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Feeding solution: Crop-livestock integration via crop-forage rotation in the southern Tibetan Plateau

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ABSTRACT

Separated, specialized crop and forage production has a long history on the Tibetan Plateau. Such isolated pattern has led to current concerns of intensified agriculture, environmental degradation and forage shortage in the increasing pressures of population and livestock growth. To tackle the predicament of feed shortage, an alternative to specialized agriculture is crop-forage rotation for potential crop-livestock integration (CLI). However, its feasibility is understudied and the potential remains unanswered in the southern Tibetan Plateau. Based on the analyses of grazing pressure index and growing degree days (GDD), we examined the practicability and modes of crop-forage rotation for feed solution in the middle reaches of the Yarlung Tsangpo Watershed (YTW). Additionally, cultivated land area suitable for forage rotation after crop harvest was defined. Livestock carrying capacity and grazing pressure indices under forage rotation were compared with those only with rangeland and crop residues. We found that the average number of livestock maintained about 9 million standard sheep unit (SU) in the period 2000–2015, which exceeded the carrying capacity provided by rangeland and crop residues. Growing season length are about 200 days ranging from late April to early November, with daily average temperature $\geq$ 5 °C and over 1500 GDD in the Yarlung Tsangpo River valley. About 158,377 ha, accounting for 74.4% of the cultivated land is suitable for annual forage rotation after crop harvest. The appropriate period for annual forage rotation is ca. 80 days, i.e. from 20th August to 8th November after spring crop harvest and from 1st August to 20th October after winter crop harvest. In addition, the information of GDD also provides elevational thresholds for implementing forage rotation practice in the future. The upper limits for forage rotation are 4000 m after spring crop harvest and 4500 m after winter crop harvest. The grazing pressure indices in most counties can be substantially reduced after filling feed gaps through crop-forage rotation. We demonstrate that crop-forage rotation could be a good solution to forage deficits. These findings also provide insights into promising potential for crop-livestock integration to alleviate grazing pressure in the southern Tibetan agricultural area. However, adoption will depend on farmers' preference and market factors. Further efforts are needed to encourage farmers' involvement into the forage rotation by policy guidance.

1. Introduction

Animal husbandry supports the foundational livelihoods of herders in rangeland ecosystems. However, rangeland degradation is globally widespread in recent decades primarily due to climate change and overgrazing, especially in arid and alpine environments (Geerken and Ilaiwi, 2004; Harris, 2010; O'Reagain et al., 2014). Rangeland conservation and forage shortage become a dilemma faced by the development of animal husbandry. The key to this problem is to foster forage production from other multiple sources. Sown pasture for forage production is a major supply of livestock rations in grazing systems due to its intensive production and high nutrient (McEvoy et al., 2011; Lee et al., 2018; Woods et al., 2018). But the establishment of a sown pasture needs to occupy a certain area of agricultural land. Incorporating forage production during the fallow periods in croplands is a possible option to solve the conflicts of feed deficits and limitation of land resources (Havet et al., 2014).

Integrated crop-livestock systems have been extensively practiced to achieve agricultural sustainability and environmental benefits (Bell and Moore, 2012; Lemaire et al., 2014; Reddy, 2016). Crop-livestock integration (CLI) has been suggested as one of effective solutions to forage deficits and livestock production in grazing system, which has higher

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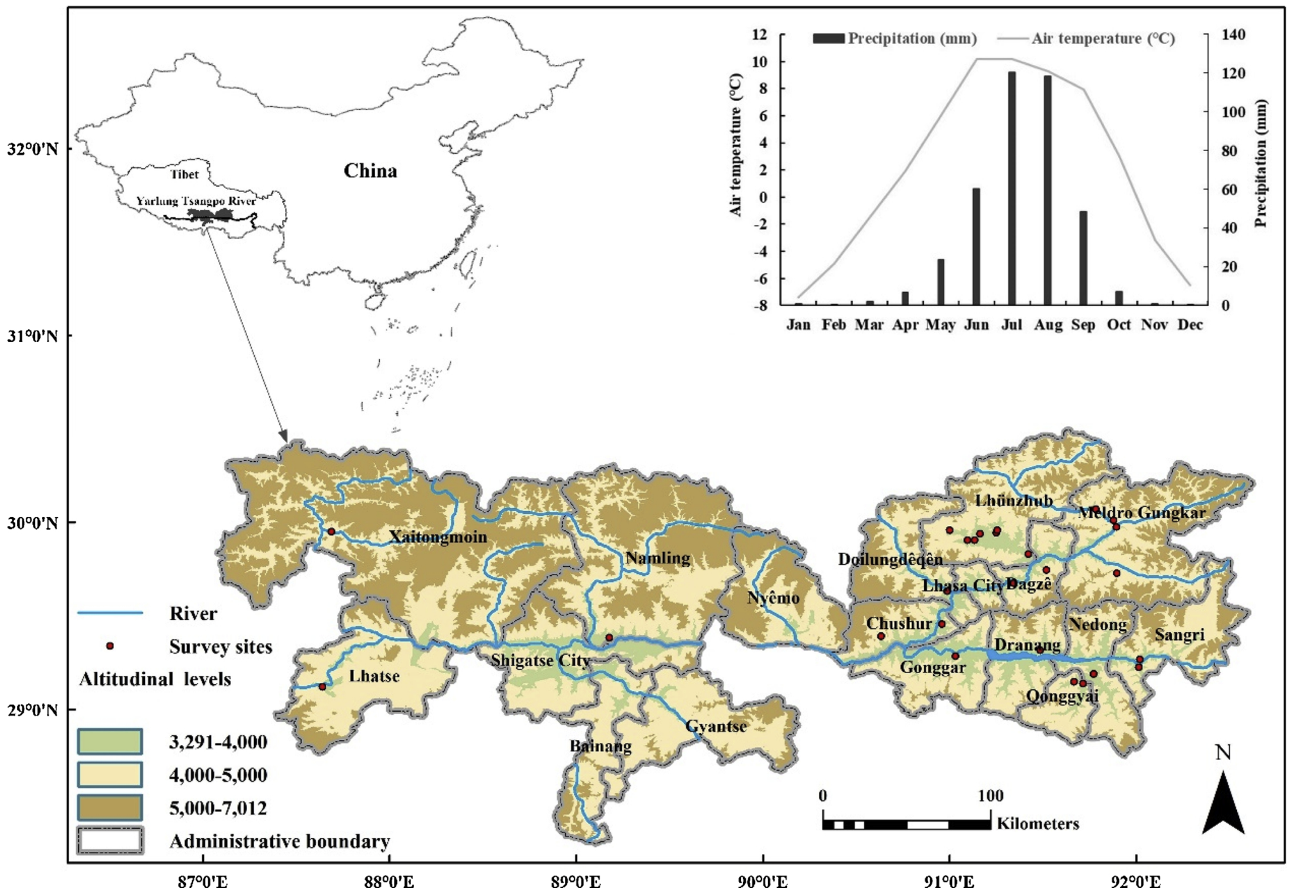

