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Kelp (*Laminaria digitata*) increases germination and affects rooting and plant vigour in crops and native plants from an arable grassland in the Outer Hebrides, Scotland

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Abstract Kelp and other seaweeds are traditionally used in many parts of the world as a soil amendment on arable fields. Seaweeds contain biochemical compounds that can act as plant growth regulators in terrestrial plants. In a low-intensity arable grassland in northwest Scotland an organic fertilizer, kelp (*Laminaria digitata*) has been used for hundreds of years, due to its anticipated positive effect as a soil conditioner and provider of plant nutrients. In this study the effects of kelp on germination and rooting of crops and native plants from this area were investigated in soil-free media. Germination was studied by incubation in the presence of kelp solutions. Rooting of plant cuttings was assessed after a pulse treatment with kelp solutions, and indole-3 acetic acid (IAA) as a reference plant growth regulator. Germination percentage of *Plantago lanceolata*, *Trifolium repens* and *Avena strigosa* seeds increased significantly when incubated with 0.05% kelp solutions. Total root weight and the individual weight of roots produced in cuttings of *Vigna radiata* and *P. lanceolata* were significantly increased when exposed to a 0.5% solution of kelp. Plant vigour, assessed visually, decreased significantly for *P. lanceolata* exposed to kelp at concentrations of 0.5 and 5.0% indicating the presence of a threshold level for an inhibitory effect of kelp at these concentrations, which may be due to high salinity. The results confirmed the presence of plant growth regulators in kelp, and indicates that amendment with kelp may potentially affect plant community composition. The threshold levels where some plants responded negatively to kelp amendment were close to or lower than the theoretical concentrations of kelp in soil water at field conditions with the current doses used on the machair, indicating that care should be taken in either administering kelp at the appropriate dose or leaching out salt before application.

Keywords Kelp · Seaweed · Plant growth regulators · Germination · Rooting · Machair

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Introduction

Kelp is used as a soil amendment in agriculture in many parts of the world (Chapman and Chapman 1980; López-Mosquera and Pazos 1997; Eyras et al. 2008), and is an inexpensive local resource in coastal agricultural areas. In the Outer Hebrides of northwest Scotland, partly degraded kelp has traditionally been spread on fields of fixed dune grassland known as 'machair' (Angus 2001), to increase soil organic matter, bind soil particles and provide plant nutrients. In recent decades, however, the labour intensive collection and spreading of kelp is being partly substituted with NPK fertilizer. About 80% of the machair is designated as Sites of Special Scientific Interest (Anonymous 1999), with the traditional low-intensity agriculture allowing native plants and wildlife to recover between cultivations. Governmental institutions, and also some of the local farmers, have questioned whether the substitution of kelp with synthetic fertilizer will be detrimental to the flora, fertility and soil stability of the machair. Application of kelp

to machair fields has little effect on soil microbiology and soil stability during a single cropping season (Thorsen et al. 2010). However, a positive effect on plant growth is possible, as kelp and other brown algae contain compounds similar or identical to plant growth hormones (Blunden et al. 1982; Finnie and Van Staden 1985; Crouch et al. 1992). Increased yield of tomatoes (Eyras et al. 2008), potatoes (López-Mosquera and Pazos 1997), carrot, lettuce, red beet, radish, oat and spinach (Greger et al. 2007) fertilized with seaweed has been reported, as well as improvement in root development in several species of plants following treatment of seedlings with a commercial formulation of kelp extract (Crouch and Van Staden 1991). Furthermore, red algae have been shown to increase seed germination in some plant species, but in contrast, composted seaweed may decrease seed germination in lettuce and radish (Greger et al. 2007). Crouch and Van Staden (1993) concluded that plant growth regulators in seaweed must be responsible for the effects on plant growth, as even at very low concentrations, impacts similar to the effect of indole-3 acetic acid (IAA) and other plant growth hormones were observed, and this has been confirmed by loss of the stimulatory effect upon ashing of seaweed (Finnie and Van Staden 1985).

This work investigated whether and how kelp affects seed germination and rooting in traditional crops and common native plants from the machair.

