and by 2020, the decreased area accounted for 15.55% of the total increased area. In 2000 and 2010, no cultivated land was distributed at an altitude of 4500–5000 m, and by 2020, the area increased by 0.51 km^2.

The artificial surfaces were also mainly distributed in the area with an altitude ≤4000 m. Compared with 2000, the artificial surfaces in this area decreased to 3.03 km^2 in 2010 but increased to 52.60 km^2 in 2020, accounting for 86.65% of the total increase in artificial surfaces. The artificial surface in the ranges of 4000–4500 and 4500–5000 m also showed an upward trend. The area of 4000–4500 m was only 0.96 km^2 in 2000, which increased to 2.01 and 8.86 km^2 in 2010 and 2020, respectively. The area of 4000–5000 m was only 0.15 km^2 in 2000, which increased to 0.32 and 0.33 km^2 in 2010 and 2020, respectively. No artificial surface was distributed in the area of 5000–5500 m in all the studied years.

3.2.3. Land Use/Cover on Alluvial Fans at Different Slope Gradients

On the whole, the changes in land use/cover of alluvial fans at different gradients were centralised in the area of ≤8° (Figure 6). The area of each land use/cover in this slope-gradient area was large. Woodland and wetland showed a downward trend, whereas cultivated land, artificial surface, shrubland, and water body showed an upwards trend. Bare land had no change.

