Productivity and persistence of perennial grass mixtures under competition from annual weeds in the alpine region of the Qinghai-Tibetan Plateau

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Summary

In the alpine region of the Qinghai-Tibetan Plateau four indigenous perennial grass species *Bromus inermis* (BI), *Elymus sibiricus* (ES), *Elymus nutans* (EN) and *Agropyron cristatum* (AC) were cultivated as three mixtures with different compositions and seeding rates, BI + EN, BI + ES + AC and BI + ES + EN + AC. From 1998 to 2001 there were three different weeding treatments: never weeded (CK); weeded on three occasions in the first year (1-y) and weeded on three occasions in both the first and second year (2-y) and their effect of grass combination and interactions on sward productivity and persistence was measured. Intense competitive interference by weedy annuals reduced dry matter (DM) yield of the swards. Grass combination significantly affected sward DM yields, leaf area index (LAI) and foliar canopy cover and also species composition DM and LAI, and species plant cover. Interaction between weeding treatments and grass combination was significant for sward DM yield, LAI and canopy cover, but not on species composition for DM, LAI or species plant cover. Grass mixture BI + ES + EN + AC gave the highest sward DM yield and LAI for both weeding and non-weeding treatments. Species ES and EN were competitively superior to the others. Annual weedy forbs must be controlled to obtain productive and stable mixtures of perennial grasses, and germination/emergence is the most important time for removal. Weeding three times (late May, late June and mid-July) in the establishment year is enough to maintain the production and persistence of perennial grass mixtures in the following growing seasons. Extra weeding three times in the second growing year makes only a slight improvement in productivity.

Keywords: perennial grass mixtures, annual weeds, sward yield, sward persistence, alpine region.

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Introduction

Plants may out-compete their neighbours through shading or accessing limited nutrients and water resources (Tilman, 1987; McGraw & Chapin, 1989; Tremmel & Bazzaz, 1993). Competition for resources can have some strong effects on survival, growth, production and reproduction of individual plants (Connell, 1983; Belcher *et al.*, 1995; Knezevic *et al.*, 2001). In cropping systems, inter-specific competition is a major cause of crop yield reduction by weeds (Bond & Grundy, 2001).

Numerous researchers (Hubbard, 1957; Van Epps & McKell, 1983; Chambers *et al.*, 1990) have reported a particular need to control competition when plants are established in stressful environments. In direct seeding, for example, Plummer *et al.* (1968) specified that competition must be low for desired species to become well established in rangeland/pasture, while Keller (1978) emphasized the importance of reducing the annual grasses and forbs for successful range seeding in the sagebrush ecosystem. Evans and Young (1977) developed management techniques that included herbicides to

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control *Bromus secalinus* L. competition in sagebrush rangelands.

Because weed–crop competition is generally for light (Loomis *et al*., 1971), much of the recent work has focused on canopy structure and competition for light (Caldwell, 1987; Tremmel & Bazzaz, 1993). Leaf area index (LAI), the indicator of light interception, can reflect the ability of a plant to deplete light resources from its neighbours (Nassiri & Elgersma, 1998). Canopy coverage, the indicator of species dominance, is a product of the outcome of individual plant competition at the sward level (Li, 1995).

Perennial grass mixtures have been recommended as a new winter forage resource to replace fodder oats for grazing livestock in the legume-deficient alpine region of the Qinghai-Tibetan Plateau of China. Currently there is a process of restoring the degraded grassland through planting perennial grass forage on the cultivated lands which were formerly dominated by annual crops under the Western Development Policy of China. Several researchers (Che, 1994; Du & Wang, 1995; Wang & Jiang, 1998) have studied the population dynamics of some cultivated perennials under weed-free conditions. However, little research has focused on performance of cultivated perennial grass mixtures under weed competition in the alpine region of Qinghai-Tibetan Plateau, except for Wang and Jiang (1998) who reported significant reduction in productivity and persistence of perennial grass pastures because of competition from annual weeds. As a consequence, local farmers were reluctant to plant perennial grasses extensively until an improved weed management system is developed. The aim of this experiment was to evaluate the productivity and persistence of three common grass mixtures in the alpine region of the plateau under different levels of weed competition by analysing sward dry matter (DM) yield, LAI and canopy coverage. The results of this study will guide the local farmers to improve production and stability of mixture pastures of perennial grasses through improved weed management.