Fig. 1. Schematic map of the Yarlung Tsangpo Watershed showed administrative districts, altitude ranges and hydroclimatic conditions.

forage yield (Franzluebbers et al., 2014; Nie et al., 2016). CLI can not only promote crop and livestock production but also can reduce environmental pollution (Tracy and Zhang, 2008; Maughan et al., 2009; Herrero et al., 2010). So crop-forage rotation, i.e. forage production after crop harvest, has been practiced by farmers to adapt to the increase livestock (Havet et al., 2014; Salton et al., 2014). Some studies suggested long-term crop-forage rotation could increase soil organic matter, nitrogen availability and thus improve soil quality (Li et al., 2015; Ghimire et al., 2018; Viaud et al., 2018). Moreover, extensive studies have also shown that forage cultivation in agricultural systems is beneficial to crops. For example, the incorporation of leguminous forages into cropland can improve crop yield effectively (de Oliveira et al., 2013; Bell et al., 2014; Reddy, 2016). Therefore, facilitating integration of crop and livestock will be one of important pathways for sustainable crop and livestock production in agro-pastoral systems.

Tibetan Plateau has a long history of separated, specialized crop and forage production. Rangeland is mainly distributed in the northern Tibetan (locally called Changtang) Plateau and high altitudes of over 4400 m (Zhao et al., 2017). Yarlung Tsangpo watershed (YTW) in South Tibet, especially in the middle reaches is the traditional agricultural area for crop production. Forage cultivation is limited in alpine grazing system due to clod environment. There exist conflicts of land use for forage and food production in southern agricultural area. Furthermore, decreasing benefits of conventional farming and livestock production have become more evident over the past years (Yu and Zhong, 2015). On the one hand, local farmers grow cereal crops for living. Long-term monoculture and uniform land use in cropping systems has led to uncertainty in farming income (He et al., 2016). On the other hand, conventional farming is in a pivotal stage of upgrading traditional modes to new agribusiness growth models. Highlighting the optimization of grazing systems has been proposed by taking advantage of plentiful heat and water resources in lower-altitude agricultural area and combining it with livestock production (Wen, 2000; He et al., 2016).

Crop and livestock integration can achieve multiple benefits by incorporating forage species into crop rotations in the middle reaches of the YTW. For example, phase farming system, adopting shorter annual forages like oats and common vetch in rotation with early-maturing highland barley cultivars can maintain household food security and improve forage production potential. The common oat-common vetch intercrop and mixture have been used as silage in the middle reaches of the YTW (Chen et al., 2015; Yuan et al., 2016). Harvesting forage with better nutritive value at early stages before maturity as silage may result in reducing dry matter yield (Jacobs and Ward, 2012, 2013). However, forage cultivation in autumn using available heat can fill feed gaps in winter and early spring comparing to purchase forages from other places. Moreover, forage cultivation is emerging as a new path to increase income for local famers. Hence, promoting forage rotation with crops will not only ameliorate feed deficits, but also alleviate grazing pressure on rangeland.

The essential question faced by the crop-forage rotation is identifying the suitability of local climate conditions for the cultivation, such as effective accumulated temperature and growing season length. An effective accumulated temperature, i.e. growing degree days (GDD) is commonly used to predict the total heat requirement for a particular plant in each growth period by assigning a heat unit to each day. Therefore, GDD model has been developed and used to estimate crop growth, grain yield, and forage quality (Elnesr et al., 2013; Elnesr and Alazba, 2016a, b; Coblentz et al., 2018). More importantly, silage is usually harvested before maturity, and GDD can be used as criterion for farmers to estimate a specific sowing date and harvesting date in practice.

Our aim is to identify the feasibility of crop-forage rotation and assess potential of crop-livestock integration for livestock feed requirement in the middle reaches of the YTW. Specifically, we intend to:

(1) estimate current livestock carrying capacity provided by rangeland and crop residues, and grazing pressure index; (2) calculate GDD and growth period, identify suitable cultivated land area, and delineate the elevational limits of forage rotation after crop harvest; and (3) assess balance between livestock carrying capacity and livestock feeds after filling feed gaps through the contribution of forage rotation. Consequently, this study is expected to provide insights into integrating crop and livestock production for sustainable agro-pastoral development in the southern Tibetan Plateau.

