EFFECTS OF FOLIAR NUTRIENT AND BIOSTIMULANT APPLICATIONS AND SOIL MOISTURE AND NUTRIENT STATUS ON ESTABLISHMENT OF NEWLY-LAID SOD OF *ZOYSIA* SPP.

Donald S. Loch* and Yi Zhou

ABSTRACT

Zoysiagrasses (*Z. japonica* Steud., *Z. matrella* (L.) Merr. and *Z. pacifica* (Goudswaard) M. Hotta & S. Kuroki, plus some interspecific hybrids) have many positive attributes as low maintenance, slow-growing warm-season turfgrasses once established, producing high quality turf with low nutrient inputs and requiring less frequent mowing than alternative turfgrass species. During establishment, however, their slow growth is seen as their major weakness. Five short-term pot experiments to simulate the laying of vegetative zoysiagrass (*Z. matrella*, *Z. japonica*) sod onto a bare soil base were conducted in glasshouses in Brisbane, Australia (27°30'S, 153°01'E), maintaining moisture in the turf sod and growing medium via capillary watering from below. This avoided the need for heavy overhead watering, thus enabling the effects of foliar nutrient and biostimulant treatments to be considered without being complicated by leaching into the sod and underlay medium. The artificial sand-peatmoss (or coir) growing media were strongly acid (pH 4.5-5.3) and low to very low in terms of sufficiency levels of N, P and K, and most other major and minor nutrients. Despite this, root development under newly-laid zoysiagrass sod and the partitioning of dry matter production into root rather than shoot growth were enhanced by maintaining low soil fertility and not applying fertiliser at establishment None of the foliar nutrient (high N, P or K) or biostimulant treatments (kelp or microbial supplementation) made during the first 21 days resulted in a positive response in terms of root development in the first 6 weeks of establishment. Growth increased with temperatures, leading to higher dry matter production but with reduced partitioning of this into roots. Drying out of zoysiagrass sod prior to laying did not disproportionately affect subsequent root development, and had relatively little effect on final establishment for the first 2 days of drying out. However, it also appears that the maintenance of good sod and soil moisture is of paramount importance during early establishment to protect delicate new root growth once this has been initiated.

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Abbreviations: MAP, monoammonium phosphate; DAP, days after planting; LSDs, Least Significant Differences; QLD, Queensland; NSW, New South Wales; DTPA, diethylenetriaminepentaacetic acid

Keywords: Australia, biostimulants, establishment, foliar nutrients, soil moisture, turf sod, *Zoysia matrella*, *Zoysia japonica*, *Zoysia* spp., zoysiagrass

INTRODUCTION

The genus *Zoysia* Willd. comprises some 10 or 11 recognised species indigenous to the western Pacific rim and Indian Ocean, of which three species – *Z. japonica* Steud., *Z. matrella* (L.) Merr. and *Z. pacifica* (Goudswaard) M. Hotta & S. Kuroki (previously referred to as *Z. tenuifolia*) – plus some interspecific hybrids have a long history of commercial use as warm-season perennial turfgrasses in many countries (Engelke and Anderson, 2003; Tsuruta et al., 2011). Although each of these species has its own common name, collectively they are usually referred to as "zoysiagrasses", which is the common name adopted in this paper.

The zoysiagrasses have a number of positive attributes as low maintenance turfgrasses once established: high turf quality, low nutrient requirements, high wear resistance (but slow recovery), good pest resistance, tolerance to a wide range of selective grass and broadleaf herbicides, and lower mowing frequencies and less encroachment due to their slower growth relative to other grasses (Murray and Morris, 1988; Dunn, 1991; Carroll et al., 1997; Fresenburg, 1997; Higgins, 1998; Murphy et al., 2004; Patton and Reicher, 2007; Brosnan and Deputy, 2008; Fry et al., 2008). During establishment, however, their slow growth rate becomes a distinct disadvantage. Sod production cycles are longer than for *Cynodon dactylon* (L.) Pers. (bermudagrass), for example, thus making the harvested turf sod more expensive to the end user. This has led to breeding programmes to produce zoysiagrass varieties with faster stolon growth rates (Okeyo et al., 2011), as well as a considerable body of research aimed at optimising cheaper vegetative planting methods as alternatives to turfing with solid sod (e.g. Richardson and Boyd, 2001; Stiglbauer et al., 2009; Sladek et al., 2011). These include sprigging, plugging and strip sodding, all of which require grow-in time to reach full ground coverage. Many of these studies are also equally applicable to the production of saleable sod.

Such studies, however, are not directly applicable to the establishment of fully turfed areas after laying vegetative sod. In this case, stolon extension rates are not relevant; rather, it is the development of a strong root system – a combination of maximising rooting depth and numbers (or mass) of roots – in the underlay medium that is the key to achieving rapid early establishment. Given the time limitations on the watering of new lawns that have been introduced in many places, this is also vital in terms of reaching the point at which the frequency of watering can be reduced. In this paper, we report the result of glasshouse pot experiments to investigate the effects of foliar nutrient and biostimulant treatments, soil fertility, and sod moisture status on root development from newly laid zoysiagrass sod.

MATERIALS AND METHODS

Five short-term pot experiments to simulate the laying of vegetative turf sod onto a bare soil base were conducted in glasshouses at The University of Queensland (27°30'S, 153°01'E) in Brisbane, Australia. In each of these, the ANOVA Twinpot Water Management System (Anova Solutions Pty Ltd, Brisbane, QLD, Australia) was used to maintain moisture in the turf sod and growing medium via capillary watering from the reservoir in the base of the outer pot (ANOVA Solutions, 2010; see Figure 1). This prevented the leaching of foliar nutrient and biostimulant treatments in Experiments One, Two and Four into the sod and the growing medium below that by heavy overhead watering.