Materials and methods

Plant materials and study site

In early May of 1998, four indigenous grass species in the Qinghai-Tibetan Plateau, *Bromus inermis* Leyss. (smooth bromegrass) (BI), *Elymus sibiricus* Linn. (siberian wild-ryegrass) (ES), *Elymus nutans* Griseb. (drooping wild-ryegrass) (EN) and *Agropyron cristatum* Gaertn. (crested wheatgrass) (AC) were combined in three mixtures with different compositions and seeding rates (Table 1). The seeding rates of each component grass were determined by combining the seeding rates in grass monocultures and the proportions in the grass mixtures recommended for the alpine region (Ren, 1998), for example, BI was seeded at 76 kg ha^{-1} in the monoculture, and at 38 kg ha^{-1} in the mixtures where its target proportion was 50%. Nine plots (2 m × 5 m) for each grass mixture were randomly established with a 15 cm distance between plots in the experiment field of the Alpine Grassland Station of Gansu Agricultural University in the Jingqinghe Region (N37°40′, E180°32′, 3000 m a.s.l.), at the north-eastern end of the Qinghai-Tibetan Plateau.

The study site was on an alpine meadow soil previously sown to forage oats (*Avena sativa* L.) and oilseed rape (*Brassica napus* L.) in a rotation. The major annual weeds present in this area were forbs, including *Chenopodium glaucum* L., *Elshotaiz argyi* Lévl., *Microula sikkimensis* Hemsl., *Hypecoum leptocarpum* Hook. and *Osmorhiza aristata* Thunb. The soil extended to a depth of 40–60 cm, with an analysis of 100 g kg^{-1} organic matter, 6 g kg^{-1} total nitrogen, 67 mg kg^{-1} total phosphorus, 170 mg kg^{-1} total potassium (DM basis) and a pH (water suspension) of 7.0–8.0 (Dong, 2001). Weather data were recorded at the nearest weather station, Wushaoling Meteorological Station (10 km from the experimental site). Analysis of 20-year average (1978–98) showed that in this area, the lowest temperature (−20°C) occurred in January and the highest temperature (17.4°C) in July, with an annual average temperature of −0.1°C and annual cumulative temperature above 0 around 1380°C. Total

Table 1 Seeding rates (kg ha^{-1}) and species proportions (%) of component grasses, *Bromus inermis* (BI), *Elymus nutans* (EN), *Elymus sibricus* (ES) and *Agropyron cristatum* (AC) in different grass mixtures

Species	Seeding rates and species proportions	BI + EN	BI + ES + AC	BI + ES + EN + AC
BI	Seeding rate	38	38	19
	Species proportion	50	50	25
EN	Seeding rate	56	–	28
	Species proportion	50	–	25
ES	Seeding rate	–	14	14
	Species proportion	–	25	25
AC	Seeding rate	–	23	23
	Species proportion	–	25	25

precipitation averages 416 mm, which occurs primarily as rainfall in July, August and September.

Treatment

The site was partially prepared during late autumn in 1997 by removing all annual plant growth, leaving it fallow for winter moisture accumulation. The entire site was weeded by manual cultivation in the following spring to remove annual seedlings, leaving a uniform loose shallow soil mulch. Prior to planting in early May 1998, the site was fenced to exclude grazing livestock, rabbits and rodents. Three competition treatments were designed as: (i) a control where all plants were allowed to grow naturally after sowing (CK); (ii) 1 year of manual weeding (1-y); and (iii) 2 years of manual weeding (2-y). Each grass mixture was repeated randomly in three plots for each treatment.

All weed seedlings in the 1- and 2-y weeding treatment were manually hoed or pulled three times a year in late May, late June and mid-July. In 1998 both treatments were kept free of other plant growth, whereas only the 2-y weeding treatments were maintained free from other plant competition in 1999. The performance of grass mixtures under all treatments were observed continuously for 3 years from 1998 to 2000.

Measurements

All measurements were taken in the third growing year of 2000. Sward yields were determined by cutting the plants with hand-held shears to ground level from 50 cm × 50 cm quadrats (three replicates per plot) and weighed according to the method recommended by Moore and Chapman (1986). The component grass species and weeds were separated by hand immediately after harvest and dried at 65°C for 48 h to determine DM content. LAIs of the swards and individual grasses were measured by using CI-203 Portable Laser Area Meter (CID, USA) in 10 cm × 10 cm quadrats (three replicates per plot). Species composition in DM and LAI were calculated as the percentages of individual grass species in sward DM yield and LAI.