2. Materials and methods

2.1. Study area

The study area is located in the middle reaches of the Yarlung Tsangpo Watershed in southern Tibet Autonomous Region (TAR), China (28°20′-30°30′N, 87°00′-92°35′E; Fig.1), with land area of 8.90 million ha. The study area is composed 18 administrative districts (two cities and 16 counties), with altitudes ranging from 3300 to 7000 m. This region is characterized by plateau monsoon climate with annual average temperature of 6–8 ℃, and annual mean precipitation of 300–500 mm. Agriculture and animal husbandry are primary and pillar industries, which provide most of the livelihoods for local farmers and herdsmen. Cultivated land covers about 212,842 ha in 2015. The dominant crops in farming systems are spring barley, winter wheat, pea, and oilseed rape, and livestock are mainly composed of cattle, yak, and sheep (Paltridge et al., 2009).

2.2. Field survey of forage cultivation

Forage cultivation was surveyed at typical agricultural areas of the middle reaches of the YTW in summer of 2018 (Fig. 1). Investigation included major forage species, average yield, modes of sowing, silage cultivation and management.

2.3. Data sources and processing

The dataset used in this study include meteorological data (http://data.cma.cn), land use (http://www.resdc.cn), statistical data (http://tongji.cnki.net), and remote sensing data (https://lpdaac.usgs.gov), which all were processed for subsequent analysis. Daily mean temperature from 2000 to 2017 was extracted to calculate effective accumulated temperature, i.e. growing degree-days (GDD). Thin plate-smoothing splines method was adopted to interpolate the GDD data into raster surfaces at 1 km spatial resolution using ANUSPLIN 4.3 (Hutchinson, 2004). Available cultivated land was identified by land use data in 2015. Net primary productivity (NPP) was derived from remote sensing data (MOD17A3H). Statistical data on grain yield, livestock population were used to estimate fodder yield provided by crop residues and the number of livestock in each administrative district.

2.4. Livestock carrying capacity

Livestock carrying capacity in this study includes rangeland carrying capacity and fodder provided by crop residues. When forage growth after crop harvest implemented, forage production is also incorporated to calculate carrying capacity. The rangeland carrying capacity was calculated according to national standard (Rangeland Standard, NY/T635-2015) published by the Ministry of Agriculture of the People's Republic of China.

According to rangeland yield calculation developed by Fan et al. (2010),

$$Y_i = \frac{NPP}{0.45 \times \left(1 + \frac{BNPP_i}{ANPP_i}\right)} \times A_i \tag{1}$$

where Y_i is annual rangeland grass yield (kg), $ANPP_i$ and $BNPP_i$ are aboveground net primary productivity (ANPP) and belowground net primary productivity (BNPP), respectively in certain rangeland type i (alpine meadow, steppe), and A_i is land area of rangeland type i (m^2) obtained from 1:1,000,000 scale rangeland resource map. Dominant rangelands are alpine meadow, steppe in the study area. NPP is net primary productivity from 2000 to 2015 (kg C. m^2), 0.45 is the conversion factor of units of carbon (Tian et al., 2017). $ANPP_i$ and $BNPP_i$ values are provided by Zeng et al. (2015).

The rangeland carrying capacity was calculated as follows:

$$R_c = \sum \frac{Y_i \times U_i \times E_i \times H_i}{I \times D} \tag{2}$$

in which, R_c is rangeland carrying capacity (sustainable number of grazed livestock on rangeland, standard sheep units, SU), U_i, E_i and H_i are the proper rangeland utilization rate, proportion of edible plants and conversion coefficient of standard dry forage respectively in a certain rangeland type i. I is the daily intake of dry forage for a standard sheep unit (1.32 kg.d^{-1}), and D is grazing days (365 days). In this equation, the conversion coefficients are 1 and 0.95, respectively, in alpine meadow and steppe, utilization rates are set 45% in steppe, and 50% in meadow as per national standard (NY/T635-2015). The proportions of edible plants are 78% and 76%, respectively, in alpine meadow and steppe (Yang, 2015).

Crop residues are usually used as fodders after crop harvest for self-sufficiency in farming areas of Tibetan Plateau. According to the calculation defined by Yang et al. (2000), the fodder's carrying capacity provided by crop residues is defined as:

$$F = \frac{\sum P_i \times C_i \times U + \sum P_i \times S_i}{I \times D} \tag{3}$$

where F is fodder carrying capacity provided by crop residues (SU), P_i is yearly crop yield of a certain crop type i (kg), which is obtained from statistical data from 2000 to 2015, C_i is conversion coefficient in a certain crop type i (proportion of crop straw and seed), U is utilization efficiency of crop straw as fodder, S_i is conversion efficiency of crop seeds for using as concentrated feed (cereal bran), 20% in cereal and 60% in oilseed rape (Yang and Yang, 2000). I and D are the same as in Eq. (2). In this study, utilization efficiency of crop straw usually is 30% in the study area, and the conversion coefficients are 1.6, 1.8 and 1.6, respectively, in cereal, oilseed rape and pea (Ma et al., 2001).

2.5. The number of livestock

The actual number of livestock for each administrative district (county) is expressed as:

$$L_n = \sum L_i \times (1 + R_i) \tag{4}$$

where L_n is actual number of livestock for each county, L_i is the number of a certain livestock type i (cattle, yak, and sheep) at the end of last year (SU), R_i is the slaughter rate of a certain livestock type i. livestock number and slaughter rate were obtained from the statistical data provided by government in the period of 2000–2015. Large animal like yak or cattle is equivalent to four SU in this study as did Fan et al. (2010).

2.6. Grazing pressure index

Grazing pressure index was used to evaluate if grazing intensity exceeded carrying capacity of rangeland and crop residues:

$$G_p = \frac{L_n}{L_c} \tag{5}$$

where G_p is the grazing pressure index, L_n is the actual number of livestock (SU), and L_c is livestock carrying capacity, provided by rangeland and crop residues (SU). Overgrazing is indicated by $G_p > 1$, and sustainable grazing is indicated by $G_p < 1$.