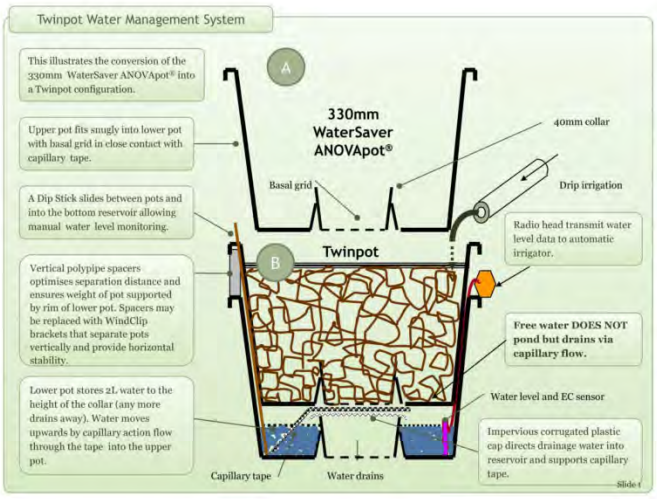

Figure 1. Cross-sectional diagram illustrating principles of the ANOVA Twinpot Water Management System (Source: ANOVA Solutions 2010).

Each experimental unit consisted of two 200 mm diameter ANOVA Pots®, the inner one filled with a free-draining 50/50 mix of medium-coarse sand and coir (Experiment One) or medium-coarse sand and peatmoss (Experiments Two, Three, Four and Five), in each case without any added fertiliser, to approximately 40 mm below the top of the pot; a 200 mm diameter circle of vegetative sod cut from standard commercial rolls of turf was then laid on top. The outer pot had a protruding 50 X 50 mm section of polypipe cemented inside around the patented central basal grid, enabling water to be captured and held as a reservoir in this space. Capillary tape inserted into the reservoir and over a piece of impervious plastic sheet covering the reservoir exit via the central polypipe fed water through the basal grid of the inner pot to water the growing medium and vegetative turf sod from below.

The inner pots were prepared by filling them with growing medium and watering well 4 days before the start of each experiment. In experiments One, Two and Three, a low-P granular mixed fertiliser (N:P:K:S = 15.4:3.0:11.0:15.4) was broadcast onto the surface of the underlay medium at a rate of 100 kg N/ha before laying a circle of turf sod directly on top of this; in Experiments Four and Five, the placement and rate of establishment fertiliser was varied as described later. After laying the circle of turf sod and filling around the edge with growing medium, each pot was thoroughly wetted through with 400 ml of water. Throughout the experimental periods, the basal reservoirs in the outer pots were topped up regularly.

For each experiment, a spare control pot was prepared and used to monitor environmental conditions using miniature Thermochron data logger buttons (OnSolution Pty Ltd, Sydney, NSW, Australia). Air temperature and relative humidity at the surface of the grass canopy and soil temperature at 10 cm depth were recorded at hourly intervals throughout the experimental periods.

Counts were made of numbers of visible roots at 10 cm depth and the maximum visible root depth was measured for each pot 16 days after planting (DAP). In Experiment One, additional root counts were also made at 23 DAP. A destructive harvest, together with root washing, was made 40-44 DAP to determine the dry weights of new shoots above the original sod leaf level, and roots below the original sod. All harvested samples were dried at 60°C.

Data from each experiment were analysed through GenStat Release 12.1 for Windows (VSN International Ltd, Hemel Hempstead, UK) using standard Analysis of Variance procedures, which also generated Fisher's protected Least Significant Differences (LSDs) for comparison of treatment means.

Experiment One. Experiment One ran from 3 Aug (planting) to 16 Sep 2010 (final harvest) and was a randomised block design with 10 replications. Pots prepared as described above and planted with sod of *Z. matrella* 'A-1' were randomly allocated to the following five treatments applied by misting the leaf canopy:

1. *Control* - water only;
2. *High N* - high N soluble fertiliser (Sure Flow™ Grow) at 10 g/L;
3. *Kelp* - Seaweed extract (Auto-Kelp ™ 350) at 10 ml/L;
4. *Kelp + Fert* - soluble fertiliser + seaweed extract (i.e. treatments 2 and 3 combined); and
5. *Microbes* - microbial inoculants (Noculate™ Liquid) at 10 ml/L.

The nutrient contents of all products used to apply treatments in Experiments One and Two are summarised in Table 1. Auto-Kelp™ 350 (since discontinued) was a proprietary product from Barmac Industries Pty Ltd (Ipswich, QLD, Australia) containing 350g/L Sargassum kelp extract. Noculate™ Liquid is a microbial inoculant containing 6 *Bacillus* spp. (24 strains), a *Trichoderma* sp. (4 strains), humic acid, kelp, vitamins derived from yeasts, amino acids, biotin, folic acid and natural sugars (Barmac Industries, 2012).

Table 1. Nutrient analysis of fertiliser and biostimulant products used in Experiments One and Two.

Product	Analysis					
	% N	% P	% K	% S	% Mg	Micronutrients‡
Sure Flow™ Grow†	23.0	6.0	17.0	0.7	0.5	+
Sure Flow™ Ripen & Harvest†	12.0	3.0	32.3	3.3	1.0	+
MAP (fertiliser grade)	10.0	21.9	0.0	1.5	0.0	-
Auto-Kelp™ 350†	0.0	2.0	8.0	0.0	0.0	-
Noculate™ Liquid†	0.0	0.0	0.0	0.0	0.0	-

† Proprietary products from Barmac Industries (Ipswich, QLD, Australia).
‡ Micronutrients included Fe, Mn, Cu, Zn, B, Mo.