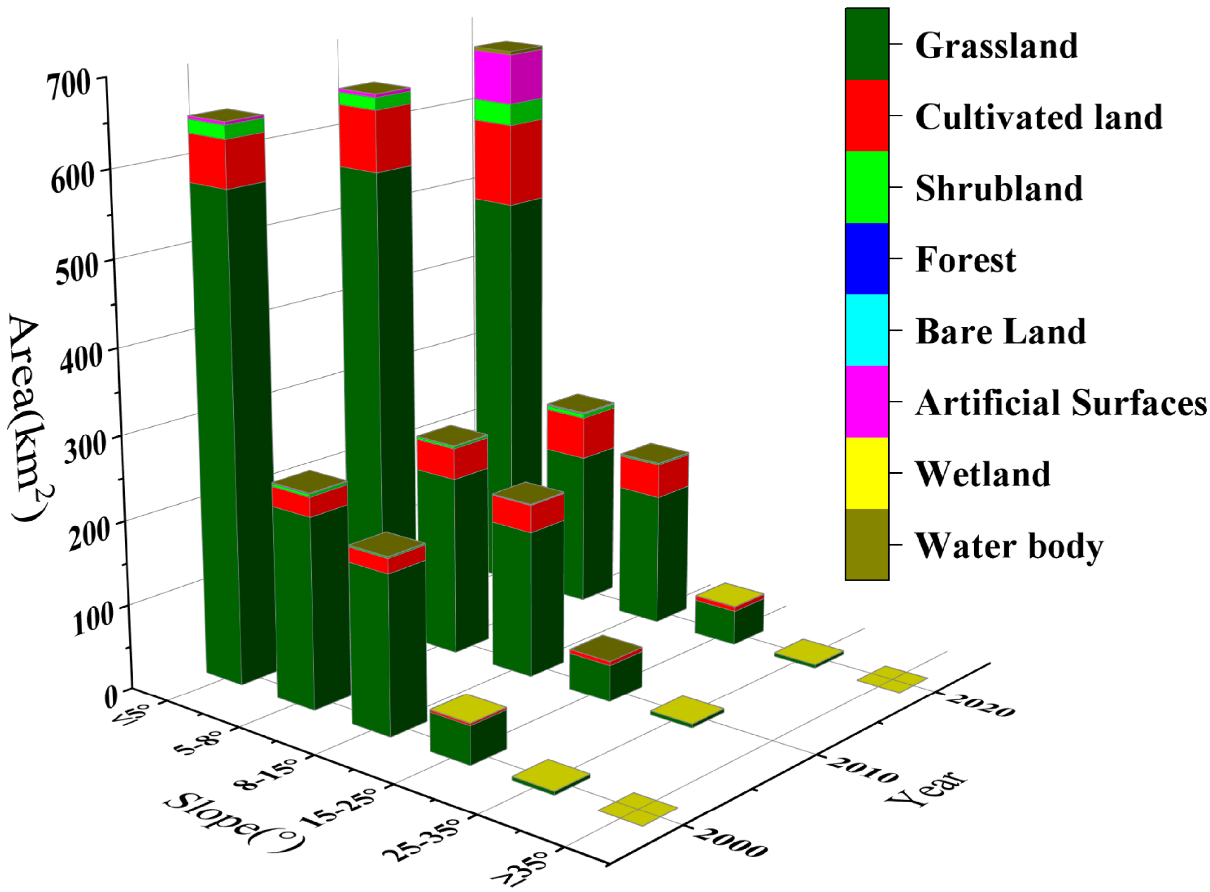

Figure 6. Area of land use/cover of alluvial fans at different slope grades.

Compared with 2000, the grassland areas of all slope gradients showed downward trends, but the area of ≤8° decreased the most. The decreased areas in 2010 and 2020 accounted for 65.52% and 79.58% of the total decreased area of grassland, respectively. The higher the slope was, the smaller the decrease in grassland was. For example, in 2000, the slope-gradient area of 8°–15° accounted for 18.12% of the total grassland area. In 2010 and 2020, its decreased area accounted for 30.02% and 17.86% of the total decreased area of grassland, respectively. The decrement trend of forestland area was similar to that of grassland.

During 2000–2020, the cultivated land of all slope gradients showed upwards trends, and the area of ≤8° increased the most. In 2000, the cultivated land distributed in this slope-gradient area accounted for 79.33% of the total cultivated land, and the increased area accounted for 65.25% and 80.86% of the total increased area of cultivated land in 2010 and 2020, respectively. In areas with high slopes, the increased area was also large. The cultivated land area of 8°–15° was only 17.53 km^2 in 2000, and its increase rates in 2010 and 2020 were 85.71% and 132.50%, respectively. The changing trend of the artificial surface in all slope gradients was similar to that of cultivated land, and the area of ≤8° had a large proportion of increasing area.

4. Discussion

The cultivated land on alluvial fans is mainly distributed in the middle and lower reaches of the Lhasa River (Figure 3), which is consistent with the main traditional distribution areas of cultivated land in LRB [20,36], including Tolung Dechen, Lhundup, and Medro Gongkar counties/districts. These counties/districts are at low altitudes, relatively rich in heat, easy to irrigate, and can be used for planting highland barley, winter wheat, rapeseed, potatoes, and other crops [20]. The main distribution region is also consistent with the analysis results of the distribution of cultivated land on alluvial fans. In 2000, the cultivated land on alluvial fans was mainly distributed in areas with altitudes ≤4000 m and accounted for 92.09% of the total cultivated land area. However, the cultivated land at 4000–4500 m was only 7.91%, and no distribution was observed at altitudes >4500 m, indicating that altitude has a great influence on the distribution of cultivated land in alpine regions. The artificial surface on alluvial fans is mostly residential [19], and the natural conditions suitable for human habitation are similar to those suitable for agricultural development (cultivated land). This finding is similar to the research results of Yang [21]. Given the poor natural conditions in Tibet, most of the cultivated land and residential areas are distributed in areas with good hydrothermal conditions below 4200 m [19]. The area distribution of water bodies on alluvial fans was small, that is, only 0.42 km^2, in 2000 (Figure 5), and most of these water bodies were small artificial pools for cultivated land irrigation and livestock drinking water (Figure 7); hence, their distribution coincided with that of cultivated land. The three types of land mentioned above are affected by slope, and they are mainly distributed in the area of ≤8° (Figure 6). Therefore, the distribution of cultivated land is limited by the slope. This result has also been confirmed in some mountainous areas of Thailand [38], Nepal [39], and [40] Europe, where cultivated land is also concentrated in a certain slope range. Therefore, the distribution area of land use/cover on alluvial fans in LRB is greatly restricted by natural conditions, but it is increasingly affected by human activities.

Figure 7. Pool located on an alluvial fan (Taken by Tongde Chen, 20200728).

However, the distribution of grassland is less restricted by natural conditions, including altitude or slope. For example, in 2000, few grasslands (0.07%) were distributed in areas with an altitude of >5000 m, and the area percentages of grassland distributed at three altitudes of <4000, 4000–4500, and 4500–5000 m were all over 22.66%. Meanwhile, the areas of grassland distributed at slope gradients of 5°, 5°–8°, and 8°–15° were all over 18.12%. Many types of plants are distributed on alluvial fans at different altitudes, topographies, and moisture conditions [36,41].