2.7. GDD and seasonal length

The expression of accumulative active temperature, GDD is,

$$GDD = \sum \left[\frac{T_{max} + T_{min}}{2}\right] - T_b \quad (6)$$

where $Tmax$ and $Tmin$ are maximum and minimum daily temperature, respectively, T_b is the base temperature for plant growth. For grain and forage grass, 5℃ is usually the threshold temperature for initiating growth. Therefore, we chose 5℃ as the base temperature to calculate GDD for crops and forages in this study.

Seasonal length is effective accumulated days of a certain forage grass at different growth period, which was obtained from published experimental data in literatures.

2.8. Forage yield

All forage yield data were collected from published literature in China National Knowledge Internet (www.cnki.net). All the data were obtained from field experiment on the Tibetan Plateau. Based on statistical area of arable land which is suitable for forage rotation after crop harvest and average yield of silages, the feed from forage rotation was calculated and included into carrying capacity at county level.

3. Results

3.1. Livestock grazing pressure in the middle reaches of Yarlung Tsangpo Watershed

The livestock grazing pressure at county level showed that most counties were in overgrazing status except for Nyêmo, Doilungdêqên, Qonggyai and Sangri County (Fig.2a). Shigatse City and four counties including Namling, Bainang, Dagzê and Gonggar were among the overgrazing areas with grazing pressure as over 0.5 times as higher than sustainable carrying capacity. The other nine counties were slightly overgrazed with grazing pressure index less than 1.5. The average number of livestock maintained about 9 million SU in the middle reaches of YTW during the period of 2000–2015 (Fig. 2b). However, carrying capacity of rangeland together with crop residues can averagely feed about 90% of the livestock population since 2004. In the study period, grazing pressure index increased despite the number of livestock showed decreasing trend in the study region.

Table 1
The seasonal lengths of forage grasses at different growth period.

Species	Growth period*	Seasonal length (days)
Oat (*Avena sativa*)	Tillering stage	32
	Stem elongation stage	17
	Boot stage	13
Common vetch (*Vicia sativa*)	Branching stage	27
	Squaring stage	35
	Initial flowering stage	15

* Vegetative period, forage grasses are harvested before maturity as silage.

3.2. Forage rotation after crop harvest

Taking commonly cultivated annual forage grasses, oat and common vetch as an example, the average duration for silage production is generally no more than 80 days (Table 1). The average days for the vegetative growth requirement of oat and common vetch are 62 and 75 respectively. The spatial patterns of GDD indicate that cultivated land has sufficient heat (≥1500 °C d) for annual crop-forage rotation in the river valley (Fig.3a). According to the observation of daily

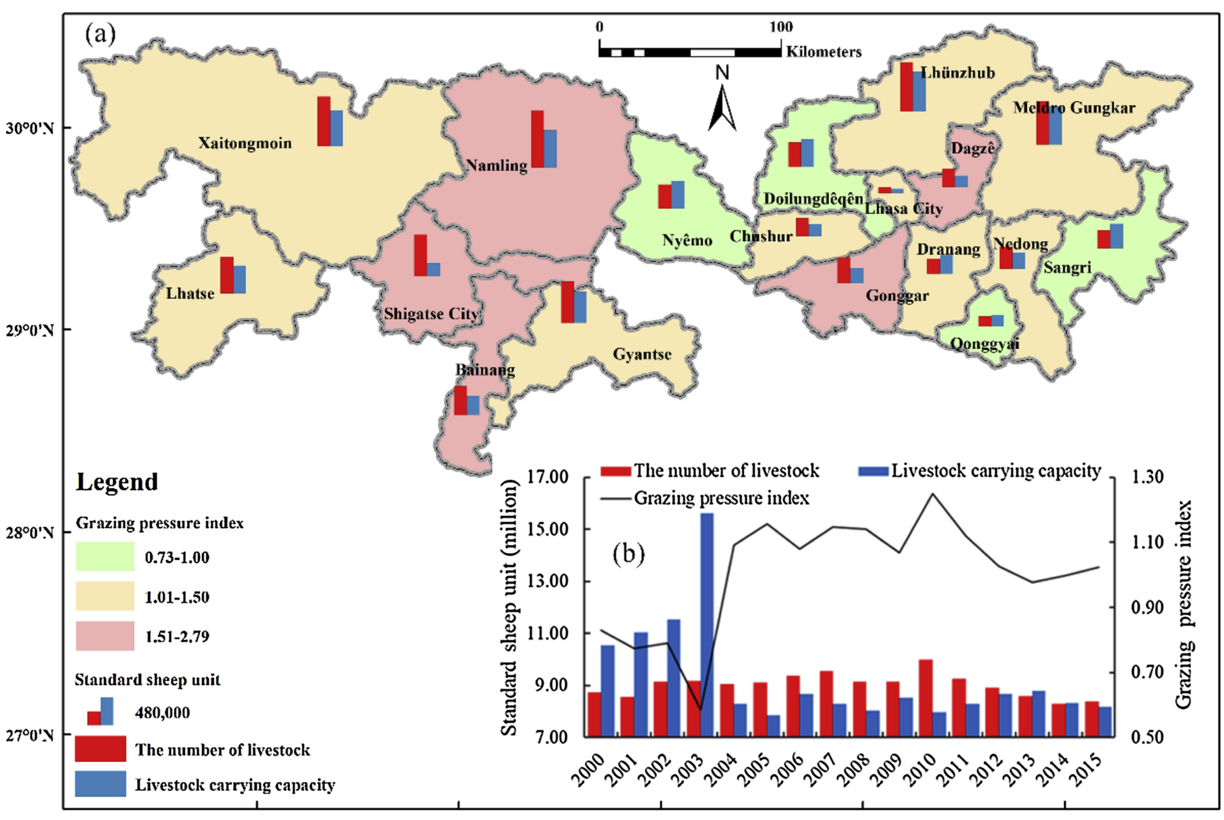

Fig. 2. Livestock carrying capacity, livestock population and grazing pressure in the middle reaches of Yarlung Tsangpo Watershed. (a) Spatial patterns of mean grazing pressure, number of livestock and livestock carrying capacity at county level. (b) The regional dynamics of livestock population, livestock carrying capacity and grazing pressure in the period of 2000–2015.