Materials and methods

Preparation of kelp and IAA treatments

Kelp was collected from the beach by Drimsdale in the Outer Hebrides (National Grid Reference NF 751375), soaked in water for 6 h to leach out salts, oven-dried at 70°C and ball milled to less than 0.250 mm particle diameter. In addition, kelp from the same beach, that had been left to decompose in a pile of several tonnes for approximately 4 weeks during the months of March and April on the machair was sub-sampled, dried and milled as described above. For the seed germination experiment this milled material was added to distilled water, autoclaved, and diluted to the equivalent of 0.05% by weight. Autoclaving has previously been shown to not affect the promoting effect of kelp on plant growth (Finnie and Van Staden 1985; Crouch and Van Staden 1991). For the rooting experiment, a dilution series of 5.0, 0.5, 0.05, 0.005 and 0.0005% solutions of fresh kelp only (not autoclaved) was prepared in distilled water, in addition to IAA solutions of 10^{-4}, 10^{-5}, 10^{-6} and 10^{-7} M. The osmotic potential of the kelp solutions used in the rooting experiment was measured at 20°C using a WP-4 Dewpoint PotentiaMeter (Deacon Devices Inc., Pullman, WA, USA). Furthermore, the concentrations of Na, P, S and K of milled fresh and degraded kelp were determined using ICP-MS.

Seed germination

The crop plants included in this study are traditionally used on the machair (Angus 2001): *Secale cereale* (rye), *Avena strigosa* (bristle oat), *Hordeum vulgare* (the traditionally used variety 'bere' barley, and also a non-traditional, modern cultivar optic barley), as well as *Lolium perenne* (perennial ryegrass) which is commonly used for undersowing on the machair. Native plants included in the experiment were the five most common plants of the characteristic machair vegetation (Angus 2001; after Dargie 1998): *Trifolium repens* (white clover), *Plantago lanceolata* (ribworth plantain), *Festuca rubra* (red fescue), *Galium verum* (lady's bedstraw) and *Ranunculus acris* (meadow buttercup).

The seed germination assay was as described by Cayuela et al. (2008). All seeds were soaked for 4 h in sterile distilled water. Crop seeds were sterilized by rinsing for 1 min in a 2% calcium hypochlorite solution, followed by several rinses in sterile distilled water. Weed seeds were not sterilized, as initial tests showed that this made the seed non-viable. The number of germinated seeds was recorded when one or more of the treatments had greater than 50% germinated seeds, for *G. verum* greater than 25%. Germination percentage of the seeds exposed to test solutions and a control with sterile distilled water was calculated based on four replicates of each treatment.

Plant rooting

The procedure for testing induction of plant rooting by kelp was modified from Crouch and Van Staden (1991), replacing the indole-3 butyric acid (IBA) with IAA as the reference plant growth regulator, because IAA is found in seaweed and seaweed products as opposed to IBA (Crouch and Van Staden 1993). The plants included in the experiment were *T. repens*, *P. lanceolata*, *L. perenne*, *S. cereale* and *Vigna radiata* (mung bean). The former four species were the only ones of the species used for the seed germination described above, that were practically suitable for the plant rooting experimental setup. *Vigna* was the genus used by Crouch and Van Staden (1991) in the original assay. The seeds were soaked in water for 4 h, placed in the surface of moist vermiculite in 8 cm deep trays, approximately 2 cm from each other. Seedlings were prepared by growing for 21 days (8 days for *V. radiata*) in a growth cabinet at 26°C, with 80% relative humidity and 24 h light. Cuttings of 7–15 cm length, dependent on species, were then taken from the tops of the seedlings. Test

solutions were placed in 15 ml centrifuge tubes and covered with Parafilm®, and the plant cuttings placed in holes pierced in the film, with 3 cm of the cutting immersed in the solution. Control tubes contained distilled water only. All combinations of test solutions and plant species were replicated eight times. After 6 h cuttings were rinsed briefly in tap water, transferred to tubes containing tap water only, and incubated again for 8 days, followed by counting of roots (root initials plus elongated roots) and measurement of root wet weight. Furthermore, the condition of the plant was arbitrarily rated, as a scoring of visual plant 'vigour' on a scale from 0 to 3, where the score 3 was given to a healthy plant (green and vigorous), 2 to a slightly unhealthy plant (green, but with some patches of brown, wilted tissue), 1 to an unhealthy plant (more than 50% brown, wilted tissue) and 0 if the plant was completely wilted.

Statistics

All data were analysed by one-way ANOVA using GenStat version 11.1 (Lawes Agricultural Trust, Rothamsted Experimental Station, UK).

