Responses of *Lotus pedunculatus* to sulphur fertiliser and defioliation regime in acid soils at low temperature

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Abstract

The potential for *Lotus pedunculatus* is greatest in acid soils on hill and high country, but requires establishment success, nutrient supply and grazing management. This work investigated the role of sulphur fertiliser and the influence of defoliation regime on production of Lotus in low pH, high aluminium soils. Yields measured in year one were positively related to soil sulphate but not phosphorus. Sulphur, applied at two sites (low or high productivity) at 0, 24 or 78 kg S/ha, failed to alter yield over three years. The site, at 1000 m a.s.l., had base vegetation of unimproved tussock, low soil pH and P (4.8 and 7 respectively) and high Al (30-40 ppm). Yields ranged between 1900 and 3200 kg DM/ha/annum and was reduced when initial plant numbers were lower. Lotus contributed 65-85% of the herbage for grazing (excluding tussocks). Yields were maximised by defoliation to 2 cm height each season or once in autumn. Establishing high plant numbers increased productivity. Single, late season grazing promoted rhizome development and resulted in the highest yields by year 3. Grazing to 2 or 5 cm residual once a season produced similar herbage, but lower rhizome development.

Keywords: defoliation, establishment, plant population, rhizomes

Introduction

The use of *Lotus spp.* in hill country pastures is very low. However, appropriate use of the predominantly spring and summer production can provide economic and resilience benefits when used to balance feed supply in variable climatic conditions (Stevens et al., 2020). The potential for *Lotus pedunculatus* is greatest in acid soils of New Zealand hill and high country. However, its productivity and longevity are sensitive, firstly to establishment success, secondly to nutrient supply and thirdly to the grazing management applied by the farmer.

Over-sowing lotus into tussock grassland can increase dry matter production by two- to four-fold, especially if resident introduced grasses are sparse (Floate et al., 1989). Seed size and quality has been implicated in effective establishment of lotus (Charlton 1989). Once seed has germinated, the plant spreads using an underground network of rhizomes to maintain longevity (Harris et al., 1997)

Effective establishment remains dependent on appropriate fertiliser inputs and grazing management, and phosphate and sulphur fertiliser are an important input (Floate et al., 1989). The role of phosphorus is critical in legume production, with lotus being more efficient at producing more dry matter when phosphorus availability is low (Hart et al., 1981). Sulphur (S) is essential for production with both direct application and lime-induced S mineralisation resulting in increased lotus yield (McIntosh et al., 1984). While Lotus is tolerant of low pH, addition of lime can improve production by lowering soluble Al and increasing P solubility, although this offers a relatively small yield increase at high altitude, where temperature restricts total productivity (Floate et al., 1989).

Defoliation research, implemented at a range of heights, concluded that reduction to 2 cm height maximised harvested yield if spells between grazing were 8-12 weeks (Sheath 1980a; Harris et al., 1997). Further research, which investigated a range of defoliation regimes, concluded that rhizome development was crucial to ongoing production, though simple grazing rules have been hard to develop (Sheath 1980b).

Low pH, acidic soils cover an estimated 2.4 million ha of both North and South Island hill and high country. Aluminium toxicity, which affects the longevity of white clover, is a feature of these highly acidic soils. However, maintaining soil nutrient status at sufficient levels to ensure a robust white clover component is not sustainable for many hill country enterprises as remedial quantities of lime and superphosphate are too costly to apply in these harsh and often remote environments (Stevens et al., 2020).

The *Lotus* species (*L. pedunculatus* and *corniculatus*) have a unique advantage over many legume species, in that they are very tolerant of both high aluminium levels and low soil fertility and could provide livestock with

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high protein feed during the summer and early autumn periods. While the ability of *Lotus* spp. to tolerate harsh environments have been acknowledged for many years (Scott and Mills 1981), its use as a valued legume in the pastoral context has never gained a great deal of traction and is now rarely part of a deliberate development strategy. This is mainly due to its previous occasional use in extensive grazing systems without appropriate subdivision to manage it to best leverage its particular needs and attributes. Consequently, there is only limited information on best management practice; the integration of the high-quality feed that lotus can produce into the farm system; and a sustainable fertiliser maintenance programme.

