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Research Paper

Pre-vegetated green roof sedum mats: Mineral nutrient status and apparent fertiliser recovery during production

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ABSTRACT

Increased urbanisation and requests for more sustainable urban environments create a strong demand for sedum mats used for green roof establishment. However, little information is available on mineral nutrient status and nutrient requirements in pre-vegetated sedum mat production. In this study we present tissue mineral nutrient concentrations in *Sedum album* L. as affected by production site, sampling date and pre-winter treatment at a commercial pre-vegetated green roof mat producer. In 2018, seasonal variation in shoot nutrient concentrations were examined at three sites (Elnaryd, Lagan, Tutaryd). In 2019, pre-winter application of phosphorus (P) and potassium (K) combined with winter coverage with polyethylene shade net (PKS) was compared with pre-winter PK fertilisation alone (PK) at the Elnaryd site. Plant sap analyses were performed at several sampling occasions both years. We observed a large variation in nutrient concentrations between sites, years and sampling occasions, which is consistent with earlier findings of large variation in nutrient concentrations for *Crassulaceae* spp. The nitrogen (N), P and K shoot concentration ranges were 0.85–3.7 %, 0.18–0.44 % and 1.1–2.7 %, respectively. In 2019, biomass was significantly higher for PKS than for PK. The apparent nutrient recovery efficiency of P and K were doubled at PKS in comparison with PK, increasing from 11 to 20 % for P and from 20 to 40 % for K. Even if the effects of winter coverage could not be separated from extra N fertiliser added to PKS, our results indicate that shade net coverage during winter could be a strategy in the production of green roof mats, promoting early deliveries. Plant sap concentrations of NO_3^- and K^+ were correlated with N and K concentrations in the dry shoot tissue, suggesting that plant sap analysis with hand-held instruments could be used by pre-vegetated mat producers to develop a more requirement-oriented fertilisation strategy.

1. Introduction

Increased urbanisation worldwide has created a demand for more sustainable urban environments. This has led to an increased interest in green roofs in the last decade (Green Roofs for Healthy Cities, 2019), primarily since the water holding capacity of the vegetation can contribute to better storm water management (VanWoert et al., 2005). Higher energy efficiency, reduction of air pollutants, urban heat island mitigation and increased biodiversity are other environmental benefits of green roofs (Getter and Rowe, 2006). The most abundant type of green roofs is extensive green roofs vegetated with *Sedum* spp., due to the ability of these plants to endure extreme habitats (Snodgrass and Snodgrass, 2006). With an increasing demand, optimisation of the production of sedum mats to make it both economically and environmentally sustainable, is particularly important.

When it comes to nutrient requirements in sedum, a limited amount of studies have been performed (e.g. Barker and Lubell, 2012; Clark and Zheng, 2012, 2013, 2014a, b, c; Lubell et al., 2013). However, the majority of studies address nutrient requirements on already installed green roofs, and recommendations during the production phase are rare (Clark and Zheng, 2014a, c). Furthermore, almost all studies available focus on the amount of nitrogen (N) added while recommendations regarding other nutrients are absent. Also, it is hardly possible to compare fertilisation of sedum with fertilisation in other horticultural crops, since the growing substrates used are different. The substrates used for sedum mats must be light and inert, as well as nutrient- and water-holding (Vinnova, 2021). Their content of organic matter is low, leading to limited growth if unfertilised, possibly with as little as 30 % ground coverage (Barker and Lubell, 2012). Clark and Zheng (2013) also acknowledge that a good fertilisation strategy is crucial for adequate

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plant growth, ground coverage and the aesthetic impressions of the mats. Rowe et al. (2006) highlight that maximal growth on green roofs is not always desirable, because of increased weight as well as higher sensitivity to extreme climatic conditions if the plants are too fast-growing.

The optimal fertilisation regime during production of pre-vegetated sedum mats is not necessarily the same as for installed roofs. While there are few studies available regarding the nutrient requirements of pre-vegetated sedum mats, two studies have been performed in Guelph, Canada (Clark and Zheng, 2014a, c). When seven fertilisation levels between 0 and 35 g N m^{-2} of controlled release fertiliser were tested on sedum mats, Clark and Zheng (2014a) concluded that 20 g N m^{-2} was sufficient to obtain satisfactory growth without markedly increasing the risk of nitrogen leaching. This is a higher recommended dose than in any of their preceding studies, performed on installed roofs (Clark and Zheng, 2013; 2014b). They also showed that the production time can be affected by the fertilisation regime; the unfertilised control needed 300 days while it took only 63 days when 25 g N m^{-2} was used (Clark and Zheng, 2014c). In an earlier study on recently installed roofs, *Sedum album* L. was shown to be favoured by pre-winter fertilisation with extra P and K (Clark and Zheng, 2012). This strategy could possibly also be relevant in sedum mat production, since a higher survival throughout the winter could make the mats ready for delivery earlier in the spring. Another strategy for shortening the period until mat delivery might be the application of winter coverage, which has been shown to increase soil temperature and greatly improve yield in comparison with the open field for other crops (Kalisz et al., 2017). Increased plant growth from early in the growing season could also contribute to a higher mineral nutrient uptake leading to an improved nutrient use efficiency. The apparent recovery efficiency of added mineral nutrients in the plants, i.e. the difference between fertilised and unfertilised plants, divided with the amount of fertiliser added, can be used as an indicator of the efficiency of fertiliser use (Fixen et al., 2015). Methods for on-site monitoring of plant nutrient status used in vegetable cultivation (Hochmut, 1994) might also be utilised in sedum mat production for improving the timing of fertiliser application and increasing nutrient use efficiency.

The aim of the present study was to investigate mineral nutrient requirements, nutrient contents and apparent nutrient recovery efficiency of pre-vegetated sedum mats. We performed a field study during two years with the objectives of evaluating the influence of production site and sampling occasion on early-season variation in plant nutrient contents, as well as the influence of pre-winter P and K fertilisation and winter coverage on plant nutrient status and apparent nutrient recovery efficiency. We also evaluated the usefulness of a hand-held K^+ and NO_3^- plant sap meter as an aid for precision fertilisation.

2. Materials and methods

2.1. Design of the study

The study was conducted during 2018 and 2019 in a commercial nursery producing pre-vegetated sedum mats in the Kronoberg county in southern Sweden. In 2018, shoot nutrient status was determined by sampling at four occasions (S1-S4) during April-June in one sedum mat (1–2 ha) at each of the three sites Elnaryd (56.7770518, 14.4496348), Lagan (56.90918, 13.99648) and Tutaryd (56.8312669, 14.049893). The plots were fertilised according to common practice in the nursery (Table 1). In 2019, shoot nutrient status was evaluated during March-May for three different management regimes at the Elnaryd site as shown in Table 1: 1) Unfertilised (UF), 2) Fertilised according to the same strategy as the plots of 2018 + pre-winter fertilisation with PK and Multicote (PK), 3) Same as 2) but with extra pre-winter YaraBela Axan N27 (Yara) and combined with polyethylene shade net coverage during winter (PKS). Each of the three treatments was carried out in one plot (0.5–1.5 ha). Sampling was done at two occasions (S1, S2). The dates of establishment, fertilisation and sampling for each plot and year are listed in Table 1.

Table 1
Establishment, fertilisation, maintenance measures and sampling dates (S1-S4) in the plots at the three sites used in the study. UF = unfertilised, PK = PK-fertiliser, PKS = PK-fertiliser + polyethylene shade. N27 = YaraBela Axan N27.