Results

Seed germination

Germination of more than 50% occurred in one or more of the treatments after 1 day in *H. vulgare* (bere and optic), *S. cereale* and *T. repens*, after 2 days in *A. strigosa* and *L. perenne*, 3 days in *P. lanceolata* and 4 days in *F. rubra*, and more than 25% germination was observed after 8 days in *G. verum*. *R. acris* did not germinate in any of the treatments. Fresh and degraded kelp significantly increased seed germination in *A. strigosa* ($P<0.001$), *T. repens* ($P<0.05$) and *P. lanceolata* ($P<0.001$, Fig. 1). For *L. perenne*, degraded kelp significantly decreased germination ($P<0.01$) in comparison with fresh kelp and the control.

Plant vigour

The vigour of *V. radiata* cuttings was not affected by either IAA or kelp solutions, although there was a non-significant ($P=0.054$) indication that the highest concentration of IAA increased plant vigour relative to the two lowest concentrations (Fig. 2). Cuttings of *P. lanceolata* had significantly decreased vigour when exposed to 0.5 and 5.0% kelp solutions compared with the remaining kelp solutions and the control (Figs. 3 and 4), but were not affected by exposure to IAA. Plant vigour was significantly increased by 10^{-6} and 10^{-7} M IAA solutions in *L. perenne* ($P<0.001$) relative to 10^{-4} and 10^{-5} M IAA and the control (Fig. 5). Similarly, all kelp treatments increased the vigour of *L. perenne* ($P<0.001$), with the kelp concentrations of 0.0005 and 0.005% giving a significantly ($P<0.001$) higher vigour than the remaining kelp treatments. Plant vigour was not affected by any of the treatments in *T. repens* and *S. cereale* (Fig. 5).

Rooting of plants

Rooting occurred for all treatments in *V. radiata* and *P. lanceolata* (Figs. 2 and 3), but for the remaining species rooting was only observed infrequently and not in all treatments (Table 1).

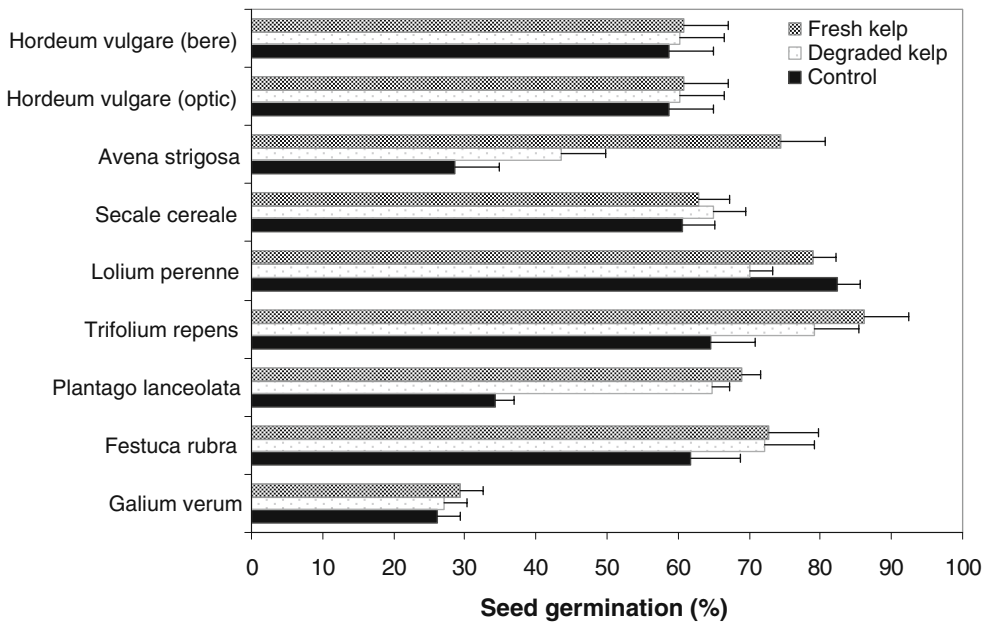

Fig. 1 Seed germination (%) of selected machair crops and native plants as affected by 0.05% kelp solutions. *Error bars* indicate standard error of differences of means