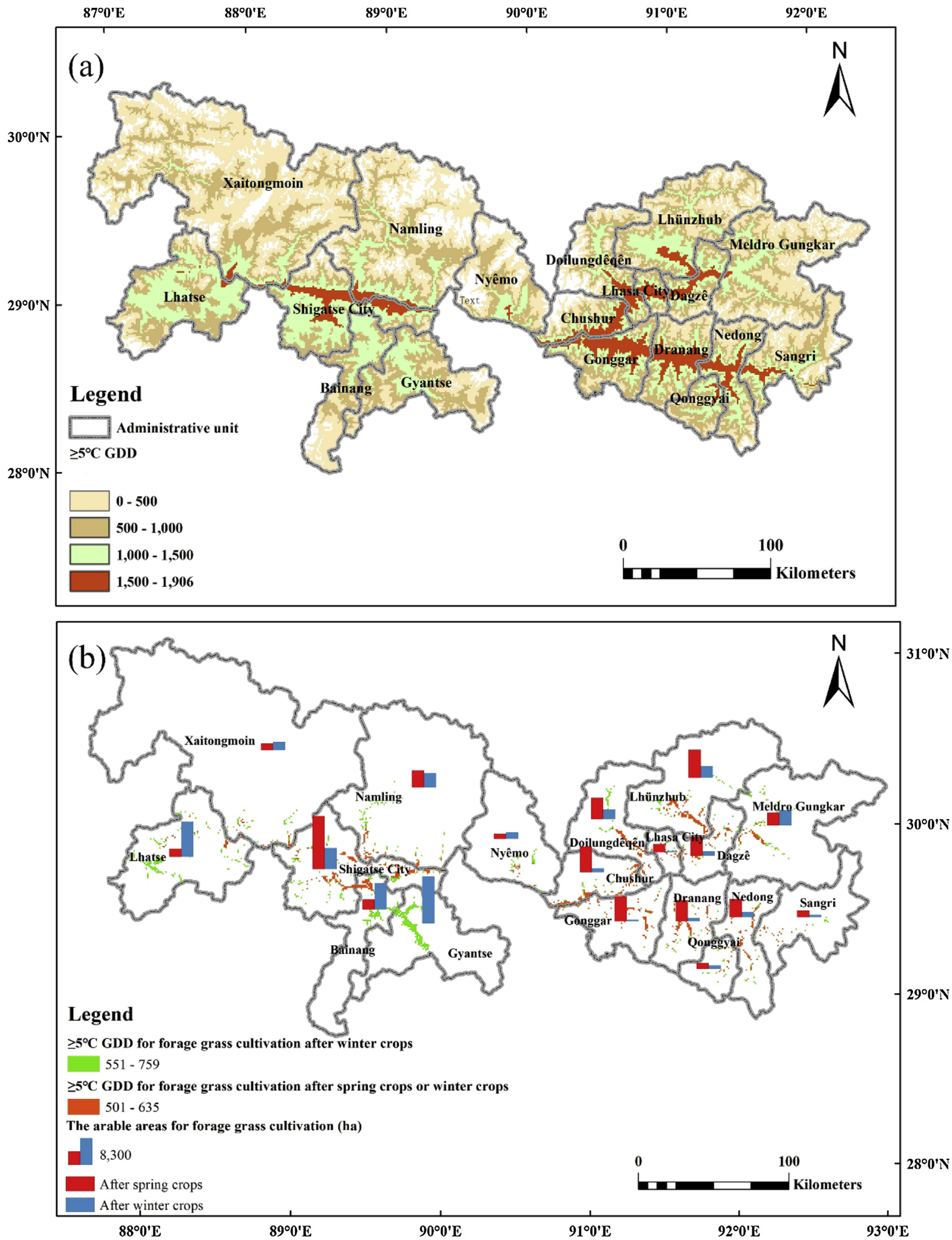

Fig. 3. Spatial patterns of growing degree days and land areas suitable for crop-forage rotation systems. (a) The annual average of growing degree days during the period of 2000-2017. (b) The arable areas and growing degree days for crop-forage rotations at county level. Two modes of silage production are consisted of annual forage rotation after the harvest of spring crops and winter crops. Spring crop-forage rotation is mostly distributed at lower altitudes in the east, and winter crop-forage rotation is mainly distributed at higher altitudes in the west of the study region.

temperature from 2000 to 2017, daily average temperature ≥ 5℃ usually started at 113 DOY (22 April) and lasted to 313 DOY (8 November). The total days of effective accumulated temperature for crop and forage rotation are 200. The average length for spring crops growth to maturation stage is 120 days ranging from 22nd April to 20th August. Therefore, there are about 80 days for silage cultivation after

Table 2
Land area of crop-forage rotation modes at county level (unit: ha).

County	Spring crop-Forage		Winter crop-Forage		Total area
	Area	Percentage/%	Area	Percentage/%	
Xaitongmoin	2,100	2.33	2,533	3.72	4,633
Lhatse	2,500	2.77	10,931	16.03	13,431
Namling	5,300	5.88	4,376	6.42	9,676
Bainang	3,100	3.44	8,103	11.89	11,203
Gyantse	0	0.00	14,554	21.35	14,554
Shigatse City	16,500	18.29	6,567	9.63	23,067
Nyêmo	1,600	1.77	2,081	3.05	3,681
Doilungdêqên	6,700	7.43	2,995	4.39	9,695
Chushur	7,900	8.76	1,218	1.79	9,118
Lhünzhub	8,700	9.65	3,639	5.34	12,339
Meldro Gungkar	3,900	4.32	4,674	6.86	8,574
Dagzê	5,800	6.43	1,328	1.95	7,128
Lhasa City	2,500	2.77	361	0.53	2,861
Gonggar	7,700	8.54	454	0.67	8,154
Dranang	6,600	7.32	1,119	1.64	7,719
Nedong	5,600	6.21	1,525	2.24	7,125
Qonggyai	1,700	1.88	985	1.44	2,685
Sangri	2,000	2.22	734	1.08	2,734
Total	90,200	100.00	68,177	100.00	158,377

spring crop harvest (from 21 st August to 8th November). But for winter crops, there are 280 days for crop growth to stage of maturity (from 20th October to 31 st July). 80 days can guarantee forage growth to maximum vegetative period (1 st August to 20th October).