L. pedunculatus (Maku lotus) was established on Avenel Station in 2014 on three blocks totalling 350ha and at an altitude of 900 m a.s.l.. A deliberate decision was taken to establish legumes into tussock country without the use of intensive approaches, such as heli-cropping or direct drilling. Adding lotus while retaining tussock cover at these high altitudes is highly valued for a range of benefits. The tussocks provide microclimate, moisture retention, shelter and vista protection, while the lotus provides high quality feed to meet improved animal performance targets. Careful grazing records kept since establishment, combined with liveweight performance, have determined the potential for maximising the contribution of the extra feed grown into the enterprise (Stevens et al*.,* 2020). Dry matter yields, climate and soil testing data, collected during 2017, raised two questions; 1. What are the sulphur fertiliser requirements to ensure on-going productivity of the lotus? 2. Which grazing managements maximise production and spread of lotus in this environment?

Materials and Methods

As a Sustainable Farming Funded project, 'Legumes for low fertility hill country', the trials investigated the impacts of sulphur fertiliser application and defoliation regime on the production and spread of *Lotus pedunculatus* at Avenel Station, near Millers Flat, New Zealand. Avenel Station (-45.67S, 169.50E) ranges from approximately 200 to 1000 m a.s.l. in a cool temperate climate (Macara 2015). Rainfall varied from 700 mm to 900 mm across this elevation range, with the greatest difference being during summer being approximately 150 mm at 200 m a.s.l. and 225 mm at 1000 m a.s.l.. Temperature again follows the elevational gradient with average winter and summer temperature ranges of 5-1°C, and 15-11°C, respectively. Soils were sampled to a depth of 7.5 cm at two sites to give six replicates consisting of 10 cores per replicate, a total of 12 samples, representing 12 plots harvested for dry matter production. These were analysed at a commercial laboratory (Hill Laboratories, Hamilton, New Zealand) for pH, soluble aluminium, P, extractable soil sulphate, Ca, K, Mg, organic matter, total carbon, total nitrogen and phosphate retention, presented as the mean values for each of the two sites (Table 1). The higher elevation tussock country (800-1000 m a.s.l.) was a relatively unmodified brown soil with a pH of 4.4–5.0 and Olsen-P values of 4–8 (Table 1). The experimental sites were typical of this type of landscape, having 0-10° slope, predominantly facing north to north-west. Both sites were at 890 m a.s.l. and site 2 was approximately 1 km NW from site 1.

Sulphur fertiliser response experiment

Dry matter yield data was harvested from six plots of 50 m^2 area at each of two sites during the first year of the study. A single caged area (0.5 m^2) was harvested to 2 cm using hand-shears, three times each year within each plot. Analysis of this data from each of the two sites determined that pasture yield was directly related to extractable soil sulphate values (Figure 1) but not to Olsen P values (Figure 2).

As a result of these initial analyses, a small, replicated fertiliser trial tested sulphur (S) fertiliser as a single application applied on 12th December 2017, either as per current recommendations or to provide the amount needed to support maximum growth recorded in this environment. One treatment followed current fertiliser recommendations of 35 kg S/ha needed to overcome an S deficiency on these brown soils. The second treatment used potential yield to calculate nutrient inputs. Using slow-release sulphur fertiliser (Sulphurgain™ Pure, 90%S) to provide a supply for two years, rates of application of either 24 or 78 kg/ha were compared to 0

Table 1 Soil fertility of two tussock sites in the Lammerlaw range at approximately 890 m a.s.l.

	Site		
	1	2	LSD[1]
pH	4.7 b[2]	4.9 a	0.14
Aluminium (ppm)	29	19	14
Olsen P (mg/L)	11.5	9.7	8.3
SO_4S (mg/kg)	12.5 a	6 b	3.4
Ca (MAF units)	2.8	3	1.4
K (MAF Units)	3.5	4.2	0.9
Mg (MAF units)	6.7	7.7	1.5
Organic Matter (%)	12.1	10.5	1.7
Total Carbon (%)	7.0 a	6.1 b	0.9
Total Nitrogen (%)	0.39 a	0.33 b	0.05
P retention (%)	55	60	6.7

[1]LSD = Least significant difference;
[2] Numbers with different letters are significantly different