	2018			2019		
	Elnaryd	Lagan	Tutaryd	UF	PK	PKS
Establishment	12 Jun 2017	12 Jun 2017	12 Jun 2017	13 Aug 2018	14 May 2018	28 May 2018
NPK 11–5–18 (20 g m^{-2})	14 Aug 2017 18 Apr 2018 6 Jun 2018	19 Apr 2018 14 Jun 2018	1 Aug 2017 23 Apr 2018 13 Jun 2018		6 Jun 2018 10 Jul 2018 9 Apr 2019	11 Jun 2018 10 Jul 2018 25 Apr 2019
N27 (20 g m^{-2})	12 Jul 2017 3 May 2018	29 Jun 2017 9 May 2018	3 May 2018			9 Aug 2018
PK 11–21 (7 g m^{-2})					25 Sep 2018	25 Sep 2018
Multicote (20 g m^{-2})					30 Sep 2018	17 Oct 2018
Cutting		29 May 2018 Shoots left *in situ*	6 Jun 2018 Shoots removed			
S1	16–17 Apr 2018	16–17 Apr 2018	16–17 Apr 2018	28–29 Mar 2019	28–29 Mar 2019	28–29 Mar 2019
S2	6–7 May 2018	6–7 May 2018	6–7 May 2018	2–3 May 2019	2–3 May 2019	2–3 May 2019
S3	28–29 May 2018	28–29 May 2018	28–29 May 2018			
S4	17–18 June 2018	17–18 June 2018	17–18 June 2018			

2.2. Plant material and substrate

The sedum mats contained eight species from three genera: *Sedum acre* L., *Sedum album* L., *Sedum sexangulare* L., *Phedimus floriferus* Praeger, *Phedimus hybridus* L., *Phedimus kamtschaticus* Fisch., *Phedimus spurius* M.Bieb. and *Hylotelephium ewersii* L.. This study has mainly focused on the nutrient status of *S. album*, since this species plays a key role for successful production and was dominating in the mats.

The mats were cultivated on the ground on top of a layer of plastic foil (polyethylene) with the function of breaking capillary transport of soil moisture. The sedum mat consisted of a carrier (polyamide framework overlaying a polypropylene mat) filled with a substrate mix consisting of 25 vol% crushed lava stone (Scoria, 2–8 mm) and 25 vol% peat, in addition to macadam, stone meal, soil, and 5 vol% clay enriched with lime (Bara Clay Calcium Plus, Bara Minerals, Bara). The substrate depth was 25–30 mm. In 2018, the density of the substrate was 1020 ± 6 g L^{-1} (Elnaryd), 1010 ± 18 g L^{-1} (Lagan) and 993 ± 8 g L^{-1} (Tutaryd) as determined by SS-EN 13040:2007 on three replicates from each site. Modified Spurway analysis, involving extraction with 0.1 % acetic acid (Karlsson, 1968), was performed by Eurofins Agro Testing Sweden, Kristianstad, on substrate collected at S1 in 2018. pH was determined for S1 and S4 (SS-ISO 10390:20). The N and P concentrations in the substrate were below the detectable level at all three sites at the start of the experiment. For K it was between 53 (Lagan) and 72 (Elnaryd) mg L^{-1}. Substrate pH decreased throughout the trial period from 7.5 at S1 to 7.2 at S4 in Elnaryd and Lagan, and from 7.2 to 6.5 in Tutaryd.

2.3. Establishment and maintenance of the mats

The plots included in the study were part of the company's commercial production and the maintenance strategies varied between plots. The dates of establishment and maintenance measures for the individual plots are shown in Table 1.

The three plots sampled in 2018 had been established during the same week in June 2017. For the plots used in 2019, the establishment in 2018 was performed during three months, with the UF treatment established notably later than the other two.

The normal fertilisation strategy in the nursery included alternate applications of the mineral fertilisers YaraMila ProMagna NPK 11–5–18 and YaraBela Axan N27. The first application for the season was given at the start of the growth period. In the second year, two additional fertilisers were included in the PK and PKS treatment: Yara PK 11–21 and Multicote 4 M 15–7–15. A detailed fertilisation scheme is shown in Table 1 and the total amounts added of each nutrient are found in Table 2.

The green polyethylene shade net used in PKS was produced by Meyer, mesh size 5 mm, shade effect 45 %. The shade net was applied on the 17th of October 2018 and removed on the 25th of April 2019.

Three different cutting regimes were performed in the plots in 2018 (Table 1). Elnaryd was not cut at all, while Lagan was cut and the cuttings were left in the plot. Tutaryd got the normal cutting treatment with removed cuttings. The cutting was done between S3 and S4.

Sprinkler irrigation was normally performed every second day during spring and summer. However, the normal watering regime could not be maintained in 2018 due to the high temperatures and limited precipitation that spring (SMHI, 2024). As the water access was especially limited in Elnaryd, that plot did not receive any water.

The mean monthly air temperatures ranged from −3.6 °C (February 2018) to 17.1 °C (June 2018) for the 2018 batches, from establishment to the end of the study (SMHI, 2024). For the 2019 batches it ranged from −1.5 °C (January 2019) to 17.4 °C (August 2018) for UF and to 21.4 °C (July 2018) for PK and PKS. The total precipitation from establishment to sampling was 674 mm for 2018 and 459 (PK), 451 (PKS) and 396 mm (UF) for 2019. Despite the higher total precipitation in the 2018 trial, the sedum mats suffered from drought during early spring, as most of the rain fell during the autumn of 2017. In 2018, 67 mm rain fell in February - April compared to 150 mm in 2019. The dry months in early spring 2018 coincided with a lower mean temperature compared to early spring in 2019 (February, March, April: -3.6, −1.9, 7.7 °C in 2018 and 2.1, 3.4, 7.8 °C in 2019). The climate data was registered in Växjö, 30–50 km from the production sites (SMHI, 2024)

Table 2
Amounts of the elements added during the study period of 2018 and 2019, respectively. The numbers within the brackets represents all fertilisation events from the establishment the previous year until the end of the study. UF = unfertilised, PK = PK-fertiliser, PKS = PK-fertiliser + polyethylene shade net.

	2018			2019		
	Elnaryd	Lagan	Tutaryd	UF	PK	PKS
g m^{-2}						
N-tot	9.8 (17.4)	9.8 (15.2)	9.8 (12.0)	0 (0)	5.2 (9.6)	5.2 (15.0)
NO_3-N	4.5 (8.08)	4.5 (7.2)	4.5 (5.38)	0 (0)	2.2 (4.0)	2.2 (6.7)
NH_4-N	5.3 (9.32)	5.3 (8.0)	5.3 (6.62)	0 (0)	3.0 (5.6)	3.0 (8.3)
P	1.8 (2.72)	1.8 (1.8)	1.8 (2.72)	0 (0)	2.5 (4.4)	2.5 (4.4)
K	7.0 (10.52)	7.0 (7.0)	7.0 (10.52)	0 (0)	6.8 (14.0)	6.8 (14.0)
Mg	0.76 (1.2)	0.76 (0.88)	0.76 (1.08)	0 (0)	0.56 (1.2)	0.56 (1.3)
S	4.7 (7.44)	4.7 (5.44)	4.7 (6.7)	0 (0)	2.1 (6.1)	2.1 (6.8)
mg m^{-2}						
Mn	100 (150)	100 (100)	100 (150)	0 (0)	64 (160)	64 (160)
B	20 (30)	20 (20)	20 (30)	0 (0)	16 (36)	16 (36)
Cu	12 (18)	12 (12)	12 (18)	0 (0)	16 (16)	16 (16)
Fe	32 (48)	32 (32)	32 (48)	0 (0)	110 (140)	110 (140)
Zn	16 (24)	16 (16)	16 (24)	0 (0)	22 (38)	22 (38)
Mo	0.8 (1.2)	0.8 (0.8)	0.8 (1.2)	0 (0)	2.4 (3.2)	2.4 (3.2)

2.4. Sampling

Sampling of plant material was performed according to Table 1. The date for S1 in 2019 was selected to match the growth stage of the *Sedum* plants at S1 in 2018 and to compensate for differences in air temperatures between the years. In each plot, all the aboveground plant material was collected from three randomly selected patches, each covering 0.25 m^2. In Elnaryd material was sampled from 0.5 or 1.0 m^2 at S1 and S2 in some of the patches, where the plant density was too low to yield enough material for analysis (DW > 10 g). The collected plant material was separated into four different categories: (i) *S. album*, (ii) other *Sedum* spp., (iii) *Phedimus* spp. + *H. ewersii* and (iv) weeds.

