Fertilization of Nootka lupin (*Lupinus nootkatensis*) for biomass production and carbon sequestration

HÓLMGEIR BJÖRNSSON

Agricultural University of Iceland, Keldnaholt, 112 Reykjavík, Iceland
E-mail: holmgeir@lbhi.is

ABSTRACT
In order to investigate the fertilizer needs of Nootka lupin (*Lupinus nootkatensis*) an experiment with phosphorus, nitrogen, potassium and sulphur fertilizer was planted on eroded sandy soil in southern Iceland in 1999. The experiment was harvested 2003–2006 and herbage and soil sampled. Fertilization with sulphur was essential for good survival of the lupin following harvest and phosphorus was also needed for maintaining the yield level. Ratios of N/S>20–22 in lupin, the limit increasing with time during the summer, are indicative of sulphur deficiency. Fertilization with potassium showed no yield response during the fairly short experimental period. Nootka lupin is very rich in calcium and magnesium and near the lupin plants the soil became enriched with exchangeable calcium and magnesium and the pH increased. Soil organic matter increased significantly near the lupin plants, especially if fertilized with P and S, and fertilization is essential for appreciable sequestration of carbon under these conditions.

Keywords: Sulphur deficiency, phosphorus deficiency, land reclamation, N/S ratio, C/N ratio

YFIRLIT
*Áburður á alaskalúpínu (*Lupinus nootkatensis*) til ræktunar lífmassa og söfnunar kolefnis í jarðveg*
Áburðartilraun með fosfór, nitur, kalí og brennistein á alaskalúpínu (*Lupinus nootkatensis*) hófst með gróðursetningu lúpínuplantna á örfoka landi á Geitasandi árið 1999. Tilraunin var slegin, uppskera mæld árin 2003–2006 og sýni af uppskeru og jarðvegi tekin til efnamælinga. Brennisteinsskortur var áberandi og brennisteinsáburður var nauðsynlegur til að lúpínan lifði vel af eftir slátt. Fosfóráburður jók einnig vöxt lúpínu og var nauðsynlegur til að viðhalda uppskeru frá ári til árs. Hlutfall N/S>20–22 í lúpínu má taka til marks um brennisteinsskort, markið hækkar eftir því sem líður á sumarið. Kalíáburður virtist óþarfur á þessum skamma tilraunatíma. Alaskalúpína er mjög rík af kalsíum og magnesíum og næst plöntunum hafði jarðvegurinn auðgast af þessum efnum á jónbundnu formi og pH hækkað. Lífrænt efni var tekið að safnast í jarðveg umhverfis plöntur, einkum ef brennisteinn og fosfór var borinn á, og áburður er nauðsynlegur til að jarðvegur safni í sig umtalsverðu kolefni við þau skilyrði sem voru í þessari tilraun.

NTRODUCTION
Nootka lupin (*Lupinus nootkatensis*) is a perennial leguminous plant that has been used successfully for revegetating eroded land areas in Iceland. Its growth is often luxurious when it has been well established and utilization for animal feed (Þórsson & Guðmundsson 1993) and for industrial purposes has been considered (Björnsson et al. 2004). Earlier investigations have shown that lupin is sensitive to harvesting unless cut late in the season, partly due to competition with other vegetation (Sigurðsson et al. 1995, Björnsson & Dalmannsdóttir 2004).

Lupin is normally established by seeding and without use of fertilizers. Frequently it becomes dominating and spreads gradually into neighbouring areas. It fixes nitrogen symbiotically with *Rhizobium* bacteria and it has shown the ability to take up soil phosphorus in soils with low solubility of P where other plants have a low P content (Arnalds 1979). Repeated harvests however will deplete the soil of nutrients that are in limited supply, such as potassium. Icelandic soils with low organic matter content, such as the typical lupin fields, are also known to be deficient in sulphur (Helgadóttir et al. 1977).

Nootka lupin plants develop gradually over a number of years from small plants in the vegetative stage in the year of germination to large fertile plants with many stems and a considerable biomass. It has a large storage root and the root/shoot ratio exceeds one in the autumn (Magnússon et al. 1995, Björnsson & Dalmannsdóttir 2004).