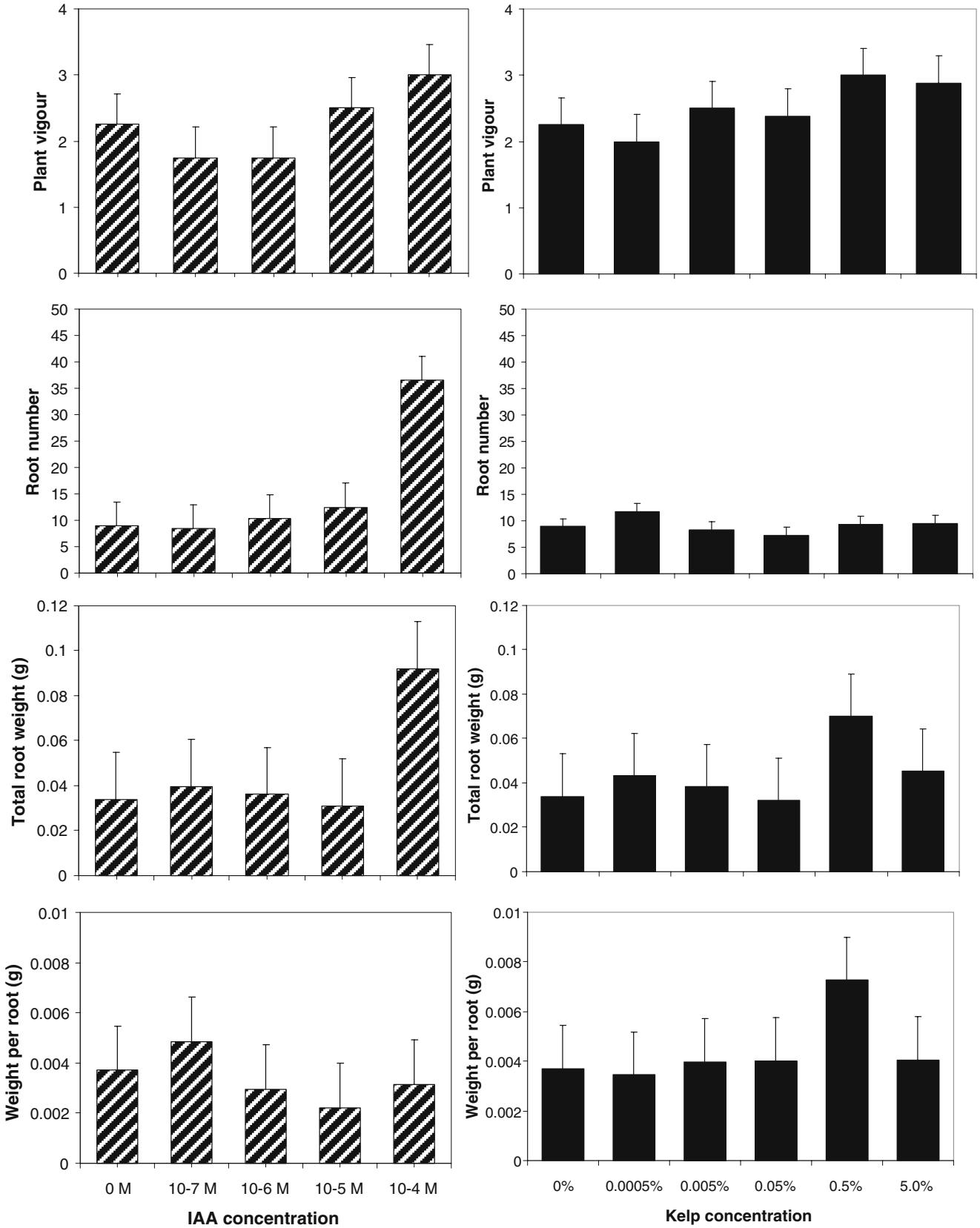

Fig. 2 The effect of IAA (*left*) and kelp concentration (*right*) on plant vigour, root number, total root wet weight and weight per root of *Vigna radiata* cuttings. *Error bars* indicate standard error of differences of means