Additional *S. album* was collected outside of, but in close connection to, each sampling patch to be used for plant sap analyses. The sampling was performed at S2-S4 in 2018, at S1 for UF and at S1-S2 for PK and PKS in 2019. Sampling was performed between 11.30 a.m. and 1.00 p.m.

2.5. Plant tissue analyses

After each sampling occasion, the fresh weights (FW) of the four plant categories were determined for each plot. For *Sedum album,* the dry weight (DW, 65 °C) was determined. Plant tissue analysis by ICP-OES was performed by Eurofins Agro Testing Sweden (Kristianstad) in 2018 (NMKL No 161 1995 mod.) and by LMI AB (Helsingborg) in 2019 (SS-028311). Total N content was determined according to the Dumas method by Eurofins Agro Testing Sweden in 2018 (Leco AN 203-821-394) and at the Swedish University of Agricultural Sciences (Alnarp) in 2019 (SS-EN ISO 16634–2:2016).

The total content of N, P and K in the plant material per unit area was estimated from the nutrient concentrations and DW of *S. album* together with the total FW of all sampling categories. It was assumed that the other species within the *Sedum* genus had the same relative nutrient composition as *S. album,* and that the proportions of *Phedimus* spp./*H. ewersii* and weeds were so small that the potential differences in their nutrient composition were negligible.

The total nutrient uptake per unit area during the experimental period was calculated as the difference in nutrient content between S4 and S1. For Tutaryd, where cuttings were removed between the two last sampling occasions, the amount of nutrients in the cuttings at S3 were also included in the total uptake.

The apparent nutrient recovery efficiency (ARE) was calculated for N (N-ARE), P (P-ARE) and K (K-ARE) as the difference in plant nutrient content between the respective fertilised treatment and the unfertilised plants, divided with the amount of fertiliser added (e.g. Fixen et al., 2015).

2.6. Plant sap analyses

After 24–48 h in cold storage, plant sap was collected by pressing the outer, youngest part (ca. 2 cm) of 10–15 *S. album* shoots by a garlic press (Garject, Dreamfarm). This was repeated three times per sampling patch and sampling occasion. The mean of the three measurements within each patch was used as one replicate, adding up to three replicates per plot and sampling occasion. The concentrations of nitrate (NO_3^-) and potassium (K^+) ions in the plant sap were determined by the handheld instruments Horriba LAQUAtwin B-741 and B-731, respectively.

2.7. Statistics

Minitab® 18 (Minitab Statistical Software) was used for all statistical analysis. Two-way analysis of variance (ANOVA) was performed for FW, nutrient concentrations and contents both years. Comparisons were based on Tukey's Studentized Range Test ($p < 0.05$). Within each production site in 2018, one-way ANOVA was used to compare the sampling occasions. One-way ANOVA was also conducted to compare the nutrient contents at S1 in 2018 and 2019 at Elnaryd. Pearson's correlation coefficients were used to estimate the correlation between nutrient concentrations in the plant sap and the plant tissue.

3. Results

3.1. Biomass production

The effects and interactions of production site and sampling occasion in 2018 and of treatment and sampling occasion in 2019 on biomass production are presented in Table 3. The absence of a significant interaction between site and sampling occasion in 2018 indicated that the three plots responded similarly over time. The total mat biomass was markedly higher at the two last sampling occasions than at S1 and S2 (Fig. 2). Elnaryd, however, showed significantly lower biomass production than the other two sites. Although *S. album* was the dominating species in all three plots, the proportion of *S. album* differed significantly ($p < 0.001$) among the plots, with the highest proportion in Lagan (93 %) and the lowest in Elnaryd (74 %).

In 2019, the variation in species composition was even larger between different plots (Fig. 2). In the unfertilised plot, *S. album* was dominant (61 %), while the share of other *Sedum* spp., was large in PK and PKS (53–54 %). A significant difference in biomass production was found between the treatments, and the interaction with sampling occasion was strongly significant (Table 3). At S1, PK and PKS did not differ significantly but both had higher FW than UF. At S2 there was also a difference between the two treatments, with PKS being superior to PK. Only PKS showed a significant increase in FW between the two sampling occasions. The FW in the unfertilised plot in Elnaryd at S1 2019 did not differ significantly from the Elnaryd plot at S1 2018.

3.2. Mineral nutrient concentrations, contents and uptake 2018

The results of the two-way ANOVA for mineral nutrient concentrations and contents in 2018 are presented in Table 3. The concentrations of most nutrients changed significantly during the trial period in 2018. Generally, when all sites were considered, there were increasing concentrations of K, Mg, B and Zn over time. Even the N, Ca and S concentrations increased but showed a slight decrease again at the last sampling occasion. The Mn, Cu, Fe and Al concentrations varied without a clear pattern throughout the trial period, while P and Mo were the only elements that were generally found in significantly lower concentrations at S4 than at S1. The data for the individual plots are presented in Supplementary Material, Tab. SM1. Most elements followed similar patterns over time in the three sites. However, a strong interaction was found for P, due to an increase in Elnaryd that was not found in the other plots. Also for Ca, Mn, Fe and Al strong interactions between sampling occasion and site were found. While the Ca concentration in Elnaryd and Lagan increased and were highest at the last two sampling occasions, it peaked at S2 in Tutaryd. Both Elnaryd and Tutaryd had their lowest concentrations of Mn at S1 and the highest at S4, while Lagan had similar levels at S1, S3 and S4, peaking at S2. Also the Fe and Al concentrations were highest at S2 in Lagan, as well as in Tutaryd. In Elnaryd the concentrations instead kept increasing throughout the whole sampling period.

The total nutrient content in the total shoot biomass, based on the assumption that all *Sedum* spp. would have the same nutrient composition as *S. album,* increased markedly for N and K in all plots, as shown in Table 4. That was also the case for P, despite the decreasing P concentrations. The content of N, P and K in the cut parts at S3 is presented in Tab. SM2. No significant differences were found between the plots. The total uptake between S1 and S4 was about 4–5 g m^{-2} of N, 0.2–0.6 g m^{-2} of P and 3–6 g m^{-2} of K.

3.3. Mineral nutrient concentrations and content 2019

The results of the two-way ANOVA for mineral nutrient concentrations and contents in 2019 are presented in Table 3. The mineral nutrient concentrations are presented in Tab. SM3. For a majority of the macronutrients (e.g. N, P, K and S) early in the season (S1), *S. album* grown under the PKS treatment showed higher concentrations than in the unfertilised plot. The same pattern was observed for B. Even the PK plot had higher concentrations than UF of P and S. There were no differences between the plots for Mg, Ca and Mn at S1, which was also true for Na, Cu, Fe and Zn at both sampling occasions and Al at S2. Although not significantly different, the Na concentration was notably higher in UF at S1 compared with the other plots and sampling occasions. The concentration of Mo and Al was higher in UF than in PKS at S1. At S2,

Table 3
The results of the two-way ANOVA for production site (LO) and sampling occasion (SO) in 2018 and treatment (TR) and SO in 2019 on total fresh mat biomass and nutrient contents in the total aboveground biomass as well as concentrations in the shoot tissues of *S. album*, $n = 3$. Missing data for Na LO*SO 2018.