Lupin fields established from seed are usually too irregular for experimentation. Therefore, in 1998 pot-grown lupin plants were planted with equal spacing for experimental studies (Björnsson & Dalmannsdóttir 2004). An experiment on fertile soil at Korpa Experimental Station in south-western Iceland was run successfully whereas a similar experiment on an unfertile sandy soil was abandoned when the growth of the lupin ceased in July in 2001; with the exception of border plants with a large growing space, the plants became yellow and gradually wilted. We now recognize the symptoms as sulphur deficiency. This paper reports on a fertilizer experiment on an even less fertile soil to test the requirements of a Nootka lupin crop for the plant nutrients nitrogen (N), phosphorus (P), potassium (K) and sulphur (S). The first Nootka lupin in the area was seeded close to the experimental site in 1977. It soon spread to a nearby grass field that was planted for seed production. The lupin however spread very slowly outside the grass field, indicating limiting factors such as the lack of a suitable seedbed or low soil fertility.

MATERIALS AND METHODS

The experimental field is located on a sandur plain in the south central lowland, Geitasandur, near Gunnarsholt, where the headquarters of the Soil Conservation Service are located. The plain was formed by fluvioglacial deposits towards the end of the last glaciation, with basaltic parent material dominating. The topsoil was lost in wind erosion, perhaps a few hundred years ago, and some movement of soil particles by wind is still taking place. In two 0 –15 cm profiles beside the experiment 20% was gravel (>2 mm), of which 42% was >4.75 mm. Particles <1 mm made up 64% of the fine soil (<2 mm). The bulk density in the profiles, determined by taking 5 cm high cylinders *in situ*, was 1.37 g cm^{-3}, dried at around 36°C. (Björnsson 2007).

A uniform experimental field was established by planting pot-grown plants on 11 June 1999 in rows 50 cm apart and at a spacing of 33 cm within the rows. There were practically no vascular plants in the field prior to the planting of the lupin. During the first winter the transplanted soil cores with each plant were lifted up by frost heave, especially those with poorly developed lupin plants. Surviving plants were pushed down in May 2000 in order to secure good contact of plants with soil and prevent their wilting. Dead plants were replaced by nearby plants of similar growth.

Experimental design

The field was divided into 32 plots, 4 rows wide (2 m) and 6 m long. The plots were arranged to accommodate 8 treatments, labelled **A** to **H**, in 4 parallel randomized complete blocks. The experiment was from the beginning designed with six treatments, leaving an opportunity for later planning of two treatments. Two treatments with annual application of P and N plus P (**A** and **B**) were started in 1999. The N application was stopped in 2003 due to invasion of other vegetation which competed with the lupin. The lupin plants developed slowly and the field was not considered ready for harvest until 2003. Three annual fertilizer treatments with K, KS and PKS (**C, D, E**) were applied in the spring of each year from 2003–06. In the light of results obtained in 2003 two PKS treatments (PKS and PK½S; **F, G**) were started in spring 2004 on plots that were harvested but not fertilized in 2003. Finally there was a control treatment (**H**) without fertilization. The applications were annual except that in 2005 only two of the four blocks of the experiment were fertilized and harvested and the other two blocks were rested. The experiment ended in 2006 when all fertilizer treatments were applied in the spring and the experiment harvested in the autumn. The levels of N, P, K and S applied were 33, 20, 42 and 18 kg ha^{-1} respectively, except that the treatment PK½S received 9 kg S ha^{-1}, half the level of the other S treatments. The fertilizer treatments were applied as triple superphosphate (P), ammonium nitrate (N), potassium chloride (K) and potassium sulphate (KS).

The plot area harvested was in most cases 4 m×1 m. Samples were taken by a core sampler for dry matter determination and chemical analysis. Samples from two replicates in 2003 and 2004 were analysed, in 2003 only one of every three nonfertilized plots. In 2006 all samples were analysed, except N in two replicates only. Samples were digested in nitric acid at 120°C overnight and P, S, Ca, Mg, K and Na measured with ICP-OES (Inductively Coupled Plasma in Optical Emission Spectrometer). C and N were determined with dry combustion with pure oxygen at 900°C using a vario MAX CN instrument from Elementar Analysesysteme GmbH, converted with catalysers into CO_2 and N_2 and calibrated against known standards.

Soil sampling and analysis

In spring 2004 soil samples were taken from the top 10 cm in nonfertilized plots and in treatment **E** in one replicate. Samples were taken approximately midway between the plants and also close to the plants, four samples altogether. On 6 November 2006 samples were taken from 0–10 cm depth in treatments **A–E** and **H** in all blocks, two samples in each plot as in 2004, except in **C** where samples were only taken between the plants. Samples were also taken at 10–20 cm depth in two replicates of **E** and **H**, between plants in all plots and near the plants in the **E** plots, six samples altogether. Finally, two samples were taken of material recently deposited with wind around large plants.