Treatments 1-4 were applied three times per week for the first 22 DAP by misting the leaf canopy of the designated pots to run off. Treatment 5 was applied three times 1, 3 and 15 DAP, watering in each time with 200 ml water. On all non-treatment days for the first 22 DAP, pots were misted once with water to wet the leaves to run off. From 23 DAP onwards, all pots in the experiment were watered only by capillary action from the reservoir in the base of the outer pot.

Experiment Two. Experiment Two ran from 9 Jan (planting) to 20 Feb 2012 (final harvest) and was a split-plot design with five overall replications. The main plots were planted to two different zoysiagrass cultivars, *Z. matrella* 'A-1' and *Z. japonica* 'Z-3'. Within each main plot, pots prepared as described previously and planted with sod of the designated zoysiagrass cultivar were randomly allocated to the following five treatments applied by misting the leaf canopy:

1. *Control* - water only;
2. *High N* - high N soluble fertiliser (Sure Flow™ Grow) at 10 g/L;
3. *High P* – high P soluble fertiliser (soluble monoammonium phosphate [MAP]) at 10 g/L;
4. *High K* – high K soluble fertiliser (Sure Flow™ Ripen & Harvest) at 10 g/L; and
5. *Kelp* - seaweed extract (Auto-Kelp™ 350) at 10 ml/L.

All treatments were applied three times per week for the first 22 DAP by misting the leaf canopy of the designated pots to run off. On all non-treatment days for the first 22 DAP, pots were misted once with water to wet the leaves to run off. From 23 DAP onwards, all pots in the experiment were watered only by capillary action from the reservoir in the base of the outer pot.

Experiment Three. Experiment Three ran from 8-12 Feb (first planting) to 19-23 Mar 2012 (final dry matter harvest) and was a randomised block design with eight replications. Pots prepared as described above were randomly allocated to the following six treatments and planted progressively with sod of *Z. matrella* 'A-1' to give the following treatments and codes:

1. *Day 0 (Leaf)* - laid on same day as sod was cut, stored leafy side up (Control);
2. *Day 1 (Leaf)* - laid 1 day after sod was cut, stored leafy side up;
3. *Day 2 (Leaf)* - laid 2 days after sod was cut, stored leafy side up;
4. *Day 2 (Soil)* - laid 2 days after sod was cut, stored soil side up (leafy side down);
5. *Day 3 (Leaf)* - laid 3 days after sod was cut, stored leafy side up; and
6. *Day 4 (Leaf)* - laid 4 days after sod was cut, stored leafy side up.

Turf sod freshly harvested on 8 Feb 2012 was held on a layer of soil in the glasshouse to eliminate the risk of rain, so that treatments 2-6 could be planted progressively over the next 4 days. Similarly, counts of root numbers, measurements of root depth and the final destructive dry matter harvest were also made progressively so that comparisons among treatments could be made at exactly the same numbers of days after planting.

A Thermochron temperature data logger was inserted at the leaf surface of the held sod to determine the temperature conditions prior to planting. As each treatment was planted, two samples of sod were taken, separated into above ground material (i.e. thatch + leaf) and soil, and dried at 60°C to quantify the decline in moisture content over the 4-day planting period.

Immediately prior to planting, the dried circles of turf sod were soaked for a short period in water to re-wet them fully. The experiment was misted with water to run off once per day for the first 22 DAP, after which all pots in the experiment were watered only by capillary action from the reservoir in the base of the outer pot.

Experiment Four. Experiment Four ran from 4 Jul (planting) to 16 Aug 2012 (final harvest) and was a 3 X 2 factorial design (fertiliser X kelp) with five replications. Pots prepared as described above and planted with sod of *Z. matrella* 'A-1' were randomly allocated to the following fertiliser and kelp treatments in factorial combination.

UNDERLAY FERTILISER:

1. *No Fertiliser* – none applied;
2. *Contact Fertiliser* - low-P granular fertiliser (N:P:K:S = 15.4:3.0:11.0:15.4) broadcast at a rate of 100 kg N/ha onto the surface of the underlay medium in contact with the sod; and
3. *Buried Fertiliser* - low-P granular fertiliser (N:P:K:S = 15.4:3.0:11.0:15.4) covered by ~1 cm of underlay medium after broadcasting at a rate of 100 kg N/ha.

KELP:

1. Control (water only); and
2. Seaweed extract (Auto-Kelp™ 350) at 10 ml/L.

The two kelp treatments were applied three times per week for the first 22 DAP by misting the leaf canopy of the designated pots to run off. On all non-treatment days for the first 22 DAP, pots were misted once with water to wet the leaves to run off. From 23 DAP onwards, all pots in the experiment were watered only by capillary action from the reservoir in the base of the outer pot.

Experiment Five. Experiment Five ran from 20 Aug (planting) to 2 Oct 2012 (final harvest) and was a randomised block design with five replications. Pots prepared as described above and planted with sod of *Z. matrella* 'A-1' were randomly allocated to the following five treatments.