Foliar percentage covers of swards and component grass were estimated from 50 cm × 50 cm quadrats (three replicates) with pins following the method of Moore and Chapman (1986). To achieve consistency with the data of species compositions in DM and LAI for statistical analysis, data of component species cover were converted into relative cover following the formula recommended by Ren (1998): (cover of individual component grass species/sum of cover of all component grass species) × 100 and recorded as species plant cover (in percentages).

Statistical analysis

A general linear model was used for factorial analysis, with weeding treatments and grass combination as the main factors, to test the effect of these two factors and their interactions on sward DM yield, LAI and canopy cover, and individual species compositions on DM, LAI and species plant cover, and to investigate the difference of these parameters between different weeding treatments. One-way ANOVA was performed to compare differences of the mean values of sward DM yield, LAI and canopy cover between grass mixtures and between weeding treatments. Analyses were carried out using SPSS10.0 (Huang *et al.*, 2001).

Results

Effect of weeding treatment

The effects of weeding treatments were significant ($P < 0.001$) on sward DM yields, LAI and canopy cover, but not significant ($P > 0.05$) on species composition in DM and LAI, and species plant cover (Table 2).

Yields of sward DM were improved by manual weeding, although the amount of additional yields varied with grass mixtures (Table 3). Around 50%, 5% and 102% improvement in DM were obtained by 1-y weeding for grass mixtures of BI + EN, BI + ES + AC and BI + ES + EN + AC, respectively, while there was only 3–5% improvement in DM for all grass mixtures after 2-y weeding when compared with 1-y weeding.

Manual weeding also resulted in increased sward LAIs, but the increment varied greatly with grass mixtures (Table 3). The LAI of grass mixture BI + ES + AC was doubled by both 1-y and 2-y weeding. That of BI + EN was increased by *c.* 70% for 1-y weeding and doubled for 2-y weeding, and that of BI + ES + EN + AC was increased by 56.3% and 68.8% for 1-y and 2-y weeding respectively. A significant improvement in sward LAIs was observed for 2-y weeding for grass mixtures of BI + EN and BI + ES + EN + AC when compared with 1-y weeding.

Similar to sward DM yield and LAI, sward canopy cover was greatly improved by manual weeding (Table 3). In the absence of weeds, perennial grass canopy cover expanded to fill most of the available space. There was no difference in canopy cover for all grass mixtures between 1-y and 2-y weeding treatments.

Although weeding treatment had no significant effect on species compositions for DM, LAI and species plant cover, DM and LAI proportions as well as species plant cover of component grasses in the same grass mixture

Table 2 Effects of competition treatment (Tr), grass combination (Co) and their interactions on sward dry matter (DM) yield, leaf area index (LAI) and cover and on species composition DM, LAI and species plant cover

Factors	Statistical parameters	DM yield	LAI	Sward cover	DM composition	LAI composition	Species cover
Tr	d.f.	2	2	2	2	2	2
	MS	3.62×10^7	8.1	2317.6	2.93×10^{-5}	2.34×10^{-4}	0.16
	F	1483.1	488.6	164.2	0.23	1.4	0.06
	Sig.	***	***	***	NS	NS	NS
Co	d.f.	2	2	2	2	2	2
	MS	6.83×10^7	15.2	361.8	0.80	0.71	6987.6
	F	2800.0	912.8	25.6	6149.9	4181.5	44.6
	Sig.	***	***	***	***	***	***
Tr × Co	d.f.	4	4	4	4	4	4
	MS	1.19×10^7	0.16	233.8	1.02×10^{-4}	4.62×10^{-4}	0.26
	F	489.5	9.5	16.6	0.79	2.0	0.11
	Sig.	***	***	***	NS	NS	NS

***$P < 0.001$; NS, not significant ($P > 0.05$).

Table 3 Sward dry matter (DM) yield, sward leaf area index (LAI) and ground covered by sward canopy (canopy cover) of three grass mixtures: *Bromus inermis* (BI) + *Elymus nutans* (EN); *Bromus inermis* + *Elymus sibiricus* (ES) + *Agropyron cristatum* (AC) and *Bromus inermis* + *Elymus sibiricus* + *Elymus nutans* + *Agropyron cristatum* under three weeding treatments