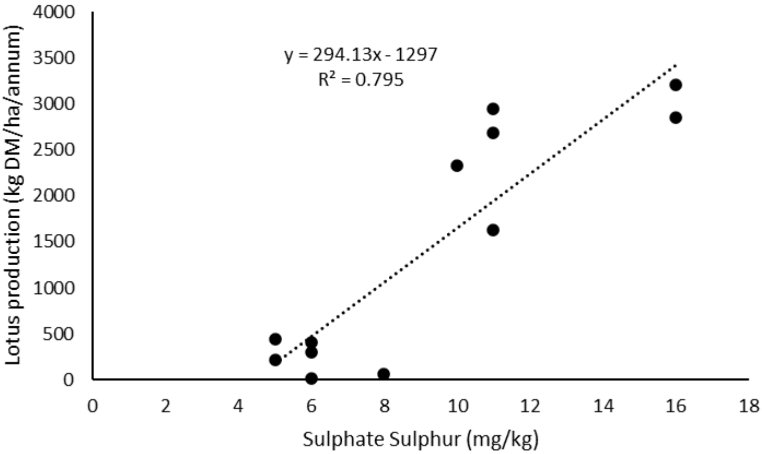

Figure 1 A relationship between the concentration of soil extractable sulphate sulphur in the 0-7.5 cm soil horizon and the production of lotus when over-sown into high-altitude tussock lands.

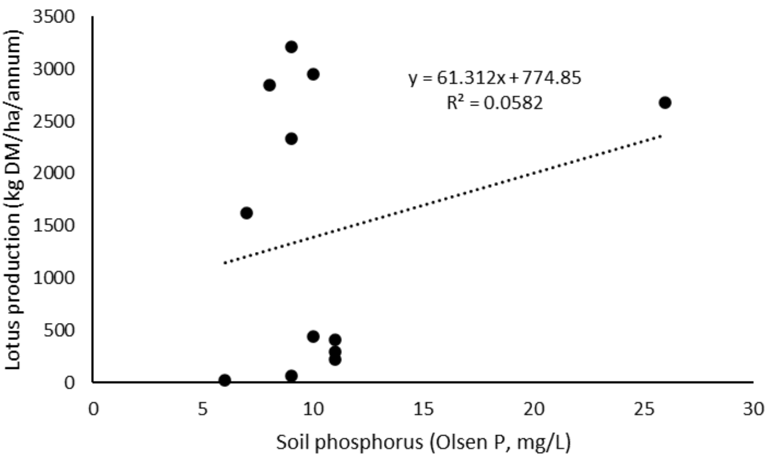

Figure 2 The concentration of soil phosphorus (Olsen P, mg/L) in the 0-7.5 cm soil horizon is not related to the production of lotus when over-sown into high-altitude tussock lands.

kg/ha as a control. A calculation based on the difference in yield between the two sites resulted in a further 8 kg S/ha of rapidly available S in the form of Epsom salts (13% S) to correct the apparent deficiency at site two.

Total dry matter yield and lotus contribution were measured over three years with six replicates taken from each of two sites. Dry matter yield was measured from six plots of 50 m^2 area at each of two sites during the first year of the study. A single caged area (0.5 m^2) was harvested to 2 cm using hand-shears, three times each year within each plot. Soil cores to 7.5 cm depth were collected each December and analysed for soil nutrient status using the method previously described. Data was analysed using a repeated measures ANOVA to determine the influence of time (as the S used was a slow-release variety) on dry matter production.

Grazing management experiment

The question of lotus persistence and spread under different grazing regimes was tested on a recently established site of 211 ha of hill country, sown with 3 kg seed/ha *Lotus pedunculatus cv*. Maku, by helicopter in October 2018. The establishment of this area was successful overall with 5-20 seedlings /m^2. A 3 x 2 factorial design examined the effects of three defoliation regimes on two initial plant densities over three growing years from October 2019 to May 2022. Defoliation regimes, developed to represent extensive grazing management strategies, were applied to either low or high initial plant populations at a single site, in six replicates.

Rainfall, and maximum and minimum temperature data was retrieved from the National Institute of Water and Atmosphere (NIWA) Virtual Climate Network at the nearest grid location (-45.625S, 169.625E) for the period 1 July 2019 to 30 June 2022 and monthly averages are presented in Table 2.