1. *No Fertiliser* – none applied;
2. *Pre 50N* - 50 kg N/ha applied at planting in a low-P granular mixed fertiliser (N:P:K:S = 15.4:3.0:11.0:15.4) and covered by ~1 cm of underlay medium;
3. *Pre 100N* - 100 kg N/ha applied at planting in a low-P granular mixed fertiliser (N:P:K:S = 15.4:3.0:11.0:15.4) and covered by ~1 cm of underlay medium;
4. *Post 50N* - 50 kg N/ha applied 21 DAP as soluble fertiliser (Sure Flow™ Grow – see Table 1); and
5. *Post 100N* - 100 kg N/ha applied 21 DAP as soluble fertiliser (Sure Flow™ Grow).

All treatments were misted daily with water for the first 20 DAP to wet the leaves to run off. Treatments 4 and 5 were applied in solution 21 DAP at 100 ml/pot and washed in by a further 100 ml/pot of water. From 22 DAP onwards, all pots in the experiment were watered only by capillary action from the reservoir in the base of the outer pot.

RESULTS

Analysis of Underlay Growing Media. Table 2 shows soil nutrient analyses of the sand-peatmoss media used in Experiments Four and Five. Both were strongly acid with very low cation exchange capacity (CEC), and very low or low levels of N, P, K and most other nutrients with the exception of Mg, Zn and Mn.

Climatic Environment for Experiments. Table 3 shows the temperature and humidity regimes across all five experiments. Experiments Two and Three (summer and late summer-autumn, respectively) were conducted under warmer and more humid conditions than Experiments One, Four and Five (late winter-spring). Mean daily temperatures during Experiments Two and Three were 2-5°C (air) and 4-6°C (soil) higher than for Experiments One, Four and Five, which received the benefit of glasshouse heating. Despite this, differences in mean minimum temperatures were even more pronounced: 8-9°C in the air and 6-8°C in the soil. Relative humidity throughout Experiments Two and Three was 18-23% higher than for Experiments One, Four and Five.

Experiment One. Analysis of variance on the data from Experiment One showed highly significant and very highly significant differences across blocks (Table 4). Specifically, root and shoot growth in Block 10 was greatly reduced compared with means for each of the other nine blocks. The pots in Blocks 1-9 were filled and pre-watered 5 days before planting, while Block 10 was filled from the same batch of growing medium on the day of planting as additional glasshouse space became available. Although these last pots were well watered before planting, it became apparent towards the end of the first week after planting that bottom watering through capillary action was not working effectively such that the pots in Block 10 were drying out and so had to be re-watered heavily from the top. No further problems were observed with capillary watering thereafter, but the effect on turf growth in Block 10 persisted through to the end of the experiment. While data from Block 10 were therefore excluded from the results (re-analysed for Blocks 1-9) presented in Figures 2 and 3, possible reasons for this failure are discussed later in the context of optimising establishment practices.

Maximum root depth 16 DAP averaged 11.0 cm and was not significantly different across all treatments (10.2-11.6 cm). Root numbers, however, were significantly lower in treatment 5 (microbes) 16 DAP; and by 23 DAP treatments 2-5 all had significantly lower root numbers than the Control

Table 2. Nutrient status of sand-peatmoss underlay media (Experiments Four and Five).

Soil attribute	Analytical method†	Experiment		Sufficiency rating‡
		4	5	
pH	1:5 water	5.3	4.5	
Organic matter (%)	Organic carbon	2.2	2.3	Medium
NO_3-N (mg/kg)	1:5 water extract, colorimetric	<1	<1	Very low
P (mg/kg)	Olsen	3	5	Very low-Low
	Colwell (bicarbonate-extractable P)	8	16	Very low-Low
S (mg/kg)	Calcium phosphate extraction	7	8	Low
K (meq/100g)	Ammonium acetate extraction	0.07	0.06	Very low
Mg (meq/100g)	Ammonium acetate extraction	1.20	0.82	Medium-Low
Ca (meq/100g)	Ammonium acetate extraction	2.90	1.75	Low-Very low
CEC (meq/100g)	Ammonium acetate extraction	4.4	2.9	Very low
Cu (mg/kg)	DTPA§ extraction	<0.1	<0.1	Very low
Zn (mg/kg)	DTPA extraction	1.9	4.7	Medium
Fe (mg/kg)	DTPA extraction	70	34	
Mn (mg/kg)	DTPA extraction	5.9	2.7	Medium
B (mg/kg)	Calcium chloride extraction	<0.1	<0.1	Very low

† See Rayment and Lyons (2011) for details of methodology used

‡ After Metson (1961), Rayment & Bruce (1984), Hazleton and Murphy (2007), Rayment and Lyons (2011)

§ Diethylenetriaminepentaacetic acid

Table 3. Mean temperature and relative humidity conditions for all experiments, with mean maximums and minimums for each period shown in brackets.

Experiment	Experimental period	Temperature (°C)		Relative humidity (%)
		Air	Soil	
1	3 Aug – 16 Sep 2010	26.7 (14.5-38.9)	23.1 (16.8-29.3)	63.5 (35.3-91.7)
2	9 Jan – 20 Feb 2012	30.7 (23.0-37.8)	28.9 (24.2-33.7)	81.5 (64.2-98.8)
3	8 Feb – 19 Mar 2012	28.7 (22.5-34.9)	27.3 (22.9-31.7)	86.9 (72.9-100.0)
4	4 Jul – 16 Aug 2012	25.8 (19.4-32.5)	22.3 (19.3-25.3)	58.6 (40.5-76.7)
5	20 Aug – 2 Oct 2012	25.2 (20.2-30.2)	23.0 (20.9-25.2)	68.5 (51.4-85.7)

Table 4. Summary of block effects and differences from analysis of variance conducted on Experiment One data.