Regarding the requirements of effective accumulated temperature and the length of growing season, about 158,377 ha of arable land is suitable for forage rotation after crop harvest, accounting for 74.41% of total cultivated land in the region. Specifically, there are 90,200 ha and 68,177 ha for forage rotation with spring crop and winter crop, respectively (Table 2). Considering the facts of differentiation of GDD in altitudinal gradients and growth habitat of crops, spring and winter crops are planned to grow in different altitudes. Higher altitude cultivated land in the counties of Lhatse, Bainang, and Gyantse in the west of study area is suitable for planting silage after winter crop harvest, with more than 550 GDD (Fig.3b). Forage-spring crop rotation is more favored in cultivated land at lower altitude in the eastern region, such as Chushur, Gonggar, Dranag, Lhünzhub, and Nedong County, with at least 500 GDD for silage production.

Our analysis also identified the elevation ranges of cultivated land for spring crops and winter crops. (Fig.4). The upper limits for silage cultivation after spring crop and winter crop are at 4044 m and 4520 m,

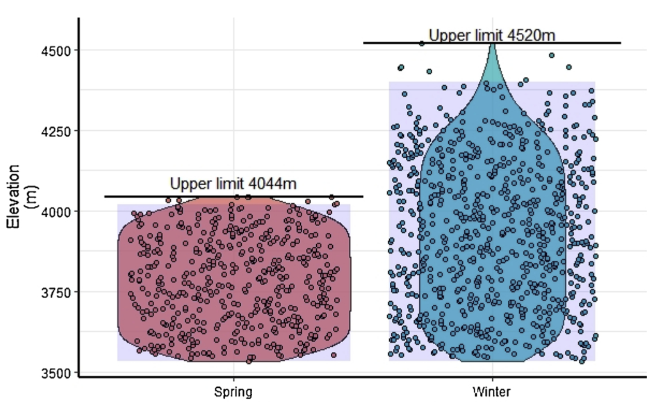

Fig. 4. The elevation ranges of cultivated land for silage production in the middle reaches of Yarlung Tsangpo Watershed. Two modes of forage-crop rotation systems are silage cultivation after spring crops and winter crops harvest in this study. Shallow blue background contains 99% sample size (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

with 99% levels at 4000 m and 4400 m respectively. In other words, cultivated land ranging from 3533 to 4000 m a.s.l is suitable for forage rotation after harvest of spring crops and winter crops, but cultivated land between 4000 and 4500 m a.s.l. is only applicable for silage production after winter crop harvest.

3.3. *Forage rotation for feed solution and potential for crop-livestock integration*

The data of forage yields of main forage grasses were collected from literature based on field experiment on the Tibetan Plateau. Among them, mixture of oat and common vetch has higher yield than monoculture. The average yields of oat-common vetch mixture can reach 10,600 $kg.ha^{-1}$ dry matter (DM) at maturity stage, whereas the average yield of all sorts of silages in maximum vegetative stage is ca. 7170 $kg.ha^{-1}$ DM on the Tibetan Plateau (Fig.5a). Together with feed from rangeland and crop residues, livestock carrying capacity will increase substantially by integrating silage from crop-forage rotation into feed solution. As a result, the grazing pressure index will significantly decline after filling feed gaps in the scenario of silage production compared to that in the period of 2000–2015 (Fig.5b). Most of the administrative districts (13 of 18) will solve the problem of feed shortage and maintain the livestock number under carrying capacity. Among the other counties, the grazing pressure indices will decrease greatly with the highest value of 1.2 only in Shigatse City and Namling County.

4. Discussion

4.1. *Feasibility of forage rotation after crop harvest*

Silage has been used to reduce grazing pressure by supplementary feeding in order to ameliorate rangeland degradation on the Tibetan Plateau, but commonly from agricultural by-products (Yuan et al., 2013; Chen et al., 2015; Yuan et al., 2016; Wang et al., 2018). Using cultivated forage as silage is not common despite some studies have suggested that heat is sufficient to support forage rotation after crop harvest in the middle reaches of the YTW (Paltridge et al., 2009, 2011; Paltridge et al., 2014). Crop-forage rotation systems have been proposed for forage production in farming areas of Tibetan Plateau (Shang et al., 2014). Our results indicated that cultivated land in the YTW could meet the requirement of heat resource for forage cultivation after