		2018			2019		
		LO	SO	LO*SO	TR	SO	TR*SO
Total mat biomass		**	***	ns	***	**	***
Nutrient concentration in S. album	N	**	***	*	***	ns	ns
	P	***	***	***	***	ns	ns
	K	***	***	ns	***	***	*
	Mg	***	***	ns	**	ns	***
	Ca	***	***	***	**	***	ns
	S	ns	***	ns	***	*	ns
	Na	ns	*		*	*	*
	Mn	ns	***	***	**	ns	ns
	B	***	***	*	***	***	*
	Cu	ns	***	ns	ns	*	ns
	Fe	ns	***	**	ns	***	ns
	Zn	***	***	ns	*	ns	ns
	Mo	***	**	*	**	*	ns
	Al	ns	***	**	**	***	**
Nutrient content in total mat biomass	N	ns	***	ns	***	ns	ns
	P	***	***	ns	***	ns	ns
	K	***	***	ns	***	**	ns

Table 4
Total content (g m^{-2}) of N, P and K in the shoot biomass in the plots at Elnaryd, Lagan and Tutaryd at sampling occasion S1-S4 in 2018. Sites that do not share a capital letter differ significantly ($n = 12$). Sample occasions within the same site (row) that do not share a lowercase letter differ significantly ($n = 3$). Means ± SE.

	2018	Site	S1	S2	S3	S4
N	Elnaryd	2.4 ± 0.5 A	0.58 ± 0.15 c	1.4 ± 0.3 bc	2.7 ± 0.3 b	4.8 ± 0.4 a
	Lagan	3.1 ± 0.7 A	0.69 ± 0.07 b	1.4 ± 0.3 b	5.4 ± 1.0 a	5.0 ± 0.4 a
	Tutaryd	3.1 ± 0.6 A	0.40 ± 0.10 b	2.1 ± 0.1 b	4.8 ± 0.6 a	5.0 ± 0.6 a
P	Elnaryd	0.16 ± 0.03 B	0.064 ± 0.015 b	0.11 ± 0.02 b	0.17 ± 0.02 b	0.31 ± 0.05 a
	Lagan	0.39 ± 0.07 A	0.20 ± 0.02 b	0.21 ± 0.06 b	0.54 ± 0.10 ab	0.60 ± 0.13 a
	Tutaryd	0.39 ± 0.07 A	0.16 ± 0.03 c	0.21 ± 0.00 bc	0.46 ± 0.06 ab	0.72 ± 0.11 a
K	Elnaryd	1.6 ± 0.3 B	0.48 ± 0.13 c	0.81 ± 0.16 bc	1.8 ± 0.2 b	3.1 ± 0.4 a
	Lagan	2.8 ± 0.6 A	0.77 ± 0.09 b	1.2 ± 0.3 b	4.5 ± 1.0 a	4.9 ± 1.0 a
	Tutaryd	3.1 ± 0.7 A	0.73 ± 0.14 b	1.4 ± 0.1 b	4.5 ± 0.5 a	6.0 ± 0.7 a

both PKS and PK had higher concentrations of N, P, Mg, S, Mn and B in comparison with UF. For K, all three treatment levels differed significantly from each other with the lowest concentration in UF and the highest in PKS. Mo was higher in UF than in PK. Ca and B increased from S1 to S2, while the opposite was true for Fe and Al. This decrease was not seen in 2018, neither for Fe nor for Al.

The total content of N, P and K in the biomass in 2019 (Table 5) were all significantly higher in PKS than in UF at both sampling occasions. For PK, N was between the other two plots and did not differ significantly from any of them, which was also the case for K at S1. At S2, the K content differed significantly between all plots, with PKS>PK>UF. The P content did not differ significantly between PK and PKS, while it was significantly lower in UF.

When the total nutrient content in UF at S1 in 2019 were compared to the contents in the Elnaryd plot at S1 in 2018, no significant differences were found for N, P or K (Fig. 3). In contrast, the contents in PK and PKS in 2019 were higher for all nutrients compared with the Elnaryd plot in 2018 (Fig. 3).

In late March 2019, the apparent nitrogen recovery efficiency (N-ARE) of PK and PKS was 34 % and 30 % respectively (Table 5). One month later, the N-ARE had increased to 34 % for PKS but decreased to 27 % for PK. For PK, the P-ARE at S1 was 12 % and had not increased in early May (Table 5). For K, however, the low K-ARE of PK in late March (15 %) increased to 20 % in early May (Table 5). For PKS, there was also only marginal increase in P-ARE from S1 to S2, while the K-ARE improved from 31 to 40 %. Hence, while the P-ARE was more than 60 and 80 % higher in PKS than in PK at S1 and S2, respectively, the K-ARE was doubled in PKS in comparison with PK for both sampling occasions.

3.4. Plant sap analysis

In 2018, there were strong interactions between SO and site for both NO_3^- and K^+ concentrations in the plant sap ($p < 0,001$). The nitrate concentration ranged from 500 ppm to 3900 ppm and decreased throughout the season in Elnaryd and Tutaryd while there were no significant differences between the sampling occasions in Lagan (Table 6). In 2019, no significant differences between the pre-winter treatments were observed for NO_3^- and the concentrations (190–380 ppm) were notably lower than in 2018. It should also be noted that the plant sap sampling was not performed at comparable dates the two years.

For K^+, there was no clear pattern in 2018. The concentrations ranged from 500 to 1000 ppm, which was similar to 2019 (460–950 ppm). At S1 2019, the K^+ concentration was higher in PKS than in the other treatments. The difference between PK and PKS had disappeared at S2, when UF was not measured.

Table 5
Total content (g m^{-2}) of N, P and K in the shoot biomass 2019 as affected by treatment, calculated based on the nutrient content in *S. album.* Data within the same row that does not share a letter differ significantly. The two columns to the right display the apparent recovery efficiency (ARE). UF = unfertilised, PK = PK-fertiliser, PKS = PK-fertiliser + polyethylene shade net. Means ± SE, n = 3.

		g m^{-2}			%	
	2019	UF	PK	PKS	ARE PK	ARE PKS
N	S1	0.51 ± 0.04 b	3.0 ± 0.8 ab	4.4 ± 0.6 a	33.6	30.4
	S2	0.40 ± 0.03 b	3.0 ± 0.4 ab	5.5 ± 1.0 a	27.1	34.0
P	S1	0.10 ± 0.01 b	0.49 ± 0.12 a	0.74 ± 0.06 a	11.5	18.8
	S2	0.11 ± 0.01 b	0.59 ± 0.07 a	0.98 ± 0.15 a	10.9	19.8
K	S1	0.47 ± 0.05 b	2.0 ± 0.4 ab	3.7 ± 0.5 a	14.7	31.1
	S2	0.54 ± 0.05 c	3.4 ± 0.4 b	6.2 ± 1.0 a	20.4	40.4

Table 6
Concentrations (mg L^{-1}) of NO_3^- and K^+ in the plant sap in 2018 and 2019 as affected by sampling occasion (S1-S4) and pre-winter treatment, respectively. Data within the same row that does not share a letter differ significantly. UF = unfertilised, PK = PK-fertiliser, PKS = PK-fertiliser + polyethylene shade net. Means ± SE, n = 3.

	2018	S2	S3	S4
NO_3^-	Elnaryd	2300 ± 300 a	1600 ± 300 ab	1100 ± 0 b
	Lagan	1300 ± 200 a	640 ± 160 a	790 ± 120 a
	Tutaryd	3900 ± 600 a	750 ± 120 b	500 ± 70 b
K^+	Elnaryd	530 ± 30 b	720 ± 30 a	500 ± 20 b
	Lagan	660 ± 50 a	580 ± 60 a	680 ± 70 a
	Tutaryd	810 ± 50 b	790 ± 40 b	1000 ± 0 a
	2019	**UF**	**PK**	**PKS**
NO_3^-	S1	190 ± 10 a	210 ± 0 a	250 ± 40 a
	S2		240 ± 30 a	380 ± 90 a
K^+	S1	460 ± 50 b	560 ± 30 b	950 ± 10 a
	S2		810 ± 110 a	710 ± 10 a

Highly significant correlations ($p < 0.001$) were found in 2018 between the concentrations of NO_3^- and K^+ in the plant sap and the dry tissue concentrations of N ($r = 0.68$) and K ($r = 0.65$), respectively. In 2019 the correlation for K was slightly weaker ($r = 0.58$, $p < 0.05$). This year, the correlation between tissue N concentration and NO_3^- in the plant sap was significant ($r = 0.60$, $p < 0.05$) only if an outlier (547 ppm in PKS at S2) was removed from the data material. The estimated linear equations for the two years differed strongly for N (Fig. 4a-b), but were more similar for K (Fig. 4c-d).