The soil was sieved through a 2 mm screen prior to chemical analyses. The results of chemical analysis of soil samples were converted to a dry matter basis assuming 93% DM (average of 17 samples dried at 105°C, s=0.6, and no relation of sample moisture to organic matter content was found). The soil was extracted in ammonium lactate (AL-method) for exchangeable cations and available phosphorus (Egner et al. 1960). Ca and Mg were determined by atomic absorption, K and Na using flame photometry and P photometrically. The soil pH was measured in a soil:water mixture of 1:2.5. AL-soluble elements and pH were measured in all 2004 samples and in 0–10 cm from two replicates in 2006, excluding treatment **B**, and in treatments **C** and **H** only in samples between plants. The same measurements were also done in samples from 10–20 cm and from wind deposits so that there were 24 samples analysed altogether. C and N were determined in finely ground subsamples of all soil samples by the same method as for yield samples, and the weighed sample size was about 2–3 g.

Sulphur in precipitation was measured daily from 1980–2004 at Írafoss, which is located at the western border of the south central lowland, 49 km north-west of the experimental location (Thorlacius 2007). Sulphur deposition

Table 1. Annual results during the experimental period and summary results for sulphur in precipitation at Írafoss, S kg ha^{-1}, based on daily measurements 1980-2004 (Thorlacius 2007).

	May–July	Year		May–July	Year
1999	1.3	7.2	**Average 1980–2004**	1.4	9.8
2000	1.3	6.2	Min.	0.5	6.1
2001	2.2	12.7	Max.	3.7	14.5
2002	0.8	6.1	**Averages for two periods**		
2003	0.5	7.5	1980–1994	1.6	11.0
2004	1.9	12.1	1995–2004	1.2	8.0

Table 2. Lupin yield and dates of fertilization and harvest 2003–2006.

			DM yield t ha^{-1}				
	Year		**2003**	**2004**	**2005**	**2006**	**2004-2006**
	Fertilizer date:		**13 May**	**13 May**	**17 May**	**18 May**	**Mean**
	Harvest date:		**2 Sept.**	**2 Sept.**		**17 August**	
	Fertilizer treatment						
A	P	Annually since 1999	3.35	1.05	1.05	1.91	1.48
B	NP	From 1999 until 2002	2.50	0.94	1.04	1.25	1.09
C	K	From 2003	2.27	0.85	0.45	0.48	0.66
D	KS	From 2003	3.36	2.28	2.59	2.53	2.49
E	PKS	From 2003	3.82	2.43	3.49	4.42	3.52
F	PK½S	From 2004	2.03	1.24	2.17	3.54	2.38
G	PKS	From 2004	2.42	1.92	2.97	4.32	3.17
H	Not fertilzed		2.15	0.54	0.29	0.58	0.51
		s.e.d.	*0.43*	*0.31*	*0.46*	*0.49*	*0.32*

[1] Mean values were calculated for each plot as the average of two years in the two replicates that were not harvested in 2005 and otherwise for three years. Averages and standard error were then calculated using these plot values.

has generally been decreasing although years with high deposition still occur (Table 1). During 1980–94 and 1995–2004 the frequency of years with <8 kg S ha^{-1} was two and eight, respectively, and the frequency of years with <1.5 kg S ha^{-1} in the spring–summer months May–July was the same.

RESULTS

Sulphur treatments produced the greatest yield response. The yield effect of sulphur alone was 1.09±0.43 (**D–C**, P=0.021) or, ignoring the effect of potassium and pooling **C** with the plots without fertilization (**F, G, H**), it was 1.14±0.34, P=0.005 in 2003 (Table 2). At harvest in 2003 plants receiving S in the spring were green and lush while other plants were

Table 3. Nitrogen and sulphur content of the Nootka lupin, the N/S ratio and the amount of N and S harvested.