Three defoliation regimes were chosen to represent potential management options that may be applied. These included spelling the sward for the whole season, with a single late season defoliation in April, or defoliating at approximately eight-week intervals, in December, February and April, to a residual height of either 2 cm or 5 cm. These treatments were applied to plots of 0.5 m^2 which were caged to prevent grazing. Areas of either low or high initial seedling density were assigned to each defoliation regime. Six replicates of each treatment were harvested. Defoliation was applied as a cutting regime of the plot. Each plot was harvested using hand-shears to the prescribed cutting height. Fresh weight of the whole sample was weighed, and a subsample of approximately 100 g dried at 60ºC to determine dry matter content, with dry matter yield then calculated. Botanical composition was measured by herbage dissection on a subsample of approximately 400 pieces.

Table 2 Virtual climate network monthly rainfall, and mean maximum and minimum temperatures over three growing seasons, sourced from the National Institute of Water and Atmosphere (NIWA) Virtual Climate Network at the nearest grid location (-45.625S, 169.625E) to the defoliation experiment.

	Monthly rainfall (mm)			Monthly mean maximum temperature (°C)			Monthly mean minimum temperature (°C)		
Year	**2019/21**	**2020/21**	**2021/22**	**2019/21**	**2020/21**	**2021/22**	**2019/21**	**2020/21**	**2021/22**
July	48.3	44.1	32.8	6.8	5.5	6.3	-1.8	-2.3	-2.1
August	48.4	48.0	14.6	7.4	9.2	8.3	-2.1	-1.1	-1.0
September	44.2	75.8	25.4	10.2	10.1	10.5	-0.8	-0.5	-0.6
October	100.4	65.2	7.3	10.9	13.5	13.6	0.9	1.3	2.8
November	97.6	49.7	0.0	17.0	15.7	16.3	4.7	3.5	4.2
December	99.9	51.4	32.9	15.8	17.2	17.0	4.9	4.9	6.2
January	32.7	90.2	8.5	19.7	17.4	20.3	6.4	6.4	7.6
February	147.8	21.0	68.7	19.8	20.3	17.8	7.5	5.9	6.0
March	34.8	13.9	5.9	14.9	16.8	18.8	3.4	5.3	5.2
April	44.1	7.7	14.8	13.6	14.0	14.3	2.0	1.8	2.0
May	12.6	10.7	15.7	10.3	10.0	11.4	-0.1	-1.2	-1.0
June	33.7	69.6	3.7	5.9	6.1	6.6	-2.3	-3.1	-0.6

Lotus density was determined by point analysis in the first and third years. Pasture yield and Lotus contribution was measured at each defoliation. Growing point number were counted and rhizome length measured in soil cores of 50 mm diameter. Fifteen cores were taken per plot in April of the third year, at the end of the experiment. Results were analysed using REML analysis of variance (Genstat).

Results

Sulphur fertiliser response

Soil pH (7.5 cm depth) was lower at site 1 than site 2, sulphate sulphur was higher at site 1 than site 2. Soil test results from 7.5 to 15cm revealed that aluminium concentrations were approximately 60 ppm at this depth. Dry matter production (Table 3) was not significantly different throughout the three years recorded.

Annual production was highly linked to spring production. A cool spring led to low total production in both years 1 and 3. However, in the native state, total productivity from this landscape is below 500 kg DM/ha/annum.

The lotus content of the swards, determined by botanical dissection at least once each season, showed that lotus comprised 65% (SEM=16%) of total annual yield.

Grazing regime and persistence

The frequency of occurrence of lotus within the sward was approximately 24% in the low-density plots and 39% in the high-density plots after the first year of measurement (Table 4). No differences were recorded

Table 3 Seasonal and annual dry matter production (kg DM/ha) of swards over-sown with *Lotus pedunculatus* on a low fertility brown soil at approximately 890 m a.s.l.