Attribute	Blocks 1-9		Block 10	Probability
	Mean	Range		
Maximum root depth (cm) (16 DAP)	11.0	10.2-12.3	2.4	P<0.001
Root nos. per pot at 10 cm depth (16 DAP)	4.7	3.0-6.8	0.2	P<0.01
Root nos. per pot at 10 cm depth (23 DAP)	14.4	8.6-21.4	2.0	P<0.01
Tops DM (g/pot)	7.22	6.08-8.92	2.01	P<0.001
Roots DM (g/pot)	1.66	1.41-1.99	0.79	P<0.001
Total DM (g/pot)	8.88	7.49-10.54	2.80	P<0.001

treatment 1 (Figure 2). Root and shoot weights from treatment 5 were also significantly lower than the Control when harvested 44 DAP, though the proportions of root and shoot were not significantly affected (Figure 3). While treatment 3 (kelp) did not increase root dry weight over the Control treatment, it significantly reduced the amount of top growth which resulted in an apparent increase in the proportion of roots. Treatment 2 (high N soluble fertiliser) gave a significant reduction in root weight, but the weight of top growth was not significantly different from the Control treatment. Treatment 4 (fertiliser + kelp) led to a significant reduction in root dry matter, and to an apparent increase in the proportion of tops despite a large but non-significant reduction in dry matter yield. Overall, the Control treatment performed better than any of the nutrient or biostimulant treatments.

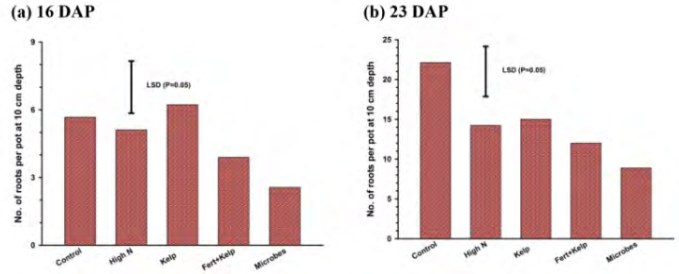

Figure 2. Progressive development of roots 10 cm below the ground surface in response to foliar 8 nutrient and biostimulant treatments (Experiment One). See text for details of treatment codes.

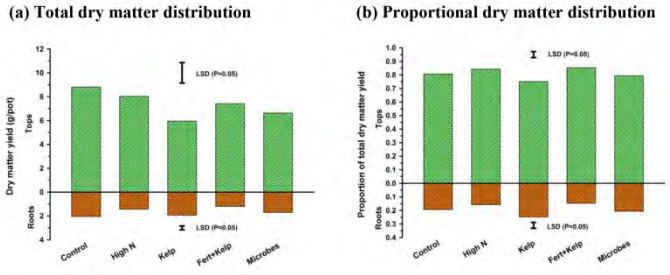

Figure 3. Effect of foliar nutrient and biostimulant treatments on 44-day dry matter yield and 11 distribution (Experiment One). See text for details of treatment codes.

Experiment Two. In Experiment Two, our primary objective was to vary the nutrient balance in foliar fertiliser applications, while also trialling kelp for a second time. Our secondary objective was to investigate what effect different zoysiagrass cultivars might have on the results. However, the results showed no significant differences between the two cultivars trialled (data not presented), even though these came from different *Zoysia* species. Figures 4 and 5 therefore show treatment effects averaged across both cultivars.

As in Experiment One, maximum root depth 16 DAP was not significantly different across all treatments, but was almost 25% higher than in Experiment One (average 13.7 cm; range 13.1-14.4 cm). Compared with the Control, treatment 2 (high N) did not increase root numbers 16 DAP or root and shoot dry matter yields and proportions. While treatment 4 (high K) did not reduce root numbers 16 DAP or shoot dry matter yield, the apparent, but non-significant, reduction in root dry matter production approached significance, leading to a significant reduction in the proportion of root dry matter.

Treatment 3 (high P), however, was detrimental to both shoot and (particularly) root growth, with significant reductions in root numbers 16 DAP, root and shoot dry matter production, and the proportion of root dry matter. Treatment 5 (kelp) gave significant increases in root numbers, root dry weight (except for treatment 2) and the proportion of roots over the foliar nutrient treatments 2-4, but was not significantly different from the Control (Treatment 1) in any of these attributes.

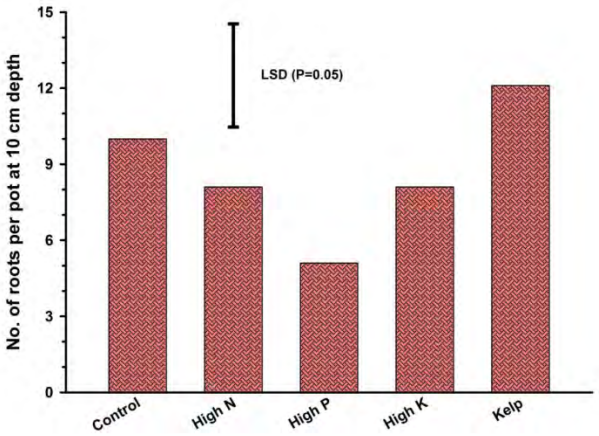

Figure 4. Effect of foliar nutrient and biostimulant treatments on 16-day root development 10 cm 15 below the ground surface (Experiment Two). See text for details of treatment codes.