4. Discussion

4.1. Plant growth at three production sites 2018

Early in the season, the fresh biomass production was similar at all sites (Fig. 2). Because of drought and limited irrigation at Elnaryd in particular, growth was subsequently inhibited in that plot, as shown by the significantly lower FW. Despite this, the growth curve continued to increase in the uncut Elnaryd plot from S3 to S4, in contrast to the cut plots Lagan and Tutaryd. Even Clark and Zheng (2014a) studied the production phase, but measured growth as plant height and ground coverage. It is also difficult to compare our findings and other's results due to the different types of growing systems. In the greenhouse study by Emilsson et al. (2007) the FW after six weeks at different fertiliser levels was 1045–1896 g m^{-2} in pre-vegetated mats, but only 133–279 g m^{-2} when the mats were established from cuttings. The one year study of winter hardiness on a roof in Canada by Clark and Zheng (2012) resulted in 1550 g m^{-2} for the unfertilised treatment and 4028–5200 g m^{-2} for different fertiliser regimes, when sampled in October. It is difficult to know whether our lower FW (260–2800 g m^{-2}) mainly depended on the earlier sampling dates or on other factors such as the limited water supply in 2018.

Sedum plants grow naturally in environments rich in lime, but as noted by Stephenson (1994), that does not necessarily mean that they have their growth optimum at a high pH, but rather that they compete well under such conditions. As seen in Fig. 2, *S. album* and other *Sedum* spp. are often the totally dominant species in the plots, despite that *P. spurius* is known as a strong competitor (Barker and Lubell, 2012) and although the grower aimed at a 50:50-mix of *Sedum* and *Phedimus*. Zheng and Clark (2013) showed that the pH-optimum differ among these species. *P. spurius* was shown to be very sensitive to high pH with a suggested optimum of 5.7, compared to 6.3 for *S. album* (Zheng and Clark 2013). In the plots in the present study, the pH was kept quite high to give the sedum mat plants a competitive advantage over the weeds. Therefore, one possibility to obtain a more even species distribution could be to lower substrate pH.

Another explanation for the low coverage of *Phedimus* spp. could perhaps be the substrate depth. In an extensive seven-year study, comprising 25 species within the *Crassulaceae* family, Rowe et al. (2012) showed that substrate depth was crucial for species composition. With 2.5 cm substrate depth, *S. album* and *S. acre* were the dominating species, while *P. spurius* together with *P. middendorffianus* Maxim. took over when substrate depth was 7.5 cm. Barker and Lubell (2012) performed a study where the proportions of *S. album* and *P. spurius* did not change over time, but their study was conducted in 10 cm deep substrate. The thicker substrate layer could possibly explain why *S. album* did not take over in that case, in opposite to the present study where the substrate depth was 2.5–3 cm.

4.2. Nutrient status at three production sites 2018

In the present study, we have interpreted the results of the plant tissue analysis (Tab. SM1, SM3) by comparisons with other studies available for *Sedum* and other cultivated species within the *Crassulaceae* (Tab. SM4) sampled from container production nurseries (Mills and Benton Jones, 1996), greenhouse (Emilsson et al., 2007; Moritani et al., 2017; Zheng and Clark, 2013) and field (Krawczyk et al., 2021) experiments. For example, Mills and Benton Jones (1996) reported concentration ranges of 0.87–4.54 % N, 0.29–0.84 % P and 1.31–4.95 % K for succulent species and cultivars in container production (Tab. SM4). Hence, for the calculation of the total nutrient contents in the aboveground material of the mats (Tables 4 and 5), our assumption that all *Sedum* spp. had the same nutrient composition may be incorrect.

For the macronutrients, the general increase in concentrations of N, K, Mg Ca and S observed after the onset of fertilisation could be expected (Tab. SM1). Cutting was probably the explanation for the decreasing trend of the N concentration in Lagan and Tutaryd between S3 and S4, that could not be seen in Elnaryd. This is in line with the findings of higher N concentration in cuttings than in the remaining at S3 (data not presented).

It is likely that the significantly higher N concentration in the plots in Tutaryd than in Lagan at S2 (Tab. SM1) was related to the additional dose of N27 given in Tutaryd prior to the sampling (Table 1). The total N content did not differ significantly between the sites (Table 4) despite the lower FW at Elnaryd, and more N could possibly have been taken up if the supply had been higher. For Tutaryd, the significant reduction of the N concentration between S2 and S4 indicated that the supply of N was less than optimal at this site.

Recommended N fertilisation in sedum mats in the literature vary from 6.5 g m^{-2} for installed roofs (Rowe et al., 2006) to 20 g m^{-2} for mat production (Clark and Zheng, 2014a). In the present study, the 9.8 g N m^{-2} supplied during two months in the early season correspond to ca. 12–18 g N m^{-2} per year, based on the normal number of fertilisation events throughout a season. The estimated uptake of 4.2–5.1 g N m^{-2} in the aboveground plant material during this period (Tab. SM2) suggest that the N supply during mat production needs to be higher than the 6.5 g m^{-2} recommended for installed roofs, both because of root N requirement and since the N efficiency will never be 100 % due to nitrate leakage and aerial N emissions. On the other hand, in a greenhouse study with a test of three different fertiliser amounts on pre-vegetated mats, Emilsson et al. (2007) found that the highest level (10 g N m^{-2}) generated a mean N concentration of 2.14 % and led to increased nitrogen leakage. Hence, in our study, the N concentration range of 2.1–3.7 % for S2-S4 indicates that the supply should probably rather be reduced than increased to reduce the risk of N loss.

The K concentrations of 1.3–2.7 % observed in our study were quite similar to the 1.6–2.4 % reported for the *Sedum/Phedimus* mix by Emilsson et al. (2007), but consistently lower than the 3.0–3.6 % K found for *S. album* (Zheng and Clark, 2013) and the 4.9 % reported for two *Sedum* spp. by Mills and Benton Jones (1996). Amendment with K was shown to increase winter hardiness in *S. album* (Clark and Zheng, 2012) and could possibly also improve the early season K status.

Similar to K, the concentrations of Mg, Ca and S were within the ranges reported for other *Sedum* spp. and other *Crassulaceae* species as shown in Tab. SM4. For Mg, the concentration range of 0.24–0.57 % found in 2018 was similar to the range reported for seven *Crassulaceae* species (0.24–0.62 %) by Mills and Benton Jones (1996), but markedly lower than the 0.65–0.98 % reported for *S. album* by Zheng and Clark (2013). Magnesium was the only element for which the total uptake corresponded to the supply in the present study (data not shown), indicating that the Mg requirement was not fulfilled under the current fertilisation regime.

A potentially low Mg uptake could also have been caused by competition with other cations such as K^{+}, Ca^{2+} and Fe^{3+} (Fageria, 2001). While the concentration of K was not particularly high, the concentrations of Ca found in the mats (2.2–4.6 %) were higher than the values (1.7–2.4 %) reported by Zheng and Clark (2013). While competition with Ca cannot be excluded, even the remarkably high tissue concentrations of Fe and Al might have contributed to the rather low Mg concentrations observed at some of the production sites and sampling occasions in our study.