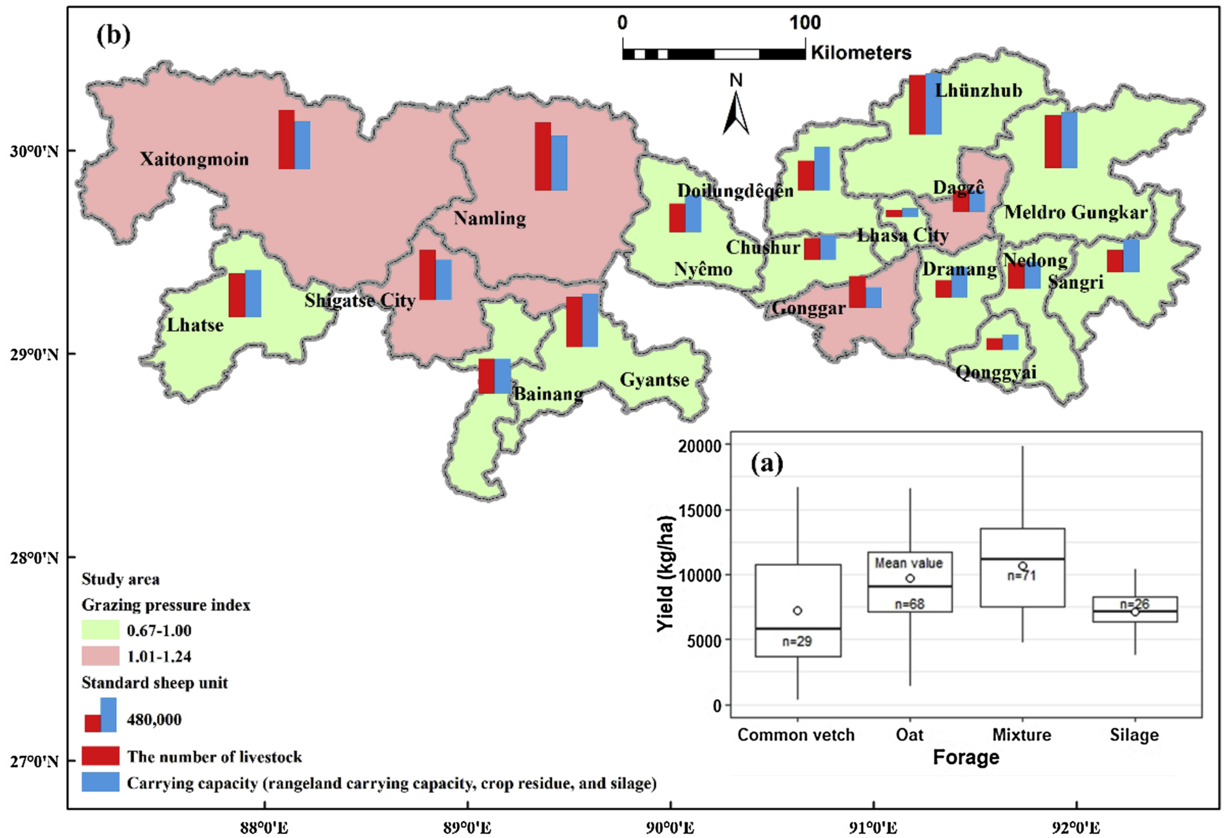

Fig. 5. Conditions of balance between grass and livestock at county level. (a) The forage yield at maturity stage and silage yield (hay) at vegetative period in Tibetan Plateau. The data obtained from field experiments on published literature. Silage includes mixture of oat and common vetch, monocropping oat or common vetch, and silage crop at vegetative period, n is sample size. (b) The livestock carrying capacity (including rangeland carrying capacity, fodder provided by crop residue, and silage) and grazing pressure index at county level after filling feed gaps in the scenario of silage production.

crop harvest. There are 80 days available for forage growth in late summer and autumn with effective accumulated temperature greater than 500. Furthermore, Zhang et al. (2018) found that growing season length was extended because earlier starting date and delayed ending date of the growing season on the Tibetan Plateau. This is in agreement with the findings of Wang et al. (2013) that growing season has significantly become warmer and longer on the Plateau. Warming autumn is beneficial for forage cultivation after crop harvest due to increasing accumulated temperature and growing season length. Andrzejewska et al. (2019) found oat sown in late summer for forage significantly reduced crown rust disease. Therefore, the heat condition is sufficient to ensure forage growth till maximum vegetative production after crop harvest in the YZW.

Considering growth habits of crops and heat requirements for forage production, crop-forage rotation must follow appropriate cropping system. Winter crops are sown in autumn, regrown and harvested in the next year. Longer life history endows its capacity to grow at higher altitude and span across two years for harvest. While spring crops are planted and harvested within one year. Higher heat condition is required in a shorter season so that it can only be planted in lower altitude (Paltridge et al., 2009, 2011). As a result, GDD determines the ranges of elevation for forage cultivation, i.e. the upper limit is 4000 m for spring crop and 4500 m for winter crop. Thus, cultivated land above altitude of 4000 m should select winter crops and cultivate cold-resistant crops and forage species. While spring and winter crops both can be cultivated at altitudes lower than 4000 m.

We have shown that the heat condition in late summer and autumn can meet the requirements of forage growth to the stage till earlier flowering, thus maximum vegetative biomass is available. Besides the requirements of heat and growing season length, field management such as irrigation, fertilization and tillage is also the important measures for forage cultivation. Different sowing date, cultivar of forage species, and plant density all contribute to forage yields of silage production (Seiter et al., 2004; Armstrong and Albrecht, 2008; Coblentz et al., 2011). Moreover, impacts of extreme weather events on forage cultivation, for instance drought, intense precipitation, cold waves are not under consideration in this study. Additionally, precipitation or soil moisture is generally not the problem for forage rotation just after monsoon season in the YTW. Nevertheless, our results only provide a potential prospect for maximizing forage self-sufficiency in the southern Tibetan Plateau. The further operational on-farm practice is urgently required to be examined and improved step by step.

4.2. Livestock grazing pressure in the middle reaches of the YTW

The national project of *Returning Grazing Lands to Grasslands* (RGLG) has been implemented since 2004 to restore degraded rangeland on the Tibetan Plateau (Yu et al., 2016). The project makes effort to rehabilitate overgrazed rangelands by reducing livestock population, grazing exclusion and supporting compensation policy (Xiong et al., 2016; Liu et al., 2017, 2018; Wu et al., 2019). However, the number of livestock showed only a slight decline trend in the period from 2000–2015. Instead, the livestock grazing pressure indices kept in high level till 2010 and then showed a slight decrease, indicating the delay impact of the policy. Although the project of RGLG reduced grazing pressure through increase slaughter rate, the number of livestock maintains 9 million SU in average over the study period, which was excess of livestock carrying capacity provided by rangeland and crop residues. It might be due to human population growth, which could cancel out a part of decrease of livestock number (Shang et al., 2014).