The land use/cover of alluvial fans is also affected by the shape or size of such fans to a certain extent. An alluvial fan with a complex shape or too small an area cannot be easily used by human beings. An example is the alluvial fan in Niezu Village, Duilong Deqing District, with an area of about 1 km^2 and a radius about 1.1 km, and its land use/cover is mainly grassland (Figure 8). Humans cannot easily build villages or cultivate farmland because of its large slope and small area.

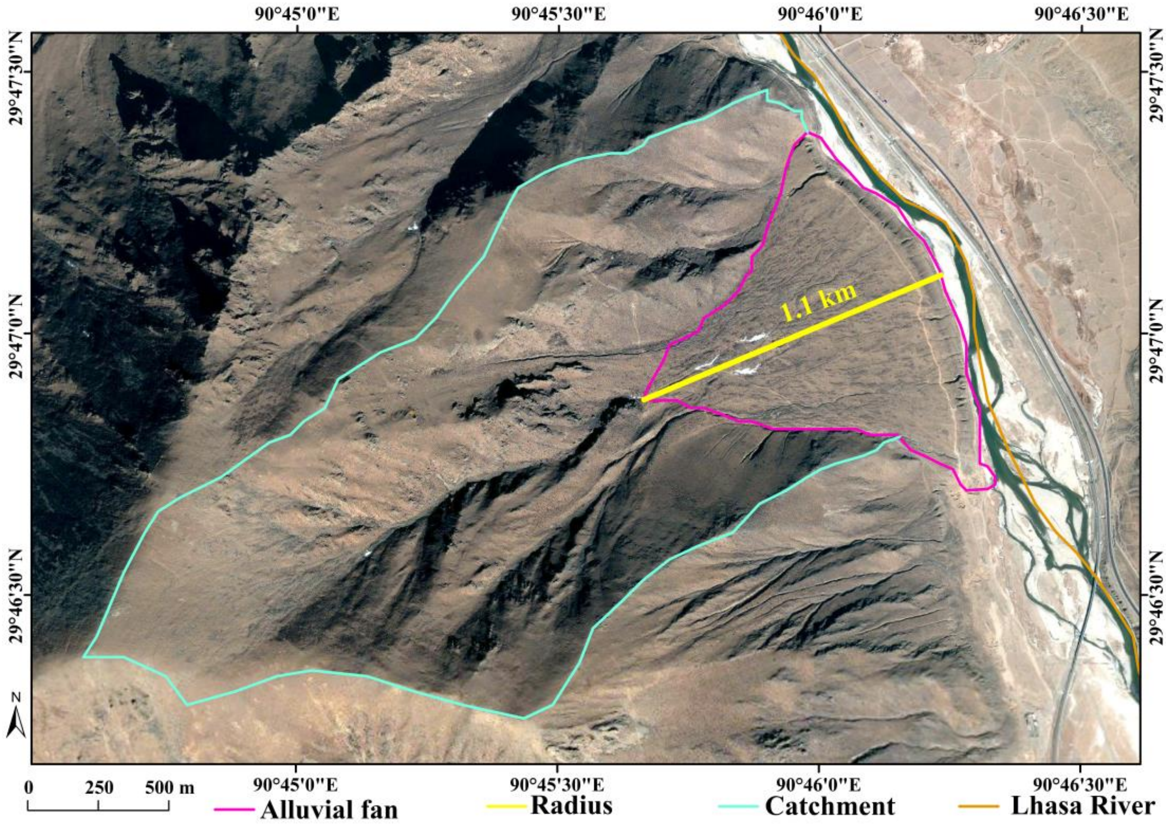

Figure 8. Alluvial fan located in Niezu Village, Duilong Deqing District.