Phosphorus was the only element that showed a significant reduction in concentration from S1 to S4. Compared with the 0.51–0.57 % P reported for *S. album* by Zheng and Clark (2013) and the range of 0.29–0.84 % P reported for different *Crassulaceae* species (Mills and Benton Jones 1996), the concentrations around 0.20 % P observed at Elnaryd were probably a bit low. The P concentrations for the two other sites at S1 (0.34–0.44 %) were comparable to the 0.41–0.46 % P for the *Sedum/Phedimus* mix studied by Emilsson et al. (2007), but declined over time. Pre-winter fertilisation with extra P have been suggested to favour *S. album* (Clark and Zheng, 2012) and might be beneficial when P concentrations are low in the autumn.

For the micronutrients, the observations from the present study are within the reported ranges for most elements. For Zn, the 2018 values were low, 14–27 μg g^{-1} compared to 47–191 μg g^{-1} in the literature (Tab. SM4). Similar to Mg, this might also be related to competition with other cations (Fageria, 2001). The most remarkable results among the trace elements, however, were the high concentrations of Fe (1100–4700 μg g^{-1}) and Al (830–3300 μg g^{-1}). This is surprising, given the relatively high pH in the plots (6.5–7.5) and the fact that these elements are less available in alkaline soils. The highest Fe concentration reported for a *Sedum* or other cultivated succulent species in comparable studies was 220 μg g^{-1} (Tab. SM4). According to Chenery and Sporne (1976), most plants have an Al concentration < 300 μg g^{-1} in the leaves, while $>$1000 μg g^{-1} indicates that the plant is an Al accumulator. In the present study, *S. album* seemed to have accumulated Fe and Al both in 2018 and 2019. The variation in micronutrient and trace element concentrations between sites might be explained by differences in local conditions and fertilisation regimes.

4.3. Effects of pre-winter treatments on plant growth in 2019

The establishment of PK and PKS three months earlier than UF complicates the comparison between the treatments. However, as there were no significant differences at S1 in FW (Fig. 1, Fig. 2), total nutrient contents (Fig. 3) or nutrient concentrations (data not shown) between the unfertilised plot (UF) in 2019 and the Elnaryd plot in 2018, the UF plot was used to evaluate the effects of PK and PKS. The significantly lower FW in UF than in PK and PKS at S1 indicates that the treatments in PK and PKS did improve shoot biomass. The comparable FW of PK and PKS at S1 with those in Elnaryd at the later sampling occasions (S3 and S4) the year before is in line with the findings of Clark and Zheng (2012) that pre-winter fertilisation with P and K can be favourable for early season growth. However, as NPK fertiliser was added to PK and PKS during the summer 2018 as well as in April 2019, combined with the addition of Multicote in the autumn of 2018 (Table 1), the better growth in PK and PKS in 2019 in comparison with UF was probably the composite effect of several occasions of fertiliser addition. The advantage of

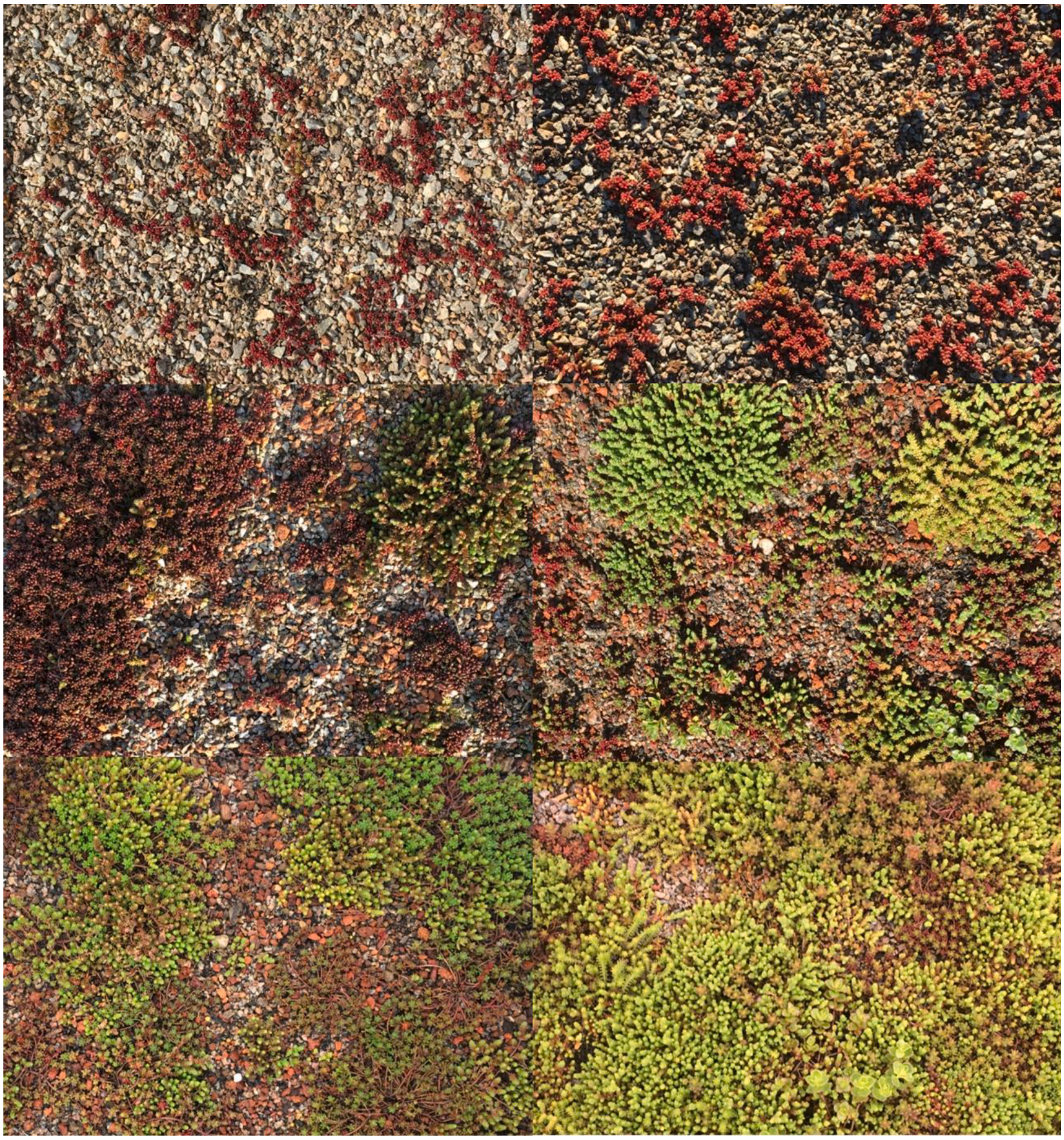

Fig. 1. Photo showing the status of the sedum mats 2019, at S1 to the left and S2 to the right. From top to bottom, the treatments UF, PK and PKS are presented. UF = unfertilised, PK = PK-fertiliser, PKS = PK-fertiliser + polyethylene shade net.

spring establishment of the PK and PKS plots in contrast to the autumn establishment of the UF plot (Table 1) probably also contributed to the superior biomass production of the former plots.

Coverage with different types of polyethylene is a commonly used method for winter protection in nurseries (Mathers, 2003). While the significant difference between PKS and PK at S2 could indicate that winter coverage strongly influenced growth in the next growing season, the effect of winter coverage cannot be separated from the effect of the additional nitrogen (N27) added to the PKS plot in August 2019 (Table 1). The high FW at S2 for PKS (3800 g m^{-2}, see Fig. 2) is also interesting in relation to 2018, where FW even for the last two sampling occasions never exceeded 3000 g m^{-2}. However, this may at least partly be explained by the lower rainfall and lower mean temperature that was registered in early spring 2018 (February-April), delaying the start of the growing season, and also by the differences in fertilisation between the years.