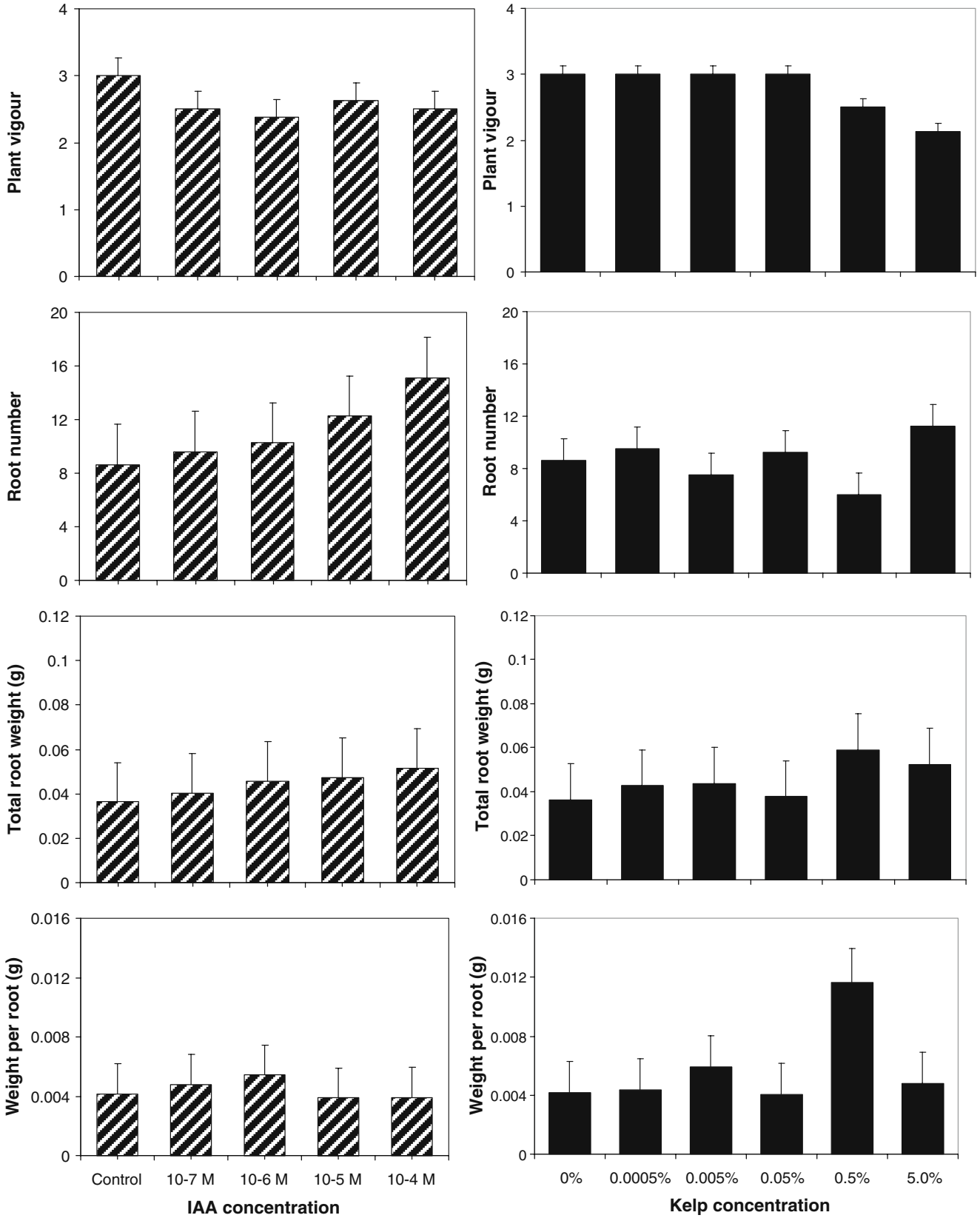

Fig. 3 The effect of IAA (*left*) and kelp concentration (*right*) on plant vigour, root number, total root wet weight and weight per root of *Plantago lanceolata* cuttings. *Error bars* indicate standard error of differences of means