Treatment		Chemical content, g kg^{-1} of DM						Ratio		
		N			S			N/S		
		2003	***2004***	***2006***	***2003***	***2004***	***2006***	***2003***	***2004***	***2006***
C, H	**Control**	14.2	13.3	19.9	0.63	0.58	0.86	22.4	22.9	22.2
A	P from 1999	13.4	14.3	16.1	0.60	0.56	0.67	22.4	25.8	23.8
B	NP 1999–2002	12.5	14.4	15.9	0.67	0.54	0.68	18.6	26.6	24.5
D	KS from 2003	19.2	20.6	19.4	0.88	1.08	0.87	21.8	19.0	21.6
E	PKS from 2003	19.3	20.0	21.6	0.89	1.06	1.24	21.5	18.9	19.4
F	PK½S fr. 2004		21.8	22.7		1.04	1.08		20.9	21.2
G	PKS from 2004		21.7	22.0		1.15	1.31		18.9	17.7
	s.e.d.	*0.87*	*0.65*	*0.80*	*0.033*	*0.030*	*0.081*	*0.57*	*0.97*	*0.81*
		Yield, kg ha^{-1}								
		N			S					
		2003	***2004***	***2006***	***2003***	***2004***	***2006***			
C, H	**Control**	27	8	15	1.3	0.3	0.7			
A, B	**Fosfor**	35	12	32	1.8	0.4	1.4			
D		61	40	44	3.0	2.2	2.0			
E		66	44	83	3.3	2.4	4.2			
F			30	81		1.5	3.8			
G			40	109		2.2	6.2			
	s.e.d.	*5.6*	*9.9*	*7.4*	*0.28*	*0.48*	*0.76*			

Figure 1. To left are lupin plants with symptoms of sulphur deficiency, 13 August 2004.

yellow and wilting (Figure 1). Plant survival in the sulphur plots (**D, E**) was good in 2004 although the yield was less than in 2003. The low yield from other plots in 2004 was partly due to poor survival (Figure 2), although some plants that appeared to be dead in spring did recover. Fertilizer application, beginning in 2004, appears to have been effective in restoring the yield potential of the lupin by 2006 (**G** and **E**). The reduced sulphur level from 18 to 9 kg ha^{-1} (from **G** to **F**) gave significantly less lupin yield. This difference, however, could have been a carry-over effect of the difference found in 2003 between the plots where these treatments were later applied, and a test for interactions with years did not confirm the significance of sulphur levels. On the other hand there were significant differences in the S content of the plants between these treatments in 2006 (Table 3).

The effect of phosphorus on growth of the Nootka lupin on experimental plots was easily observed in 1999 (**A**), the year of planting, and later confirmed by the yield measurements (Table 2). Application of P, beginning 2003, also gave increased yields (**D** and **E**), although not statistically significant in the beginning. Other plant species, mostly grasses, started to develop in the plots fertilized from 1999, especially if nitrogen was applied (**B**). These species later invaded other plots and, at harvest in 2006, the cover was around 20% on plots fertilized with S or P, while on treatment B the cover was near 80% although the lupin still dominated in the yield.

Figure 2. Plots without fertilizer (left), with KS (center) and with P (right) on 13 May 2004, the spring following the first year of harvest. The picture shows strong spring growth when plants were fertilized with S the previous year, poor survival without fertilization and intermediate results after applying only P.

Table 4. Contents of mineral nutrients in lupin yield. s.e.d. applies to differences between means of two treatments.

		Chemical content, g kg^{-1} of DM								
		P			**Ca**			**Mg**		
		2003	**2004**	**2006**	**2003**	**2004**	**2006**	**2003**	**2004**	**2006**
C,H	**Control**	0.82	0.86	1.16[1]	17.7	19.0	17.6[1]	6.4	6.1	6.7[1]
A, B	**Fosfor**	1.06	0.95	1.36	12.5	16.6	13.0	3.7	4.7	3.9
D	**S-2003**	1.06	1.04	1.18	17.8	18.4	15.8	6.7	7.8	6.5
E		1.23	1.02	1.54	16.3	17.7	12.7	6.1	7.2	5.1
F, G	**S-2004**		1.11	1.49		18.6	13.9		7.4	5.3
	s.e.d.[2]	*0.034*	*0.031*	*0.051*[3]	*0.55*	*0.76*	*0.37*[1]	*0.16*	*0.35*	*0.23*[1]

		K				**Na**		
		2003	**2004**	**2006**		**2003**	**2004**	**2006**
H	**Control**	11.3	12.1	12.2[1]	**C, H**	1.9	2.1	1.4[1]
C		11.3	13.0	14.9				
A, B	**Fosfor**	9.7	12.7	12.5		1.4	2.3	1.5
D, E	**S-2003**	11.9	11.5	13.5		2.0	2.3	1.8
F, G	**S-2004**		12.7	14.5			2.4	2.1
	s.e.d.[2]	*0.64*	*0.91*	*0.40*[1]		*0.18*	*0.21*	*0.13*[1]

[1] Results from one plot with very low yield omitted.
[2] Standard error of difference between pairs of two treatments, n=4 in 2003 and 2004 and 8 in 2006.
[3] Treatments C and H were excluded when experimental error of P content was calculated in 2006.