Experiment Three. The aim of Experiment Three was to document the effect of allowing harvested turf sod to dry out before being laid. Holding the sod and allowing it to dry out for 2 days after harvest caused large reductions in moisture content (Table 5), but did not result in significant reductions in root and shoot growth provided the sod was stored with the leafy side up (treatments 2 and 3) (Figures 6 and 7). Holding sod with the soil side up (treatment 4) reduced soil moisture content only marginally while the protected leaf retained a much higher moisture level, but led to significant reductions in both root and top growth during establishment. Moisture levels in the harvested sod were quite high following overnight rain before harvest, and this may have led to reduced root development in the Control treatment planted on day 0.

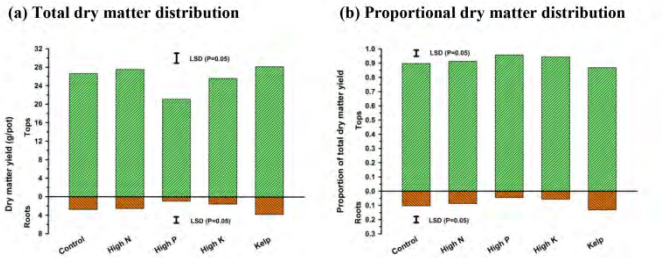

Figure 5. Effect of foliar nutrient and biostimulant treatments on 42-day dry matter yield and 21 distribution (Experiment Two). See text for details of treatment codes.

Sod held without water for 3-4 days after harvest (treatments 5 and 6) had almost completely dried out and established very poorly with greatly reduced amounts of weak root and shoot growth. These treatments also took around 2 weeks after planting before the first few green shoots started to appear again, and root growth 16 DAP was both short and sparse. The small apparent increase in the moisture content of sod planted on day 4 may have resulted from increased humidity, but most likely represents sampling error.

Despite the large growth reductions that resulted from holding harvested turf without water, root and shoot growth remained in general proportion without any significant differences among treatments. However, the very small weights harvested from treatments 5 and 6 also mean that possible errors here could be larger than in the more productive treatments.

Experiment Four. In Experiment Four, our primary objective was to study the effect of underlay fertiliser: specifically, whether this was necessary or not, together with the placement of fertiliser applied before laying sod. As a secondary objective, these treatments were combined with ±Kelp treatments; however, the addition of kelp again had no significant effect on any of the attributes measured (data not presented). Placement of underlay fertiliser in contact with sod or lightly covered also had no significant effect on root development, dry matter production and the partitioning of this between shoot and root growth (Figures 8 and 9).

Table 5. Mean daily temperatures (with the minimum-maximum range in brackets) and Sod Moisture contents X Treatment for the pre-planting period in Experiment Three.

Period	Sod temperature (°C)	Treatment #	Sod moisture (%)		
			Thatch + Leaf	Soil	Overall
Day 0		1	70.5	43.2	50.7
Day 0-1	35.5 (20.5-50.5)	2	41.4	23.	27.3
Day 1-2	34.8 (21.0-48.5)	3	19.8	9.9	11.2
		4	38.1	9.7	16.9
Day 2-3	39.5 (21.5-57.5)	5	2.3	3.0	2.9
Day 3-4	46.5 (22.0-71.0)	6	7.2	4.1	4.6

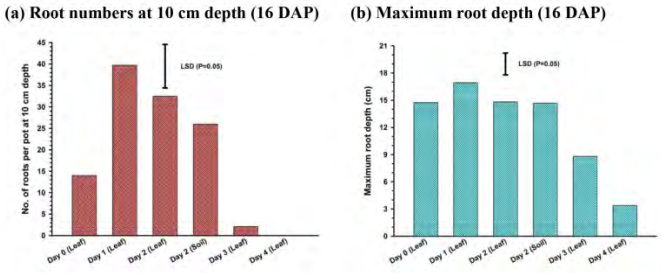

Figure 6. Effect of drying out of harvested sod prior to laying on 16-day root development 10 cm 24 below the ground surface (Experiment Three). See text for details of treatment codes.

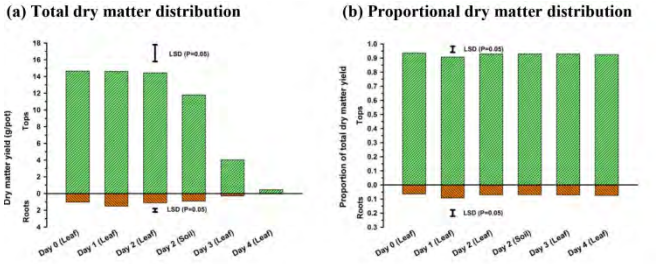

Figure 7. Effect of drying out of harvested sod prior to laying on 40-day dry matter yield and 39 distribution (Experiment Three). See text for details of treatment codes.

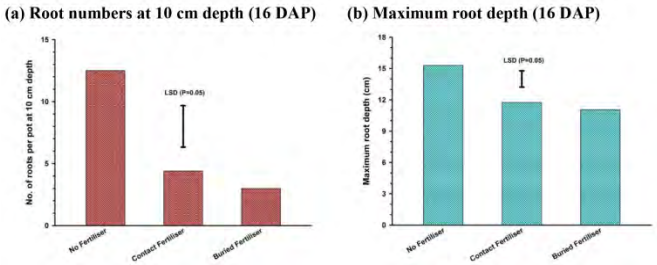

Figure 8. Effect of underlay fertiliser treatments on 16-day root development 10 cm below the 42 ground surface (Experiment Four). See text for details of treatment codes.