4.4. Effects of treatments on nutrient status and recovery in 2019

The generally higher concentrations of N, P, K and S for the fertilised treatments PK and PKS in comparison with UF (Tab. SM3) could be expected. In 2019, the comparably low N concentration range (0.85–2.3 %) in all plots might have been influenced by the drying of the samples at 105 °C before N determination. Nonetheless, it is surprising that no clear response in neither N concentration nor total N content was seen in PK or PKS at S2 after spring fertilisation (Tab. SM3, 5 and 6). Although PKS did not have higher N concentrations than PK, PKS was significantly separated from UF at both sampling occasion and PK only at S2. Although only significant for K and for Ca at S2, the trend was that most concentrations were higher in PKS than in PK. Despite the higher FW in PKS, no dilution effect could be seen. Together, this made PKS superior to the other treatments when both biomass production and nitrogen status is considered.

For K, the PKS treatment again generated the greatest response, since the total content of K in PKS was significantly higher than in both UF and PK for both sampling occasions. While the concentrations increased in both PK and PKS after spring fertilisation, PKS increased more, possibly because of a head start provided by the winter coverage with polyethylene shade net and/or the extra N27 given in August 2018. The Mn concentrations in PKS (130–200 μg g^{-1}) also tended to be higher than in

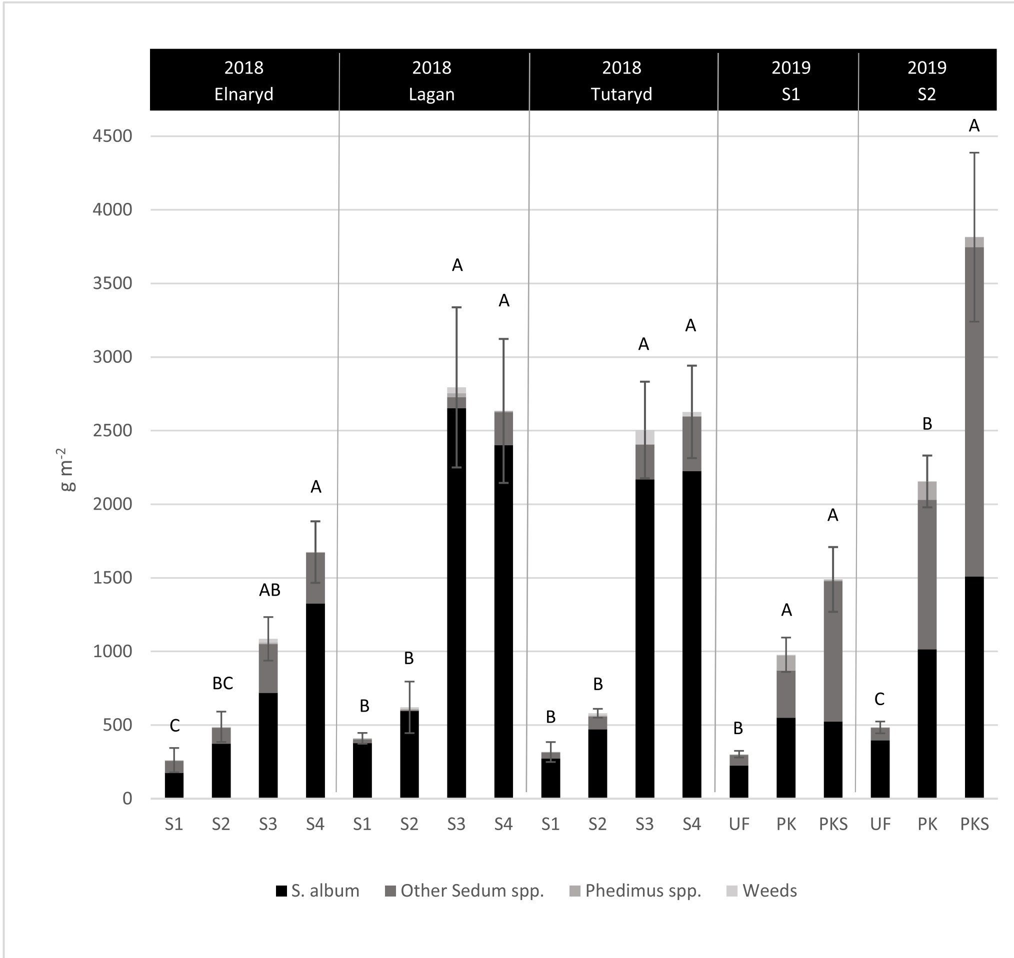

Fig. 2. Total mat FW (g m^{-2}), separated for *Sedum album*, other *Sedum* species, *Phedimus* spp. including *H. ewersii* and weeds as affected by site and sampling occasion (S1-S4) in 2018 and sampling occasion (S1-S2) and treatment in 2019. UF = unfertilised, PK = PK-fertiliser, PKS = PK-fertiliser + polyethylene shade net. Bars within the same site in 2018, and within the same sampling occasion at Elnaryd in 2019, that do not share a common letter differ significantly. Means ± SE, n = 3.

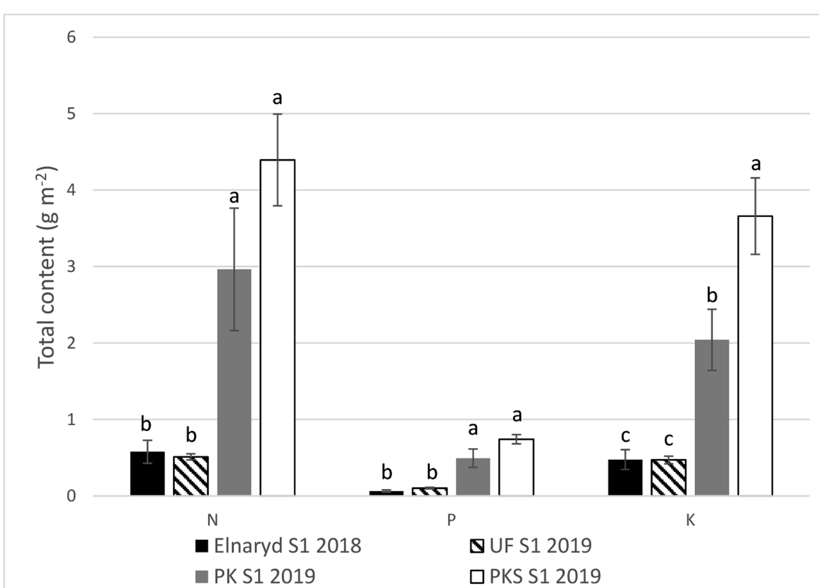

Fig. 3. Comparison between sampling occasion 1 both years, for total content of N, P and K, for Elnaryd 2018 and the three treatments (UF = unfertilised, PK = PK-fertiliser, PKS = PK-fertiliser + polyethylene shade net) of 2019. Bars that do not share a letter differ significantly. Means ± SE, n = 3.

PK (94–97 μg g^{-1}). Probably the shade net retained more moisture in the substrate, increasing the availability of Mn (Porter et al., 2004). On the contrary, the Mg concentrations, even lower than in 2018, were not higher in PKS than in the other treatments. It is possible that the elevated supply of K negatively affected the uptake of Mg.

Both of the efficiency of fertiliser use and potential nutrient loss can be estimated using the apparent recovery efficiency of added mineral nutrients (Fixen et al., 2015). As far as we know, this is the first estimation of apparent nutrient recovery during sedum mat production. As UF was established in August 2018, these plants had a shorter time for establishment and nutrient accumulation in comparison with PK and PKS, which were established in May 2018. Hence, the calculated recovery of 27–34 % for N, 10–20 % for P, and 15–40 % for K might be an overestimation of the actual recovery from the added fertilisers. It is interesting, however, to compare the apparent nutrient recovery for the PKS and PK treatments. For N-ARE, the slightly lower value for PKS than for PK at S1 (Table 5) could be due to the extra N added to PKS. In contrast, the somewhat higher N-ARE for PKS in comparison with PK at S2 was probably related to the markedly larger growth of PKS at this sampling occasion (Table 5, Fig. 2).