Grass combinations and competition treatments	DM yield		LAI		Canopy cover (%)	
	Mean (kg ha^{-1})	Increment (%)†	Mean*	Increment (%)	Mean (%)	Increment (%)
BI + EN						
CK	5331.7 f	–	1.3 g	–	66 c	–
1-y	7962.4 c	49.3	2.2 f	69.2	98 a	48.5
2-y	8144.2 c	52.8	2.8 e	115.4	99 a	50.0
BI + ES + AC						
CK	6426.7 e	–	1.4 g	–	57 d	–
1-y	6764.1 d	5.2	2.9 de	107.1	96 a	68.4
2-y	6974.4 d	8.5	3.1 cd	121.4	98 a	71.9
BI + ES + EN + AC						
CK	6873.2 d	–	3.2 c	–	89 b	–
1-y	13876.3 b	101.9	5.0 b	56.3	100 a	12.3
2-y	14325.7 a	108.4	5.4 a	68.8	100 a	12.4
SEM	127.5	–	0.1	–	3.1	–

*Mean LAI is the leaf area of each sward per unit area of ground surface in m^2.
†Increment is (weeding mean − CK mean)/(CK mean).
Mean values followed by different letters within a row are significantly different ($P < 0.05$).

varied slightly with different weeding treatments (Figs 1–3).

Effect of grass combination

Grass species combinations significantly affected ($P < 0.001$) sward DM yields, LAI and canopy cover (Table 2). BI + ES + EN + AC had the highest ($P < 0.05$) sward DM yield and LAI among all grass mixtures under both weeding and non-weeding treatments. BI + EN was comparatively higher ($P < 0.05$) than BI + ES + AC in sward DM yield at 1-y or 2-y weeding, while BI + ES + AC was relatively higher ($P < 0.05$) than BI + EN in sward LAI at each level of weeding management. No significant ($P > 0.05$) difference of sward canopy cover was observed among all grass mixtures at both 1-y and 2-y weeding managements.

Different grass combinations (seeding rates and seed proportion) resulted in different ($P < 0.001$) species composition DM and LAI, and species plant cover (Table 2). Although the seeding rate (38 kg ha^{-1}) and species seed composition (50%) of grass BI in the grass mixtures of BI + EN and BI + ES + AC were the same (Table 1), higher ($P < 0.05$) DM and LAI proportions and species plant cover of BI were observed in the grass mixture of BI + EN than BI + ES + AC (Figs 1–3). The grass mixture of BI + ES + AC had higher ($P < 0.05$) DM and LAI proportions and species plant cover of ES, but relatively lower ($P < 0.05$) DM

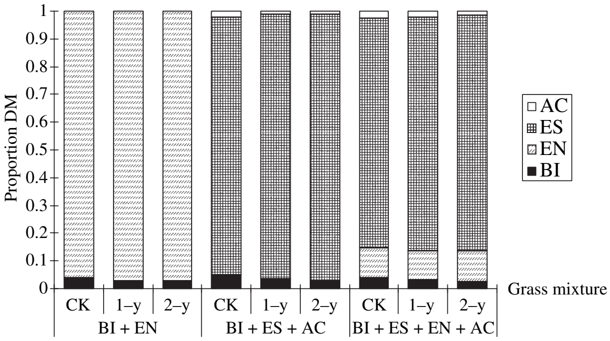

Fig. 1 Species proportions as DM of grass mixtures: *Bromus inermis* (BI) + *Elymus nutans* (EN), *Bromus inermis* (BI) + *Elymus sibiricus* (ES) + *Agropyron cristatum* (AC) and *Bromus inermis* + *Elymus sibiricus* + *Elymus nutans* + *Agropyron cristatum*, with treatments: natural growing, i.e. no weeding (CK), 1-year manual weeding (1-y) and 2-year manual weeding (2-y). Interactions of weeding treatment and grass combination on species composition in DM are presented in Table 2.