Different from the distribution of land use/cover on alluvial fans, the spatiotemporal changes in all land use/cover types are mainly dominated by human activities. In recent years, the conflict between humans and land in LRB has increased, and the closer a location is to the central city (Chengguan District), the more intense the demand for cultivated land and residential land is [19,42]. In this study, the area of cultivated land and artificial surface on alluvial fans showed an increasing trend, but the areas of grassland, woodland, and wetland showed a decreasing trend (Figure 2a). During 2000–2020, the increase rates of cultivated land and artificial land were 98.74% and 1023.13%, respectively. However, the decrease rates of grassland, woodland, and wetland were 16.39%, 62.20%, and 100%, respectively. Moreover, the main increased areas of cultivated land were Chengguan, Tolung Dechen, Lhundup, Medro Gongkar, and Taktse counties/districts and some areas close to urban areas. This result reflects the increased local demand for cultivated land. This demand also corresponds to other mountainous areas in the world [38–40]. Therefore, the main driving force of land use change is human activities, which is similar to recent studies that have shown this [7,11,18].

The changing trend of land use/cover at different altitudes and slope gradients can also determine if local residents have an increased demand for cultivated land and residential land. For example, from 2000 to 2020, grassland declined sharply in areas with altitude $\leq$4000 m or slope $\leq 8^\circ$, whereas cultivated land and artificial surface increased sharply. The area with an altitude >4000 m or slope $>8^\circ$ is not the priority area for the development of cultivated land and artificial surface, but the area of cultivated land and artificial surface at this altitude is increased. The increase in cultivated land, artificial surface, and shrubland mainly originated from the decrease in the grassland area. For example, from 2000 to 2010, the area of cultivated land transferred from other land types was 87.93 km^2, and the area transferred from grassland was 97.22%. From 2010 to 2020, the total transferred cultivated land was 117.52 km^2, and the proportion from grassland was as high as 99.25%. Similarly, some grasslands have been transformed into shrubland mainly because of afforestation, wind and sand control projects, and soil erosion control projects in Yarlung Zangbo River Basin. Some grasslands have been planted with shrubland plants, such as Hippophae rhamnoides, Caragana sinica, and Sophora moorcroftiana [43]. Therefore, the shrubland area has increased. Evidently, the main driving force of land use/cover change on alluvial fans in LRB is human activities.

By examining the temporal and spatial changes in land use/cover on alluvial fans in LRB, this study summarises the trends of various types of land use/cover changes and discusses and analyses the main reasons for land use/cover distributions and land use/cover changes in alluvial fans. However, quantifying the effects of human activities on land use/cover and the changes in land use/cover is difficult due to the lack of data on human activities in alluvial fans. The reason for the lack of data on human activities is that LRB has 826 alluvial fans, which are scattered in all parts of the basin. Conducting population, economic, and social investigations is therefore difficult. These data play an important role in the calculation of the ecological carrying capacity, and these aspects will be studied in the future.

5. Conclusions

There is less land suitable for human life in LRB due to its cold environment and steep terrain. Therefore, alluvial fans are a significant land resource for LRB, which provided a large number of cultivated lands on the artificial surface from 2000–2020. Furthermore, the areas of cultivated land and artificial surface increased quickly, whereas those of grassland, woodland, and wetland decreased dramatically. The increased area of cultivated land and artificial surface mainly originated from the decreased grassland area. Our results confirm that the demand for cultivated land and artificial surface in LRB is increasing, and alluvial fans are a very important kind of land resource to meet the demand. The protection and utilization of alluvial fans will be an important topic in this area. In other alpine mountain areas in the world, we still need to pay attention to the low-gentle-slope land resources such as alluvial fans to alleviate the land shortage problem all over the world.

Author Contributions: Conceptualization, T.C. and J.J.; methodology, T.C. and J.J.; formal analysis, W.W.; investigation, T.C., J.L. and Z.Z.; resources, J.J.; data curation, W.W.; writing—original draft preparation, T.C.; writing—review and editing, H.Y. and H.M.; visualization, J.L.; supervision, J.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by "the Second Tibetan Plateau Scientific Expedition and Research Program (STEP), grant number No. 2019QZKK0603" and "the Strategic Priority Research Program of Chinese Academy of Sciences, grant number No. XDA20040202", and "The APC was funded by the Ministry of Science and Technology of the People's Republic of China".

Data Availability Statement: Not applicable.

Conflicts of Interest: We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service, and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled "Spatiotemporal variation in the land use/cover of alluvial fans in Lhasa River Basin, Qinghai–Tibet Plateau".

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