		Fertiliser treatment			
		Control (0 kg S/ha)	**Sulphur Low (24 kg S/ha)**	**Sulphur High (78 kg S/ha)**	**LSD**
Spring	Year 1[1]	788	769	548	
	Year 2[2]	1236	1160	1315	
	Year 3	605	512	633	408
	Mean	876	814	832	
Summer	Year 1	1540	1413	1045	
	Year 2	1374	1093	1300	
	Year 3	1148	1029	1175	426
	Mean	1354	1178	1173	
Autumn	Year 1	407	300	378	
	Year 2	600	392	397	
	Year 3	215	214	194	172
	Mean	407	302	323	
Annual	Year 1	2735	2482	1971	
	Year 2	3209	2646	3012	
	Year 3	1969	1755	2002	707
	Mean	2638	2294	2328	

[1]Year 1 was used as a baseline measurement year to determine current production.
[2]Sulphur fertiliser applied after harvest in spring of year 2.

between the grazing regimes. After three years, the presence of lotus in the sward in low and high initial plant densities, though significantly different, was similar to the results from the end of the first season. A use of a single late season defoliation resulted in significantly greater lotus presence in the sward. The presence of lotus was similar in both 2 or 5 cm grazing regimes, although grazing to a residual of 5 cm rather than 2 cm resulted in a significant increase in both the number of growing points and rhizome length. The use of single defoliation at the end of the growing season resulted in further increases of both growing point number and length.

Low initial plant density produced significantly less dry matter than swards with high initial plant density for the first two years (Table 5). This difference was not apparent in the third year. The dry matter yields from the three defoliation regimes were similar in the first year. Yields, when defoliated to 2 or 5 cm, were not significantly different throughout the three years. However, single late harvest defoliation gave significantly greater annual yields than the regular defoliation treatments in the third year. Lotus contribution to total yield was higher in the high initial plant population treatment throughout. The contribution of lotus to total yield in the first two years was significantly greater in the plots harvested to 5 cm compared with harvesting to 2 cm. While data was not collected for the single late season defoliation in the first two years, there were no differences in lotus percentage between defoliation regimes in the third year, with lotus contributing approximately 50% of total yield.

Discussion

Dry matter production in this environment was much greater after the introduction of *Lotus pedunculatus*. Production increases of two to four-fold have been reported (*e.g.*, Floate et al*.*, 1989, Stevens et al*.*, 2020), however, the reason for the variable production across the landscape remains unclear. The need for nutrients once the root system is established relies on the rate of availability from the soil, but the use of sulphur fertiliser in this experiment did not show any increase in yield. As legumes fix their own nitrogen, a supply of sulphur, an integral element in essential amino acids, can be calculated from the maximal yield likely in any given climatic condition (Sinclair et al*.*, 1994; Morton et al*.*, 1998). The ratio of N:S in pasture plants is relatively

Table 4 Effects of initial plant density and defoliation regime on the frequency of occurrence, rhizome length and growing point number of *Lotus pedunculatus* in swards three years after over-sowing into low fertility tussock grassland.

		Density				Defoliation regime				
		Low	High	LSD	P value	2 cm	5 cm	Single late season	LSD	P value
Presence	May-20	24.4	38.7	11	0.005	29.3	36.7	28.7	9	0.232
	Apr-22	32.8	38.7	5.3	0.014	28.8	28.8	49.6	4.4	0.001
Rhizome density (Growing points/m2)		1480	1875	612	0.163	592	1217	3190	747	0.001
Rhizome length (m/m2)		25.98	35.46	12.60	0.125	9.64	19.80	62.72	15.43	0.001

Table 5 Effects of initial plant density and defoliation regime on the dry matter production and contribution of *Lotus pedunculatus* in swards during three years after over-sowing into low fertility tussock grassland.

		Density				Defoliation regime				
		Low	High	LSD	P value	2 cm	5 cm	Single late season	LSD	P value
Annual yield (kg DM/ha)	Year 1	1890	2550	715	0.064	2400	1940	2310	876	0.488
	Year 2	2520	3240	532	0.013	2930	2590	3110	651	0.245
	Year 3	2710	3010	560	0.273	2690	2280	3610	686	0.004
Lotus contribution (%)	Year 1	35	55	12	0.058	38	52	ND	15	0.007
	Year 2	51	65	8	0.005	54	62	ND	9	0.064
	Year 3	43	54	11	0.052	47	48	51	13	0.785

constant at 12-15:1 for optimal growth (Morton et al., 1998). Maximum annual yield measured in the sulphur experiment was 3200 kg DM/ha. At 25% protein, this equated to 128 kg N/ha, requiring 8.5 kg S/ha/annum at an N:S ratio of 15:1. If these soils had a bulk density of 1 and a depth of 10 cm, then they contained one million kg soil per ha. With an extractable sulphate sulphur content of 5-16 mg/kg soil (Figure 1) this suggested that between 5 and 16 kg S was available from the soil, which explained the lack of response to S in this experiment.