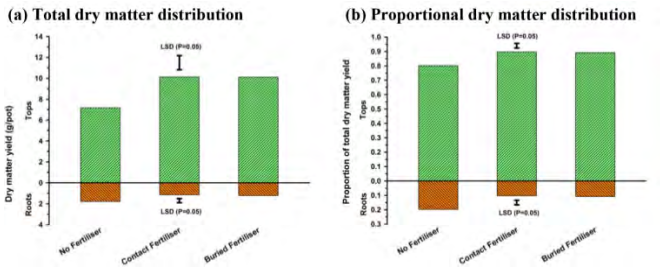

Figure 9. Effect of underlay fertiliser treatments on 43-day dry matter yield and distribution 45 (Experiment Four). See text for details of treatment codes.

Applying no fertiliser had major positive effects on sod establishment. Early root development without fertiliser was faster and roots penetrated deeper than in the two fertilised treatments (Figure 8). While withholding fertiliser at planting reduced overall dry matter production, it increased the partitioning of dry matter production into roots, leading to approximately 40% less shoot dry matter but 50% more root dry matter yield with zero fertiliser compared with the average of the two fertilised treatments (Figure 9).

Experiment Five. While no significant differences in early root development 16 DAP were recorded in Experiment Five (data not presented), withholding fertiliser at planting again reduced overall dry matter production and increased partitioning of dry matter production into roots (Figure 10). At the final harvest 43 DAP, the zero fertiliser treatment showed 79% less shoot dry matter but 63% more root dry matter yield than the treatment with 100 kg N/ha at planting; this advantage was reduced to 51% lower shoot yield and 26% more roots when compared with adding only 50 kg N/ha at planting. Compared with the zero fertiliser treatment, adding 50 or 100 kg N/ha 21 DAP still reduced the partitioning of dry matter production into roots and gave lower root dry matter yields 43 DAP.

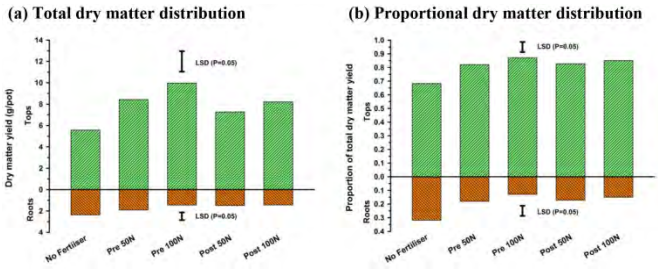

Figure 10. Effect of fertiliser treatments on 43-day dry matter yield and distribution (Experiment 49 Five). See text for details of treatment codes.

DISCUSSION

Temperature. In the Control treatments, total dry matter production from *Z. matrella* under the higher temperature conditions prevailing in Experiments Two and Three was 45-150% greater than in Experiments One; but, at the same time, dry matter partitioning into roots was reduced by 63-67%. Total dry matter production from the comparable fertiliser treatments in Experiments Four and Five (conducted in winter-spring under much the same environmental conditions) was similar to Experiment One, though partitioning of this into roots was intermediate between Experiment One (47 and 33% less, respectively) and the two summer experiments. In the case of Experiments Two and Three, the latter experiment was conducted under lower light conditions in a different glasshouse, which probably contributed to the reduction in total dry matter production compared to Experiment Two. Patton et al. (2007) reported genotypic differences in dry matter partitioning into leaves, stolons and rhizomes; but, although suggestive, differences in the proportions of leafy tops and roots between *Z. matrella* (93.1 and 6.9%, respectively) and *Z. japonica* (86.3 and 13.7%, respectively) cultivars in the Control treatment of Experiment Two just failed to reach significance.

Soil Fertility. The sand/peatmoss (or coir) growing medium was prepared without any added fertiliser, and analysis of the last two batches confirmed that this was low to very low in N, P and K, and in most other major and minor nutrients. The basal pre-plant granular mixed fertiliser (equivalent to 100 kg N, 20 kg P_2O_5 and 72 kg K per hectare) was therefore the major source of soil fertility at planting in the first three experiments, which were focused on foliar treatments. Residual fertiliser present in the sod due to turf farm practices was not quantified, but was an additional

(though physically limited) source of soil nutrients in our experiments.

In their classic article entitled "Establishing and maintaining zoysiagrass", Murray and Morris (1988) made two pertinent points: firstly, that it is a mistake to manage zoysiagrass like other turfgrass species; and, secondly, that zoysiagrass requires less supplemental fertiliser than most other turfgrasses. These points are relevant to, and consistent with, our results in Experiments Four and Five, which focused on the level of fertility below ground. In both cases, applying no fertiliser to growing media highly deficient in most nutrients proved beneficial in terms of encouraging root development (presumably scavenging for the small amounts of nutrient available) and increasing the partitioning of dry matter production into roots rather than shoots. When fertiliser might be applied safely to newly-established zoysiagrass remains unresolved, and essentially depends on how long it takes to develop a strong mature root system; however, fertilising 3 weeks after planting was clearly too early in Experiment Five.

The underlay media used in our experiments were strongly acid (pH 4.5-5.3). However, this should not have imposed any limitation on growth, based on experience in Alabama where Sturkie and Rouse (1968) reported that *Z. matrella* grew well down to their lowest pH of 4.7.