For the presentation of nutrient content in herbage it was found convenient to form four treatment pairs, labelled **Control, Fosfor, S-2003** and **S-2004** for (**C, H**) K only or no fertilizer, (**A, B**) P or NP annually from 1999, (**D, E**) S or PS annually from 2003 and (**F, G**) PS annually from 2004, respectively. Results are shown as the means of both treatments that form a pair, except when treatment effects within a pair for a particular element were of interest (Tables 3 and 4).

There was a lower plant content of N, and in particular S, in treatments without than in those with sulphur fertilizers and the N/S ratio was generally higher (Table 3). In 2006 this effect extended to treatment **D** (nil P) and the N/S ratio was also significantly higher in treatment **F** with a lower level of sulphur fertilization than in **E** and **G**. The quantity of N and S removed as dry matter was very low in treatments without sulphur, especially in 2004 and 2006. For a wide range of means, as for nutrient yield, experimental error is heterogeneous and different values of the standard error should be used, depending on the level of means being compared.

Increased P content in plants following fertilization compared to **Control** was evident in all years and in 2006 a further increase was obtained if S was also applied (Table 4). The content of Ca and Mg was lowest for **Fosfor** and the effect of P on these elements was also found when combined with S, especially in 2006 when Ca was as low in treatment **E** as for **Fosfor**, and Mg was also significantly less than in treatment **D**.

Fertilization with potassium alone had no effect on yield and little effect on the K content in the plants. In 2003 the treatments fertilized since 1999 had the lowest K content. Only in 2006 was the K content higher in all treatments fertilized with K (**C to G**) than in those without fertilizer (**A, B** and **H**). In 2003 the fosfor treatments had the lowest content of Na and in 2006 an increase in Na content was found with the application of S.

The soil content of both C and N was always higher in samples taken near plants than between plants in the 20 plots where samples were taken in both positions (Table 5). In most plots other than in treatment **B** the C/N ratio was higher near the plants.

The C/N ratio was highest in treatment **B** where the surface was nearly covered with grasses and it appeared to be independent of position within the plot. The only significant effect found between plants was an increased C content and C/N in treatment **B**. Near plants both C and N were significantly higher in the PKS treatment (**E**) than on average in treatments without both P and S (**A, C, H**), whereas the intermediate KS treatment (**D**) did not differ significantly from the other treatments at the 5% level. Although only two samples were measured the increase of C and N near plants in treatment **E** appeared to extend down to 10–20 cm.

Only a few significant treatment effects were found for pH and AL-soluble minerals in the soil (Table 6). The differences between samples from spring 2004 were small and, hence, only the mean and standard deviation are shown. For the presentation of results at 0–10 cm depth in 2006, samples in which results were not affected by fertilization or the vicinity to lupin plants were selected for reference and the effects of fertilization on lupin plants shown as deviations from the reference

Table 5. Content of C and N in oven dry soil. Samples were taken from near plants, equi-distant between plants, and from recent wind deposits.

		C, $g\ kg^{-1}$		N, $g\ kg^{-1}$		C/N	
		Position of soil sample relative to lupin plants					
		Near	Between	Near	Between	Near	Between
Samples from 0–10 cm							
A	P from 1999	6.0	4.3	0.45	0.34	13.3	12.6
B	NP 1999–2002	6.7	5.0	0.45	0.35	14.7	14.4
C	K		3.8		0.32		12.1
D	KS from 2003	7.7	4.1	0.57	0.34	13.2	12.0
E	PKS from 2003	9.5	4.4	0.71	0.35	13.6	12.5
H	Control	6.4	4.0	0.49	0.33	13.2	11.9
	s.e.d.	*1.14*	*0.31*	*0.073*	*0.021*	*0.62*	*0.52*
Samples from 10–20 cm, E and H		4.1	2.5	0.29	0.18	14.0	14.2
From wind deposits		1.5		0.16		8.9	

Table 6. Soil pH and AL-soluble nutrients in 2004 and 2006. Results in 2006 at 0–10 cm depth are presented as reference (soil unaffected by fertilization and lupin plants) and effects of fertilizer, respectively, vicinity to lupin plants, calculated as deviations from the reference.