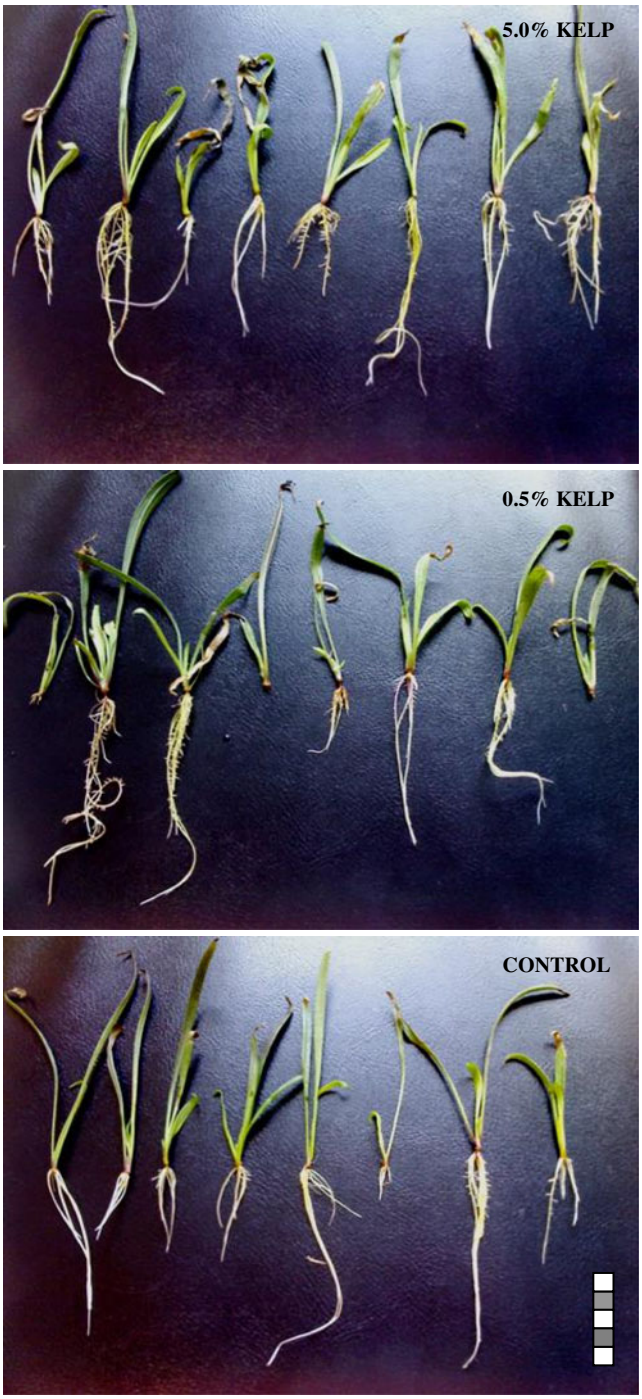

Fig. 4 Effect of kelp on rooting in *Plantago lanceolata*. The images show 8 replicate cuttings exposed to a pulse treatment of 5.0 and 0.5% kelp solutions, and a control. Note differences between treatments in root lengths, root branching and plant vigour. Scale bar is 5 cm

V. radiata cuttings treated with 10^{-4} M IAA had a significantly greater number of roots ($P<0.001$) and total root weight ($P<0.05$) than the remaining treatments and the control; however, this treatment had no effect on weight per root (Fig. 2). Exposing *V. radiata* to kelp had no effect on rooting (Fig. 2). In contrast, rooting in *P. lanceolata* cuttings was unaffected by IAA, but weight per root was significantly higher ($P<0.05$) in the 0.5% kelp treatment; however there were no significant differences between treatments with respect to root numbers (Figs. 3 and 4). Root development in the 0.5% kelp treatment was heterogeneous, and for both the 5.0 and 0.5% kelp treatments, the roots appeared longer and more branched than in the control treatment (Fig. 4).

Due to the small number of plant cuttings producing roots in *T. repens* and *S. cereale*, and the absence of rooting in *L. perenne* (Table 1), statistical analysis was not performed on these data. There was a trend for rooting in *S. cereale* to increase with IAA concentration, whereas roots were absent in the 0.5 and 5.0% kelp treatments (Table 1). Rooting was also absent in *T. repens* in the 0.5 and 5.0% kelp treatments, but there was no pattern in rooting otherwise (Table 1).

Elemental analysis of fresh and degraded kelp showed that Na was approximately 5 times lower in the degraded kelp compared to the fresh, soaked kelp (Table 2), with the concentrations corresponding to 0.09 and 0.49% in the dry matter, respectively. The P and S contents of the two materials were comparable, whereas the K content of the degraded kelp was approximately 29 times lower than in the fresh kelp. The osmotic potential of 5.0 and 0.5% fresh kelp solutions were −1.00 and −0.15 MPa, respectively (Table 2).