Total dry matter production is an interaction between the climatic conditions, mainly temperature and rainfall, and the availability of nutrient from the soil (Moir et al., 2000). Productivity on these high-altitude tussock grasslands was restricted by all these parameters, with production ranging from near zero to approximately 3 t DM/ha (Lowther 1983; McIntosh et al., 1984; Enright and Floate 1988; Fraser et al., 1988). Yield variation in these experiments was associated with the climatic conditions. Growing degree (GDD) accumulation (above a threshold of 5°C) averaged 924, 950 and 1080 GDD/annum between September and May over the three growing seasons of the defoliation experiment (Table 2). Legumes respond to temperature at approximately 4 kg DM/GDD, so potential maximum predicted yields were 3.7, 3.8 and 4.3 t DM/ha. Rainfall during the three growing seasons (September to May) totalled 614, 385 and 179 mm respectively. This indicated a potential soil moisture deficit that may have further reduced the actual yield, especially in years 2 and 3. Therefore, the reported yields of 1.9-3.2 t DM/ha approached the biophysical limit in this environment. Data reported by Stevens et al. (2020) in this same environment indicated that improved tussock over-sown with ryegrass/white clover with the addition of 2 t lime/ha and 500 kg/ha superphosphate had a similar dry matter production to these lotus swards. This suggested that the environmental conditions had a significant role in determining the potential dry matter yields, making the potential response to the addition of extra fertiliser to Lotus stands marginal in this environment.

While both P and S fertiliser is essential to ensure good establishment (McIntosh et al., 1984), farmers should consider current performance of the pasture, and the background soil fertility before adding fertiliser. In this instance no fertiliser had been added since establishment.

Subdivision of hill and high-country blocks will improve the longevity of lotus stands. Ensuring an adequate number of lotus plants establish is key to enabling longevity (Lowther 1977). Defoliation height had an impact on the underground density of rhizomes, with grazing to 2 cm resulting in approximately half the growing points and rhizome length than grazing to 5 cm, though the density of growing points did increase, albeit not significantly. These results were consistent with previous research across a range of environments (Sheath 1980a; Maroso et al., 2007) which recommend long spelling periods and relatively lax defoliation. Maintenance of adequate rhizome biomass has significant implications to long-term survival of lotus, as natural reseeding opportunities are limited in this environment due to low temperatures resulting in late flowering and lack of thermal time to complete seed development (Wedderburn and Lowther 1985).

The use of a single graze at the end of the growing season for three years resulted in approximately three times more growing points and rhizome length than grazing three times during the year. Evidence of frost damage was seen (though not quantified) in the plots that were not grazed until late autumn, but the greater below-ground biomass was expected to provide a more robust pasture into the future. While this experiment provided a singular point of reference for this practice, other studies of rhizome development point to this long spelling (rest period) being successful (Sheath 1980b; Harris et al., 1997).

A key difference between this and other environments where lotus has been tested was growing conditions. Lotus produces rhizome material in response to short daylength, while, at the same time, requiring relatively high temperatures to maximise the response (Blumenthal and Harris 1998). Depleted lotus swards and those which start with low plant numbers may be able to be recovered with careful management using this approach, though successful rhizome spread, in this case, may need several years to achieve this due to falling autumn temperatures restricting the expression of this trait. The number of seasons that may be needed to develop this biomass advantage was not resolved from the data, as plot size was too small to use destructive sampling during the experiment.

Dry matter production was greater in swards with higher initial plant numbers, though swards with low initial plants numbers did strengthen and produce similar amounts of dry matter by year 3. Defoliation regime had relatively little effect on dry matter production until year 3, when the single late harvest produced the greatest amount. The farmer must remember that continual close grazing over time does appear to deplete growing point number, and occasional whole-season spelling would enhance both total production and the resilience and longevity of the lotus sward. Spelling of different blocks for whole seasons would provide a stockpiled feed source for autumn use, particularly for cows after weaning, in this environment.

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