	pH	Chemical content, $mg\ kg^{-1}$				
		P	Ca	Mg	K	Na
Samples 2004, n=4	6.6	8.4	1398	425	156	110
Standard deviation	*0.17*	*1.1*	*62*	*8*	*29*	*6*
Samples 2006						
Reference in 0–10 cm[1]	6.51	7.1	1260	455	123	129
Effect of fertilizer[2]		+8.9; +19.9[3]			+113	
Standard error of effect		*2.1*			*23*	
Effect of lupin plants	+0.20	+0.1	+211	+48	+124	+7
Standard error of effect	*0.15*	*1.9*	*59*	*25*	*23*	*4.1*
In 10–20 cm, n=6	6.44	6.2	1673	541	118	131
Standard deviation	*0.11*	*1.0*	*111*	*35*	*31*	*9.7*
In wind deposits, n=2	6.4	12.8	1140	438	168	138

1 n=4 for K, n=8 for P including samples near plants without P fertilizer, n=10 for other elements.
2 n=4 for each P treatment and n=6 for K.
3 Treatment E and A respectively.

values. The reference values differed little from the results in 2004. The effect of phosphorus fertilizer on AL-soluble P in **A** and **E** was approximately proportional to the number of years applied, 8 and 4 years respectively. P was the only element not affected by sample location. The concentration of all cations, on the other hand, increased near the plants, as did the soil pH and organic matter (Table 5). At 10–20 cm depth no significant differences were found between treatments and location and the results are presented as an average and the standard deviation. These results are not fully comparable to the reference at 0–10 cm but comparison of results at both depths within control plots confirmed the higher levels of Ca and Mg and lower pH at 10–20 cm than at 0–10 cm.

DISCUSSION

The results of the present experiment show that Nootka lupin can be harvested annually late in the season on a sandy soil while it is still green and is able to maintain yield across years if fertilized with sulphur and phosphorus. The effect of fertilization on yield was already considerable in the first harvest year, which was also the first year of some fertilizer treatments, and without S the yield declined during the following years, mainly due to the poor stand. The yield also decreased in the later harvest years if P was not applied with S. In an experiment without fertilization on fertile soil at Korpa Experimental Station the yield in early September declined from 5.5 to 4.0 t DM ha^{-1} in five annual harvests (Björnsson et al. 2004) and this may be an indication that some nutrient deficiency was developing. Half of the plots harvested in 2006 were not fertilized or harvested in 2005. A rough estimate of the residual effect on yield of resting the lupin for one season is 1 t DM ha^{-1} on plots fertilized with sulphur. Adjusting for this residual effect the annual yields of lupin fertilized with PKS remained between 3.5–4 t ha^{-1} in three out of four years.

Sulphur was the most important fertilizer element for lupin growth. S is essential for the formation of proteins, the N/S ratio being 15 in chloroplast proteins (Mengel & Kirkby 2001). N/S ratios exceeding 20–22 are indicative of S deficiency. There was no sulphur deficiency in the Korpa experiment and there S declined more during the growing season than N and the N/S ratio increased at the rate of 0.46 over a period of 30 days (Björnsson 2007). The late harvest dates in the present experiment may have led to fairly high N/S ratios found in treatments fertilized with sulphur. The results for N/S (Table 3) indicate that S deficiency was most prominent in 2004 even though S in precipitation was above average that year (Table 1). Fertilization with 9 kg S ha^{-1} was not sufficient to eliminate the deficiency. The low N/S ratio of 18.6 in 2003 on plots receiving nitrogen 1999–2002 (**B**) was unexpected and could have been due to the different botanical composition of that treatment.

Norton (1981) reports mean values of 1.86%, 0.29% and 0.19% for Ca, Mg and Na respectively in temperate legumes. These values are very close to the results for Ca and Na in Table 4, while the values for Mg reflect the high level of exchangeable Mg in the soil (Table 6). High values for Mg have also been obtained in Iceland for annual lupins under similar soil conditions (Guðmundsson & Runólfsson 1988). Mg below 0.5% was found in red clover (Sveinbjörnsson 1997) and Nootka lupin (Magnússon & Sigurðsson 1995) on more fertile soils, except in leaves of the Nootka lupin, where values exceeding 0.5% were measured in August. Ca also increased in leaves of the Nootka lupin from spring to values exceeding 2% in autumn, while in stems and reproductive organs it remained near 0.5% throughout the season (Magnússon & Sigurðsson 1995).