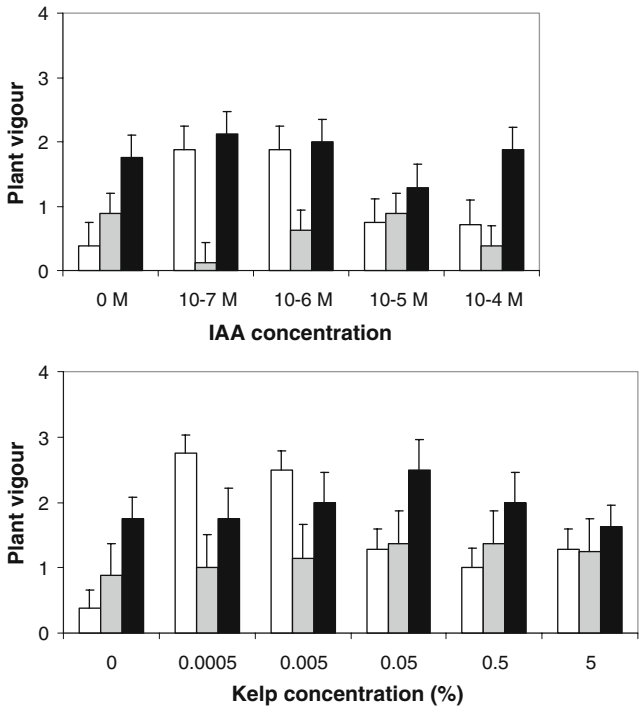

Fig. 5 The effect of IAA (*top*) and kelp concentration (*bottom*) on plant vigour of *Lolium perenne* (*white bars*), *Trifolium repens* (*grey dotted bars*) and *Secale cereale* (*black dotted bars*). *Error bars* indicate standard error of differences of means

Table 1 Occurrence of rooting in cuttings of *Lolium perenne*, *Trifolium repens* and *Secale cereale* for different concentrations of IAA and kelp

	% cuttings with roots									
	IAA (M)				Kelp (%)					Control
	10^{-7}	10^{-6}	10^{-5}	10^{-4}	0.0005	0.005	0.05	0.5	5.0	
Lolium perenne	0	0	0	0	0	0	0	0	0	0
Trifolium repens	12.5	0	12.5	0	12.5	0	12.5	0	0	12.5
Secale cereale	25.0	25.0	28.6	37.5	25.0	25.0	25.0	0	0	12.5

Discussion

The effects of kelp on seeds and plants

This study is, to the best of the authors' knowledge, the first to demonstrate an effect of kelp on seed germination and on rooting of crops and native plants from an agricultural system in northwest Scotland where kelp is currently used as a soil amendment.

Kelp contains compounds that can induce plant growth (Crouch and Van Staden 1993). In particular, the presence of cytokinins, gibberellins and/or betaines in kelp is likely to have caused the increase in germination in *P. lanceolata*, *T. repens* and *A. strigosa*. Cytokinin-like compounds and gibberellins have been detected in the commercial kelp extract Kelpak 66 (Finnie and Van Staden 1985) and betaines in species of the brown algae order Laminariales (Blunden et al. 1982). Any of these groups of compounds could be responsible for the enhancement of seed germination in the present experiment. Gibberellins are required for breaking dormancy in some *Ranunculus* species, and can increase germination substantially in *R. acris* (Williams 1983). As *R. acris* did not germinate in the present experiment, it may be that cytokinin-like substances and/or betaines, not gibberellins, caused the increased germination in the remaining species tested.

The stimulus required for induction of seed germination varies between plant species, as germination of some seeds is physically inhibited by the structure of the seed coat but has a non-dormant embryo, whereas in other species germination is inhibited by the embryo itself being dormant (Bewley 1997). The lack of effect of kelp on germination in *S. cereale*, *F. rubra*, *H. vulgare* (bere and optic) and *G. verum* may indicate that they are of the former type, and that these plant species do not require exposure to growth regulators to induce germination.

The decrease in plant vigour seen in *P. lanceolata* and *L. perenne* with increasing kelp concentration could be due to salt, as the osmotic potential of the 5.0 and 0.5% kelp solutions was sufficiently high to cause severe salt stress in plants. However, the Na concentration in the kelp material used here was lower than the 2.78% Na in kelp used by Temple and Bomke (1988). A detrimental effect of high plant growth regulator concentrations, however, could also have played a role, as significantly decreased plant vigour was also observed with increasing IAA concentration in *L. perenne*.

The induction of rooting in *V. radiata* and *P. lanceolata* by the kelp treatments could be due to presence of auxins, or auxin-like compounds other than IAA. Although Hess (1961) concluded that the mung bean root assay is insensitive to IAA, there were significant responses in rooting parameters to the IAA treatment in the present work. However the pattern of plant responses to IAA was different to that of kelp (Figs. 2 and 3), suggesting that a different growth regulator may be responsible for the effect of kelp, or possibly an interference with polysaccharides in kelp, as sugars are known to affect plant growth in a way similar to hormones (Rolland et al. 2002). Zeatin is another candidate for induction of rooting in plants by kelp (Finnie and Van Staden 1985), which is likely to be the explanation in the present case, as this compound could also be responsible for the induction of seed germination observed here. The differences in response to IAA versus kelp could also be due to differences in growth regulator concentration, or interactions between IAA and other growth regulators in kelp.