For P and K, the apparent nutrient recovery efficiency was approximately twice as high for PKS as for PK at both sampling occasions (Table 5). As the same amounts of both P and K had been added, we suggest that winter coverage was the most important reason for the greatly improved recovery of these nutrients for PKS in comparison with PK. While the growth-related shoot demand on P and K would be negatively affected at low temperature (Engels, 1993), effects of winter coverage on soil temperature and moisture during winter and spring could also have affected the rates of nutrient transport in the soil (Jungk and Claassen, 1989).

The environmental incentives not to recommend extra applications of conventional P fertiliser are strong, as increasing the P supply would mean an increased risk of leakage and eutrophication (Karczmarczyk et al., 2018; Clark and Zheng, 2014a; Mitchell et al., 2017). Malcolm et al. (2014) showed that P occurred in higher doses in the runoff water from green roofs than from other roofs. Clark and Zheng (2014a) as well as Mitchell et al. (2017) suggest that the P levels must be low at installation of the roofs to minimise the environmental impact.

4.5. Plant sap analyses

Plant sap analysis is economically advantageous compared to other types of analyses and generates results directly in field, enabling quick management decisions (Hochmuth, 1994). Hence, it was promising that clear correlations between plant sap and plant tissue concentrations could be found in 2018 for NO_3^- and K (Fig. 4). Similarly, Hochmuth (1994) showed clear N and K correlations between petiole sap and dry plant tissue concentrations for 11 vegetable crops. It should be noted that while plant sap normally is collected from the petioles only, the whole tip of the *S. album* shoot (ca 2.5 cm) was used in the present study.

For 2019, the outcome of K was similar to 2018 with a similar estimated linear equation. In contrast, the concentration of nitrate in the plant sap was very low in 2019 with a mean of < 300 ppm, compared to 1700 ppm the year before. The N concentration in the dry tissue was also

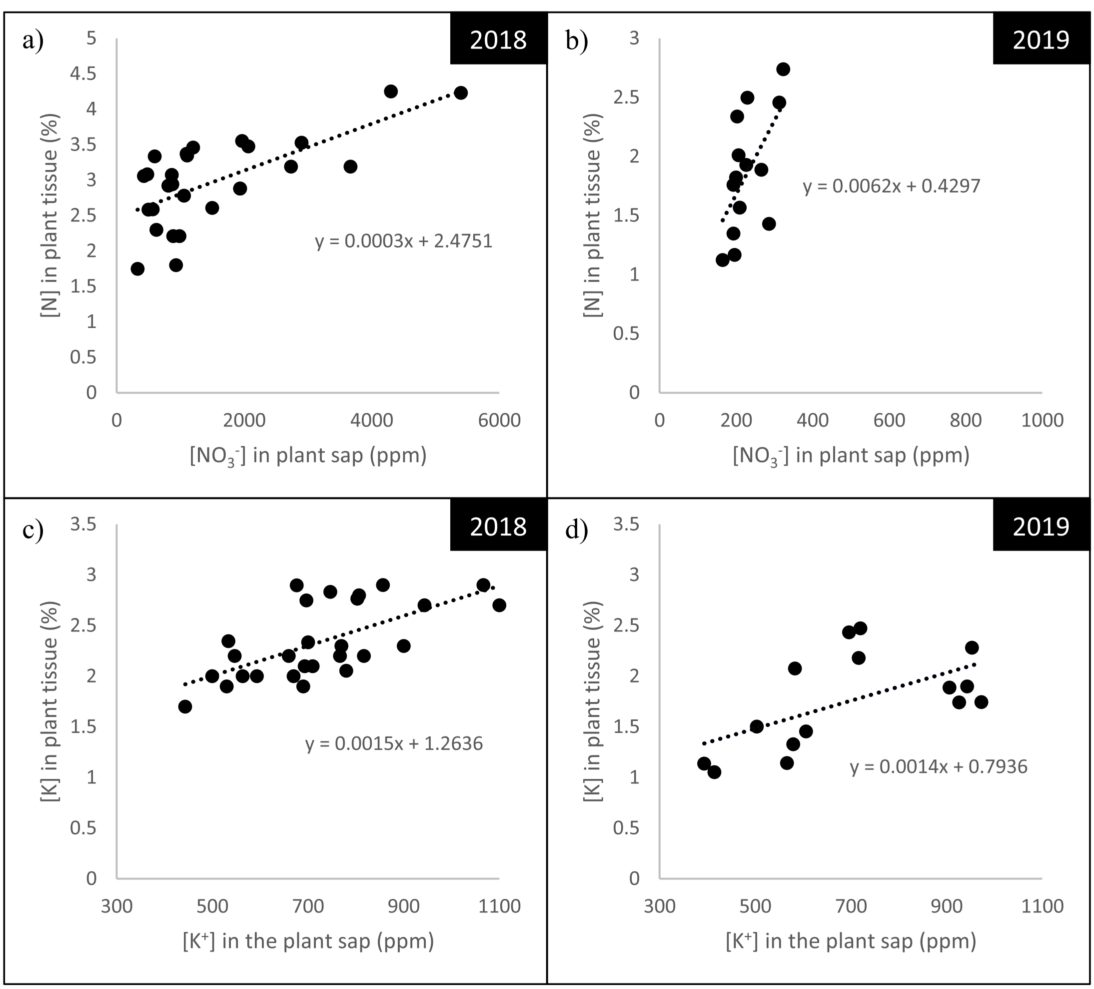

Fig. 4. The correlation between the concentration of N in dry plant tissue and NO_3^- in plant sap for 2018 (a) and for 2019 with one outlier removed (b) and K in plant tissue and K^+ in plant sap for 2018 (c) and 2019 (d).

a little lower the second year, but not to a comparable degree as the plant sap. One reason could be the higher rainfall and the higher spring temperature in 2019, leading to improved early-season plant growth (Fig. 2) and more dilute concentrations of limiting nutrients in the plant sap.

4.6. Conclusions

From the present study covering three separate production sites and two years, we conclude that there was a large variation in *Sedum album* mineral nutrient contents during early-phase pre-vegetated mat production. Our observation corroborates the large span in *Sedum* spp. concentrations reported in the literature. The uptake of NPK was relatively even throughout the season, suggesting that split fertiliser application or a constant supply by fertigation should correspond well with the nutrient requirements of the plants. Differences in plot management strategies including irrigation, fertilisation and cutting, as well as local variation in climate, might explain the large variation observed in growth between the three sites studied in 2018.

Our results indicate that winter coverage of sedum mats could be a promising method for improving growth as well as N, P and K recovery, reducing the risk of nutrient loss. However, further experiments on winter coverage, using replicate plots and controlled fertilisation, are needed to confirm our observations.

We also conclude that the use of plant sap analysis with hand-held equipment could be a tool for the development of a more requirement-oriented fertilisation strategy in the production of sedum mats. Further studies of the correlations between the concentrations of NO_3^- and K^+ in the plant sap and the N and K concentrations in the dry shoot tissue are needed to identify recommended plant sap values during the growing period.

CRediT authorship contribution statement

Camilla Oskarsson: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Lina Pettersson:** Writing – review & editing, Resources, Methodology, Funding acquisition, Conceptualization. **Helene Larsson Jönsson:** Writing – review & editing, Methodology. **Siri Caspersen:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Camilla Oskarsson reports financial support was provided by Veg Tech AB. Lina Pettersson reports a relationship with Veg Tech AB that includes: employment.

Data availability

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scienta.2024.113428.

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