Lupin fertilized with P had a lower content of Ca and Mg than plants not receiving P fertilizer (Table 4). For treatments **A** and **B** this could have been caused by loss of leaves of plants deficient in sulphur. Increased exchangeable cations in the soil near lupin plants (Table 6) can most easily be explained as the result of pumping, *i.e.* uptake of nutrients over the whole area and release to the soil near the plants. Soil processes stimulated by biological activity in the root zone could also have been a factor.

Assuming the volume weight of oven dry soil in 0–10 cm of 1.25 g cm^{-3} and 20% gravel, the volume weight of fine soil particles is then 1.00 g cm^{-3} and the results in Tables 5 and 6 can thus be read as t ha^{-1} and kg ha^{-1} for g kg^{-1} and mg kg^{-1} respectively. Nootka lupin is rich in calcium and magnesium and using it as a crop would remove relatively large quantities of these minerals from the field. Harvesting 14 t DM ha^{-1} containing 16 g Ca kg^{-1} over a period of four years would mean that 224 kg Ca ha^{-1} would be removed. The soil supply was about 1260 kg ha^{-1} exchangeable Ca in 0–10 cm (Table 6). Lupin has great root depth so the source of Ca can be expected to be much greater and, in addition, about 50 kg Ca ha^{-1} were supplied over the four years with the phosphate fertilizer. The initial soil pH was fairly high and the basaltic parent material is rich in Ca, which is continuously released by weathering (Gudmundsson et al. 2005). For a Ca-demanding crop like lupin periodic liming is likely to become necessary sooner or later in order to maintain favourable root zone conditions. The higher levels of exchangeable cations in 10–20 cm than in 0–10 cm may be an indication of nutrient leaching from the surface layer although this is contradicted by the slightly higher pH in the surface. The increased carbon content of soils following land reclamation usually leads to decreased pH (Gretarsdottir 2002) although within the short time scale of the present study this was not found.

Fertilization with potassium did not affect yield even though increased K concentration was detected (Table 4). This could be regarded as luxurious uptake of K associated with increased availability of K in the soil (Table 6). In earlier studies the K content of Nootka lupin decreased during the summer to 11 g kg^{-1} (Björnsson 2007) or 13 g kg^{-1} (Magnússon & Sigurðsson 1995) in late summer, similar to the values found here. The concentration of K was not found to be consistently higher in leaves than in other plant organs. In harvesting 14 t DM ha^{-1} containing 14 g K kg^{-1} over a period of four years, 196 kg K ha^{-1} would be removed whereas the exchangeable K in 0–10 cm was 123 kg ha^{-1}. The level of fertilization with K over 4 years was 168 kg K ha^{-1} and exchangeable K in 0–10 cm increased by 124 kg ha^{-1} (Table 6). The results indicate that fertilization with K is not needed under these conditions for the initial years. Icelandic soils, although low in exchangeable K, can supply K for a number of years under a negative nutrient balance (Gudmundsson et al. 2005). However, fertilization with K would probably be required within a few years if harvesting is continued.

Phosphorus increased yield significantly and, when sulphur was not limiting, the effect reached 1.9 t ha^{-1} y^{-1} in 2006 (**E–D**). The P content was highest on plots fertilized with both P and S and lowest on plots without P and S. The P recovered in the herbage and the increased AL-soluble P in the soil are less than half of the applied fertilizer P, indicating fixation in the soil. The role of P in plants is closely related to that of N and the concentration of both elements declines during the growing season, though in Nootka lupin P declines more than nitrogen (Magnússon & Sigurðsson 1995, Björnsson 2007). This explains the high N/P ratios, in most cases exceeding 15, that can be derived from the results in Tables 3 and 4, high values for fertilization with S in 2004 and low values for fertilization with P in 2003 and 2006. The results do not indicate that Nootka lupin fills the group of lupins that are known for their special ability to utilize soil P through mechanisms such as proteoid roots (Longnecker et al. 1998).