Abscisic acid (ABA) inhibits root development, and is found in kelp (Crouch and Van Staden 1993). If ABA was present in kelp solutions used here, the inhibiting effect on rooting must have been weaker than the promoting effect of auxins and/or zeatins, as none of the rooting parameters

Table 2 Elemental analysis and osmotic potential of fresh and degraded kelp

	Elemental composition (mg/g dry weight)				Osmotic potential of kelp solutions (MPa)	
	Na	P	S	K	5.0%	0.50%
Fresh kelp	4.9242	0.6500	3.4922	35.2851	−1.00	−0.15
Degraded kelp	0.9418	0.7419	5.1894	1.1968		

were significantly decreased in the kelp treatments compared with the control.

Management implications of effects of kelp on plants

As kelp increased germination of one crop and two native plant species from the machair, it can be hypothesised that abandoning the use of kelp in favour of synthetic fertilizers on machair fields would negatively affect plant numbers of those species through decreased reproduction rate. Such an effect could furthermore be magnified through competition between plant species, leading to changes in the plant community composition (Connell and Slatyer 1977). However, since plant growth regulators are effective even in very low concentrations as used here, the amount of kelp used is probably not crucial for the effect on seed germination. Therefore decreasing rather than abandoning the use of kelp is unlikely to have severe effects on plant community composition. The concentration of kelp that machair crop and native plant seed are exposed to in soil water is approximately 0.53% by weight, when estimating use at a rate of 338 g kelp/m^2 (Thorsen et al. 2010), a ploughing depth of 25 cm, soil bulk density of 1.3 g/cm^3 and soil water content at field capacity of 19.7%. However, farmers who do not supplement the kelp amendment with synthetic NPK fertilizer use about 676 g kelp/m^2. Furthermore, soil water contents may be less than 10% during dry spells (Thorsen et al. 2010). Kelp applied at 676 g/m^2 combined with a soil water content of 10% could result in kelp concentrations of up to 2.1% (dry weight) in soil water. The results in this study show that the latter is close to a critical level for some plant species. However, kelp is often unevenly distributed in the soil as it is ploughed in with a mouldboard, so locally in the soil concentrations could be both higher or lower than the values calculated above.

This study also showed that the degradation stage of the kelp used for soil amendment may be important for the induction of seed germination in some plant species, as fresh and degraded kelp gave different responses in germination percentage in *A. strigosa* and *L. perenne*. In contrast, Eyras et al. (2008) found that seaweed compost matured for up to 20 months had a significantly positive effect on tomato yield, which together with the present results for seed germination for *T. repens* and *P. lanceolata* suggest that the effect of some of the plant growth regulators in seaweed may be preserved even when the seaweed is partly degraded. As mentioned before, sugars in kelp may be responsible for some of the effect on plant growth (Rolland et al. 2002), and these may be modified or lost during degradation.

Crouch and Van Staden (1993) suggested that the beneficial effect of kelp is possibly enhanced by supplementing with synthetic NPK fertilizer, which as mentioned above is now becoming common practice on the machair.

The previously reported adverse effects of seaweed amendments on crops above a threshold level (Temple and Bomke 1988; Crouch and Van Staden 1991; Parsons et al. 2001) was confirmed in the present study, but only for some plant species, and with varying threshold concentrations. An important implication of this observation is that because of species differences in tolerance to kelp, overdosing kelp can potentially cause shifts in the machair plant community composition, analogous to the differences in response in germination percentage between species. Consideration of the effect of salt stress may be needed, as the practice of allowing kelp to degrade with salt leaching by rainfall is not universal in agricultural systems that apply kelp to fields (Chapman and Chapman 1980).

As the rooting assay used in the present study relied on plant cuttings in soil-free media, it cannot be excluded that in a field situation kelp could have an effect on *T. repens*, *L. perenne* and *S. cereale*, as well as other crops and native plants.

Conclusions

Kelp improved seed germination in some crops and native plants of the machair. Abandoning the use of kelp on the machair could therefore potentially lead to a change in plant community composition through selective pressure.

A positive effect of kelp on rooting was only seen when exposing plant cuttings to a 0.5% kelp solution, however this concentration and higher had a negative effect on plant vigour in some species, which coincided with high salinity of the solutions. In conclusion, application of kelp at appropriate rates and leaching of salts before application is crucial in order to obtain optimal beneficial effect on rooting. The above results show that kelp can be an inexpensive, organic alternative or supplement to synthetic NPK fertilizers in coastal areas, acting by increasing plant rooting and germination, in addition to its known benefits of providing organic matter and nutrients to the soil.

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