Nutrient Balance. Ten foliar applications of the High N fertiliser treatment in Experiments One and Two added approximately 175 kg N, 45 kg P_2O_5 and 130 kg K per hectare to the above-ground foliage. Variable responses have been reported following the application of fertiliser N to zoysiagrass sprigs or plugs, with Stiglbauer et al. (2009) reporting faster establishment while Fry and Dernoeden (1987) and Richardson and Boyd (2001) found no effect. In those situations, establishment to give complete ground coverage is largely dependent on lateral extension by stolons and rhizomes, whereas establishment of newly laid sod (as in our experiments) is solely dependent on root development. Establishment from sprigs or plugs also takes from several months to a year or more, depending on the initial planting density, whereas our experiments covered the first crucial 6 weeks of sod establishment at which stage new roots had grown through the full 25 cm depth of the growing medium while only a very few rudimentary new rhizomes had started to develop. In Experiment One, foliar applications of High N fertiliser significantly reduced root development without a compensatory increase in leafy top material. In Experiment Two where dry matter partitioning into roots was less than half that of the previous experiment, the absolute and proportionate weights of roots and tops in the equivalent High N treatment were not significantly different from the control. In this regard, we note that Wherley et al. (2011) also reported reductions in root dry weights of zoysiagrass following N fertilisation.

While the addition of 45 kg P_2O_5 per ha in the foliar High N treatments showed no beneficial effects on rooting in the first two experiments, 175 kg P_2O_5 per ha in ten foliar applications of the High P treatment in Experiment Two was quite damaging to both root and shoot growth. Sturkie and Rouse (1968) also reported adverse effects from high P levels on the growth of *Z. matrella* (but not bermudagrass) in Alabama where they applied up to 225 kg P_2O_5 per ha per year in two split applications. It is therefore appropriate to speculate on the approximate level at which P might become toxic to zoysiagrasses. However, as suppression of root growth was evident in the High P treatment after 16 days (Figure 4) compared with little or no negative effect in the High N treatment (Figures 2-5), P probably reached toxic levels in the 50-100 kg P_2O_5 per ha range, and most likely towards the bottom end of this range. The negative interaction between Kelp and High N in the combination treatment in Experiment One, particularly in relation to root development, supports this suggestion, as the Kelp component would have added a further 15 kg P_2O_5 (together with another 61 kg K) per ha. In experiments conducted in both native soil and sand-based greens, Rodriguez et al. (2001) reported optimum coverage of hybrid bermudagrass from sprigs at a ratio of 1N:0.4P, and found decreased rates of coverage at two sites for P levels in excess of this ratio.

Ten foliar applications of the High K treatment in Experiment Two added 92 kg N, 23 kg P_2O_5 and 244 kg K per hectare to the above-ground foliage and also suppressed root growth, but not top growth, with the distribution of only 5.7% of total dry matter into roots compared with 10.3% roots in the Control treatment. Similarly, applications of up to 186 kg K per ha per year in two split applications by Sturkie and Rouse (1968) did not result in any visible decline in *Z. matrella* turf quality, but increased P and decreased Mg tissue levels while not affecting Ca levels. In hybrid bermudagrass, Miller (1999) found that there was a critical fertilisation level of 74-84 kg K per ha. Beyond this level, K fertilisation led to decreases in the levels of extractable Ca and Mg in the growing medium and to decreases in plant tissue levels of Ca and Mg.

Biostimulants. The microbial supplement (treatment 5) in Experiment One caused significant decreases in both root and shoot development, though the reason(s) for this are not immediately apparent. While neutral in terms of its effect on root development, Kelp led to a significant reduction in shoot growth in Experiment One (and, hence, to an increase in the proportion of roots in total dry matter production). In Experiment Two, Kelp was not damaging to shoot growth, and the apparent increase in root mass was not statistically significant. These minor differences in the response to Kelp between Experiments One and Two may reflect differences in humidity or perhaps the fact that dry matter partitioning into roots relative to shoots was much weaker under higher temperatures in the second experiment, or they may simply be due to experimental error as demonstrated by Edmeades (2002). Kelp had no effect on any of the measured attributes in Experiment Four, which was similar to the first experiment in terms of the environmental conditions. Overall, the lack of any significant positive effect by kelp on plant growth is consistent with Edmeades (2002) extensive review of experiments involving similar seaweed-based products.

Sod Moisture. Drying out of harvested sod prior to laying did not seriously affect establishment for the first 2 days, particularly if the leafy rather than the soil side was exposed uppermost. While the total dry matter produced after

40 days establishment declined rapidly to negligible levels after this, the proportions of root and tops remained about the same throughout. While this does not explain the strongly negative effect apparently due to drying out of sod in Block 10 of Experiment One, drying in the latter case would have started to dry after fresh new root growth was initiated in the newly-laid sod, not before laying as in Experiment Three. The apparent sensitivity of zoysiagrass sod to drying out after new root growth has been initiated is supported by Dunn (1991) who noted that drying out of newly-planted sprigs could lead to loss of the stand or at least set back its development substantially.

CONCLUSION

Root development under newly-laid zoysiagrass sod was enhanced by maintaining low soil fertility and not applying fertiliser at establishment, which is contrary to the accepted norm with bermudagrass and other warm-season turf species. Further work is required to determine when to start applying low rates of fertiliser to zoysiagrass after establishment. High summer temperatures also appeared to reduce root development and the partitioning of dry matter production into roots, pointing to the need for further studies of the effect of temperature on root-shoot balance in the growth of zoysiagrasses. None of the foliar nutrient or biostimulant treatments applied resulted in a positive response in terms of root development and the partitioning of dry matter production into root rather than shoot growth during the first 6 weeks of establishment for newly-laid zoysiagrass sod.

Drying out of zoysiagrass sod prior to laying did not disproportionately affect subsequent root development. However, it also appears that the maintenance of good sod and soil moisture is of paramount importance during early establishment to protect delicate new root growth once this has been initiated after laying of the sod.

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