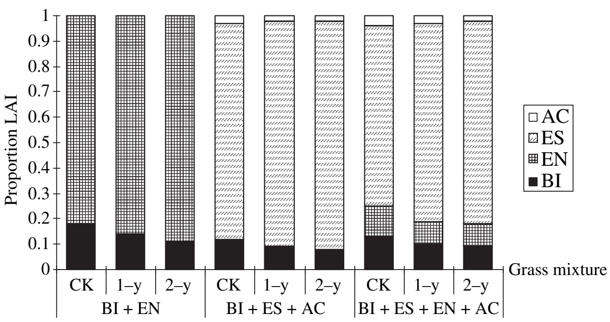

Fig. 2 Species proportions as LAI of grass mixtures: *Bromus inermis* (BI) + *Elymus nutans* (EN), *Bromus inermis* + *Elymus sibiricus* (ES) + *Agropyron cristatum* (AC) and *Bromus inermis* + *Elymus sibiricus* + *Elymus nutans* + *Agropyron cristatum* with treatments: natural growing, i.e. no weeding (CK), 1-year manual weeding (1-y) and 2-year manual weeding (2-y). Interactions of weeding treatment and grass combination on species composition in LAI are presented in Table 2.

and LAI proportions and species plant cover of AC when compared with BI + ES + EN + AC, while Table 1 shows that the grass mixtures BI + ES + AC and BI + ES + EN + AC had the same seeding rates and species seed compositions of these two species, ES (14 kg ha^{-1}, 25% respectively) and AC (23 kg ha^{-1}, 25% respectively).

Interaction between weeding treatments and grass combination

As shown in Table 2, there was a significant ($P < 0.001$) interaction between weeding treatment and grass combination on sward DM yields, LAI and canopy cover, but no significant ($P > 0.05$) interaction on species composition for DM and LAI, and species plant cover. Great variations of sward DM yields, LAI and canopy cover may be partly caused by weeding treatment and grass combination interactions.

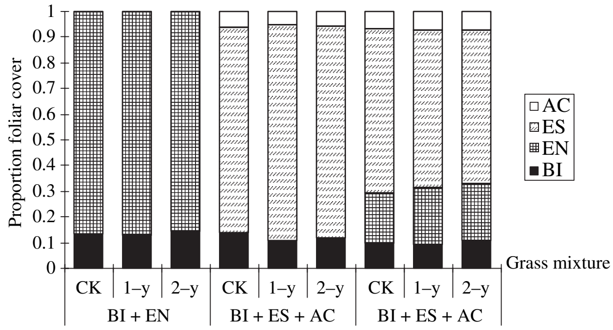

Fig. 3 Plant cover of component species in grass mixtures: *Bromus inermis* (BI) + *Elymus nutans* (EN), *Bromus inermis* + *Elymus sibiricus* (ES) + *Agropyron cristatum* (AC) and *Bromus inermis* + *Elymus sibiricus* + *Elymus nutans* + *Agropyron cristatum* with treatments: natural growing, i.e. no weeding (CK), 1-year manual weeding (1-y) and 2-year manual weeding (2-y). Interactions of weeding treatment and grass combination on plant cover are presented in Table 2.

Discussion

This study showed that intense competition of weedy annuals had a negative influence on the productivity of perennial grass mixtures. Similar findings have been obtained by other researchers studying crop–weed relationships (Li, 1995; Bond & Grundy, 2001; Knezevic *et al.*, 2001). Manual removal can reduce the competitive impact of annual weeds on perennial grass mixtures in the alpine region of the Tibetan Plateau. The effects of reducing weed competition are generally reflected in greater DM yields of mixed grasses. In addition, grass combination and its interaction with weeding treatment also have significant effects on the productivity of perennial grass mixtures. These effects were ultimately reflected in different sward DM yields of different grass mixtures under different weeding treatments.

Sward LAI is the major indicator of the ability to capture light resources (Gay, 1993; Nassiri & Elgersma, 1998). In this study the sward LAI of grass mixtures was negatively related to the level of weed competition. The ability of perennial grass mixtures to use light resources would be reduced with increased annual weed competition. Manual weeding resulted in higher LAI of grass mixtures, which improved the ability of the plants to capture more light. This appeared to be the prime factor attributed to increased productivity of grass mixtures under reduced weed competition. As for the DM yields of swards, LAIs of grass mixtures were significantly affected by species combinations and the interaction between species combination and weeding treatment.