Revegetating eroded land areas contributes significantly towards balancing increasing greenhouse gas effects through sequestration of atmospheric carbon dioxide in soil and vegetation. Soils of volcanic origin, Andosols, are potentially more effective for carbon sequestration than other soils (Arnalds et al. 2000, Aradóttir et al. 2000). The carbon sequestration in Icelandic soils has been estimated indirectly for nine soil erosion areas including nontreated land by regressing soil carbon contents on the age of revegetation, six areas with reclamation by fertilization with or without grass seed, typically fertilized in the initial year and for two subsequent years, and three areas with lupin of varying age. In seven areas the estimates for the top 30 cm ranged from 0.46 to 1.5 t C ha^{-1} y^{-1}, whereas in two areas, one with fertilization and one with lupin, only a minimal increase was found (Aradóttir et al. 2006). The sequestration of carbon is closely linked with the accumulation of nitrogen in the soil organic matter and other nutrients such as sulphur and phosphorus are probably accumulated in the organic matter as well. A good nutrient supply is therefore continuously required for the sequestration of carbon to take place. In four areas with low organic matter content, as in the present study, 0.1–0.7 % C and C/N ranging from 13.3–14.9 in eroded soil, the increase in soil carbon following revegetation was modest and the C/N ratio decreased in areas in the southern part of the country and increased in the north-east (Gretarsdottir 2002). In this study increased ratios were found near lupin plants, as could be expected when fresh organic material is present in soil with a low organic matter content and the highest value was found where grasses rather than lupin were the source of organic matter. Values of C/N≤15 are expected for carbon sequestration under freely drained conditions and the sequestration rate of 1 t C ha^{-1} y^{-1} would require a minimum of 67 kg N ha^{-1} y^{-1} accumulated in the soil. Nitrogen fixing plants, such as Nootka lupin, have an obvious advantage in this respect. The rates of sequestration found in other reclamation areas suggest other sources of N. On a fertile soil with grass the mean annual increase of C in soil over 43 years was 0.6–1.0 t C ha^{-1} y^{-1}, and on plots without nitrogen fertilization 102 kg N ha^{-1} y^{-1} were removed with herbage, i.e. the net addition to the system appears to have been ≥150 kg N ha^{-1} y^{-1}, suggesting major sources of nitrogen, such as fixation of atmospheric N, that are not fully understood (Gudmundsson et al. 2004).

The results presented here show that sulphur is potentially a highly limiting factor for the sequestration of carbon in land reclamation areas although the treatment effects (Table 5) are to some extent due to the poor lupin stand following harvest on plots without S fertilization. The main natural source of sulphur is sulphate in precipitation. Most of it falls outside the growing season and much is lost by runoff. Sulphate entering the soil is especially retained by soil organic matter (Mengel & Kirkby 2001). Most land reclamation areas are very low in soil organic matter and are inefficient in trapping sulphate from the rain water. Assuming as before that 1 g C kg^{-1} is equivalent to 1 t C ha^{-1} in the top 10 cm and, for the sake of argument, let us assume that the samples near the plants represent 25% of the plot area. An increase from 4.4 g C kg^{-1} between plants to 9.5 g C kg^{-1} near lupin plants is then equivalent to 1.28 t ha^{-1} over four years or 0.32 t C ha^{-1} y^{-1}, thus assuming that the accumulation prior to fertilization was negligible. To that can be added an increase at a maximum of 0.1 t C ha^{-1} y^{-1} in 10–20 cm. The removal of about 1.7 t C ha^{-1} y^{-1} with harvest has undoubtedly reduced the carbon sequestration. The weighting of samples is only hypothetical and a reliable estimate is not available, but it appears fair to interpret the results such that the sequestration may exceed 0.5 t C ha^{-1} y^{-1} under these particular soil conditions if plant nutrition is not limiting. This is much less than found in some of the earlier reported cases. The results demonstrate the heterogeneity of soils in lupin fields and more destructive sampling methods than core sampling are needed for the estimation of carbon sequestration (Aradóttir et al. 2000), and the evaluation is also complicated by the fact that volume weight is strongly affected by soil organic matter content.

CONCLUSIONS

Sulphur deficiency is acute on eroded sandy soils low in organic matter. Fertilization with sulphur is essential for the cultivation of plants on these soils (Helgadóttir et al. 1977) but the requirements may become less as organic matter accumulates. Fertilization with phosphorus is important for good development of Nootka lupin although it has often been considered less demanding in this respect than other plant species. A good supply of sulphur and phosphorus is also essential for fully utilizing the carbon sequestration potential of the Nootka lupin in eroded areas. The potassium requirements appear to be modest, but Icelandic soils are low in potassium and a shortage of potassium is expected to develop after a few years of harvesting. Nootka lupin has, like other leguminous plants, high calcium requirements and the need for liming is also likely to develop sooner or later even though soil pH in this study was favourable and the soil supply of calcium was sufficient.

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