Total livestock number is expected to increase because average livestock number per capita is stable. Additionally, traditional wealth view of local people lets them keep as many livestock as possible and reluctant to slaughter animals. Similarly, Li et al. (2014) also revealed that the actual number of livestock of most counties still exceeded rangeland carrying capacity after adding fodder provided by crop residues on the Tibetan Plateau. Furthermore, we found that large herbivore like yaks accounted for an increasing proportion in grazing system in the southern Tibetan Plateau, resulting in the number of livestock (SU) beyond sustainable carrying capacity in the study period. The structure of livestock groups is of paramount significance on maximizing the use of rangeland grazing and supplementary feeds. Thus reshaping livestock group structure is vital to livestock carrying capacity of rangeland and the livestock industry in Tibetan Plateau (Shang et al., 2014).

In addition to rangeland and crop residues, sown pasture, purchased forage, and forest land (edible leaves and grass) were not included in this study. Sown pasture (including annual and perennial) was developed for livestock feeding in recent years. For example, Shigatse Prefecture had 21,000 ha sown pastures until 2017. The TAR government is planning to establish about 67,000 ha new sown pastures in Tibet, which has great potentials to increase livestock carrying capacity. Establishing large areas of sown forage can produce forage supplements for livestock, but the major challenge facing forage production from sown pastures is lack of sound management and pastures degradation in the long-term (Shang et al., 2014). Thus, sustaining large areas of sown pastures is urgently required, especially at altitudes above 4000 m in Tibetan Plateau.

Our results suggest that widespread livestock grazing pressure can be alleviated through forage cultivation after crop harvest in the middle reaches of the YTW. The livestock feed deficits will be solved after the additional contribution of silage production through crop-forage rotation compared to that in the period of 2000–2015. Furthermore, crop-forage rotation is a potential pathway to promote crop and livestock integration in farming system. Studies have shown that intensification of CLI can increase food self-sufficiency, soil fertility, farm productivity, and decrease the detrimental environmental effects (Alvarez et al., 2014; Soussana and Lemaire, 2014). But farmers also should have expectation that adopting CLI would strengthen both profitability and environmental sustainability.

4.3. Implications for crop and livestock integration

Filling feed gaps in grazing system through CLI is a solution to cope with rangeland restoration and livestock production. However, CLI adoption is complex, a range of policy incentives, technology, infrastructure, management and market support should be implemented as considering viable practice (Thornton and Herrero, 2014; Ryschawy et al., 2017). Removing barriers to CLI practice is imperative when integrating crop and livestock production in the middle reaches of the YTW. On the one hand, the excessively high livestock stocking rate has imposed grazing pressure on rangeland, therefore, regulating properly proportion of large herbivore in livestock system and raising some omnivore, such as chicken and pig are beneficial. On the other hand, increasing diversity in cropping systems provides an opportunity for farmer to enhance agricultural sustainability and secure high yields (Jensen et al., 2008; Smith et al., 2008; St-Martin et al., 2017).

Besides forage rotation after crop harvest, crop and forage grass intercrop is an approach to enhance forage supply as well. Numerous field studies have revealed that intercropping legumes with cereals can improve crop yield, forage quality, and reduce plant diseases and pest insects (Ross et al., 2005; Hauggaardnielsen et al., 2008; Dhima et al., 2014). Several benefits of higher N retention, higher crude protein and dry matter yield of cereal-legume intercrops silages than other grasses for ruminants have been reported (Adesogan et al., 2004; Maxin et al., 2017; Coblentz et al., 2018). Furthermore, the crop-forage intercrop has been practiced in the river valleys of central of Tibet (Paltridge et al., 2014). In addition, cultivated land abandonment is common because of low yield and high altitude in recent decades (Yang et al., 2015). Using abandoned cropland to cultivate high yield corn silage and forage grass is also a pathway to enlarge feed resources and enhance farm incomes.

We observed forage rotation after crop harvest is not common during our survey. Local farmers are accustomed to grazing in cultivated land rather than forage cultivation, even though the area has great potentials to practice. Kassie et al. (2015) found that famers' preferences and decisions on agricultural intensification were mainly affected by social capital, extensive services, governmental assist, resource constrains, and market access when practical solution was adopted in agricultural systems. Implementation of forage cultivation needs additional labor cost. Farmers have to trade-off the benefit between on-farm forage production and other employment. Besides, the risks of freeze injury to forage cultivation in later autumn will affect the forage yield and income. It is likely that these issues will reduce the enthusiasm of local farmers to practice crop-forage rotation. Therefore, enabling policy environment is crucial to subsidize and motivate farmers' involvement into crop-forage rotation.

5. Conclusions

This study has indicated that crop-forage rotation has promising prospects for maximizing forage self-sufficiency and alleviating grazing pressure in the middle reaches of the Yarlung Tsangpo Watershed. The cultivated land in the Yarlung Tsangpo River valley provided more than 500 GDD to ensure forage rotation after crop harvest. The feasible planting period for forage rotation is from 20th August to 8th November after spring crop harvest and from 1 st August to 20th October after winter crop harvest (80 days). The upper limits of forage rotation are 4000 m after spring crop harvest and 4500 m after winter crop harvest, respectively. Furthermore, the grazing pressure indices of most counties will evidently decline after filling feed gaps through crop-forage rotation. Therefore, crop-forage rotation will be a good solution to enlarge feed sources and alleviate grazing pressure. However, further efforts are needed to encourage farmers' initiatives and enable policy environment for greater adoption of forage cultivation.

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