This was primarily reflected in different sward LAIs of different grass mixtures under different weeding treatments.

Sward canopy cover can be a consequence of not only the competence of plants to acquire and utilize available resources, but also the ability to occupy limited space (Grime, 1973; Tilman, 1987; Tremmel & Bazzaz, 1993). Competition for space between many plants occurs through interactions among immediate neighbours (Slatkin & Anderson, 1984). Germination/emergence is a critical time in a plant's development to acquire space, with plants that emerge first in the field gaining a competitive advantage (Li, 1995; Bond & Grundy, 2001). In the alpine region, emergence of cultivated grasses occurred quite late in the establishment year (Chambers *et al.*, 1990) and growth of the seedlings of these grasses was slow where there was weed interference (unpubl. obs.). This explains why the grass mixtures occupied less space, as shown by lower canopy cover under intense weed competition. Removal of weed competition might have stimulated the grasses to tiller, and thus improve the capacity of seedlings to occupy more space (cover).

Plant competition occurs between individual plants for the limited resources available (Bazzaz, 1990) and alters species compatibility and sward persistence of grass mixtures, which can be reflected in the dynamics of species compositions (Dong, 2001). Plant competition in such grass–weed communities will include grass–weed competition, interspecific competition among component grasses and intraspecific competition among plants of same grass species. In this study, interspecific competition (represented by the factor of combination) was significant and grass–weed competition (represented by the factor of weeding treatments) and their interactions insignificant in altering the species compositions according to the statistical analysis, although the effect of intraspecific competition was not assessed. Great variation in species composition in both LAI and DM in this study illustrated poor species compatibility and sward persistence of these grass mixtures. Grasses ES and EN were more compatible under all weeding treatments and should be further examined as a new mixture in future research.

The competitive ability of a plant not only includes the capacity to deplete resources before other plants can acquire them, but also includes the capacity of individuals to grow, survive, and reproduce in the presence of other plants despite the depletion of resource levels by neighbours (Goldberg & Werner, 1983). Both species contribution to LAI, the indicator of the ability of the plant to capture light resources, and species contribution to DM yield, the indicator of the ability to grow, survive and reproduce even when resources are depleted by neighbours, can indicate the competitive ability of individual species. Capture of above-ground resources (light) depends on the leaf area borne by plants and how this leaf area is arranged in a canopy (Morris & Myerscough, 1991). Although the LAI of individual species in this study shows the competitive ability of the plants to intercept light, further study is needed to analyse the canopy structure of the grass mixtures, which can affect light attenuation within canopies (Tremmel & Bazzaz, 1993). DM proportions of individual species in this present study may, more or less, synthetically reflect the ability of the plants to grow, survive and reproduce despite the depletion of resources by neighbours.

Species plant cover, an indicator of dominance, illustrates the outcome of competition. When weed competition was most intense, grass species could not dominate the communities over three consecutive growing years. Whether weeds were controlled or not, EN in the mixture of BI + EN and ES in the mixtures of BI + ES + AC and BI + ES + EN + AC are competitively superior to other component grasses in the mixture, as shown by higher DM and LAI proportions. It can thus be concluded that plants that can strongly withstand competition are likely to dominate in the mixture, while species that poorly withstand competition are apparently not able to respond even if the weed competition is eliminated. This finding supports the findings of other researchers (Holmgren, 1956; Hubbard, 1957; Van Epps & McKell, 1983).

The effects of weeding treatment, and its interactions with grass combination on the productivity and persistence of three grass mixtures in this study indicate that annual weedy species must be controlled to obtain productive and stable mixtures of sown perennial grasses in the alpine region of the Qinghai-Tibetan Plateau. Germination and emergence is the critical period to target weed control. Weeding three times (late May, late June and mid-July) in the establishment year was sufficient to ensure the production and persistence of perennial grass mixtures in the following growing seasons. Additional weeding (late May, late June and mid-July) in the second growing year maximized the productivity and stability of perennial grass mixtures, but weeding in the second year did not provide as much improvement as the first year weeding. These results were obtained with the exclusion of grazing animals. Before a clear conclusion can be drawn about which is the most desirable grass combination and which grass species should form the basis of such a combination, it will be important to study the effects of grazing on grass mixture productivity over a longer time period following this establishment phase.

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