CHAPTER TWO - DRY MATTER PARTITIONING EXPLAINS DIFFERENCES IN ZOYSIAGRASS ESTABLISHMENT RATES

Abstract

A barrier to widespread zoysiagrass (*Zoysia* spp.) use is its slow establishment rate. Our objectives were to quantify differences in establishment rate of zoysiagrass cultivars as well as determine the underlying factors associated with the difference in growth rate among cultivars. Thirty-five cultivars of zoysiagrass were collected and transplanted into field plots in June of 2004 and 2005. Establishment rate of zoysiagrass cultivars and stolon growth were measured in the field and then four cultivars with contrasting establishment rate were used for further growth analysis in a growth chamber. Mean establishment rate [$\log_e$ (coverage) d^{-1}] and coverage (cm^2) 91 days after planting (DAP) in the field were greater for *Z. japonica* than *Z. matrella* cultivars. The experimental *Z. japonica* cultivar '6186' had the highest coverage 91 DAP. 'El Toro', 'Chinese Common' and 'Palisades' were among the *Z. japonica* cultivars that produced more coverage 91 DAP than the mean (1943 cm^2) while 'Meyer' produced less coverage than the mean. 'Zorro' was among the fastest establishing *Z. matrella* cultivars and 'Diamond' was the slowest. Growth analysis indicated El Toro and Zorro, which establish faster than Meyer and Diamond, partition more dry matter to stolons and rhizomes than leaves. This is consistent with field data where El Toro and Zorro have greater total stolon length than Meyer and Diamond. Zoysiagrass cultivars that partition more dry matter to stems instead of leaves establish the quickest.

Japanese lawngrass (*Zoysia japonica* Steud.) and Manilagrass (*Zoysia matrella* (L.) Merr.) create a high-quality turf and are used for lawns and golf courses (Beard, 1973). Both species are commonly referred to as zoysiagrass and they are best-adapted to the transition, warm-arid, and warm-humid climatic zones of the United States. Zoysiagrass is relatively inexpensive to maintain because of excellent heat, drought, pest, and wear tolerance compared to cool-season grasses (Youngner, 1961; Biran et al., 1981; Reinert and Engelke, 2001; White et al., 2001).

The disadvantages of zoysiagrass are few, but its main disadvantage is slow establishment (Busey and Myers, 1979; McCarty, 2001), which likely limits more widespread use. Researchers have found that methods commonly used to hasten establishment in other turfgrasses including nitrogen fertilization and plant growth regulators have little effect on zoysiagrass establishment (Youngner, 1958; Fry and Dernoeden, 1986, 1987; Borden and Campbell, 1987; Dunn, 1991; Richardson and Boyd, 2001). However, *Z. japonica* cultivars are reported to have faster establishment rates than *Z. matrella* cultivars (Forbes and Ferguson, 1947; Turgeon, 1991; McCarty, 2001). Additionally, cultivar selection can influence establishment rate (Dunn, 1991; Sifers et al., 1992; Hall et al., 1998). Among the most commonly used zoysiagrasses, ‘El Toro’ and ‘Palisades’ zoysiagrass are among the fastest establishing *Z. japonica* cultivars, whereas ‘Meyer’ and ‘Emerald’ establish more slowly (Hall et al., 1998; Gibeault and Cockerham, 1988; McCarty, 2001; Morris, 1998; Morris, 2004; Shearman and Morris, 1996; Sifers et al., 1992).

Mechanisms influencing differing establishment rates among zoysiagrasses species and cultivars are not understood. Growth analysis is a useful tool for determining causes of differential growth rates. Reviews of these methods are available from Causton and Venus (1981), Hunt (1990, 2003) and Evans (1972). In general, growth analysis uses plant weights and leaf area in formulae to provide a holistic approach to interpret plant performance (Hunt, 2003).

Crop growth rate (CGR) is the simplest index of plant growth, but unlike relative growth rate (RGR), CGR does not take into account differences in initial plant size when comparing species (Hunt, 2003). Relative growth rate provides information on plant growth using the natural logarithm of plant weight so that growth rates of different-sized plants may be compared. Additionally, the mean unit leaf rate (ULR) (also referred to as mean net assimilation rate) is a subcomponent of RGR and provides information about the efficiency in which leaves accumulate dry matter. Leaf area ratio (LAR) is a subcomponent of RGR and provides information on the amount of biomass that is partitioned into leaf area. Additionally, specific leaf area (SLA) describes leaf area per leaf weight and ratios such as leaf weight ratio (LWR), stem weight ratio (SWR) and root weight ratio (RWR) describe how a plant partitions its dry matter into various plant parts.

Numerous growth analyses have generally found that grasses with higher RGR values have higher SLA (Poorter and Remkes, 1990; Garnier, 1992; Atkin and Lambers, 1998), which is similar to findings in dicots (Dijkstra and Lambers, 1989; Poorter and De Jong, 1999). Grass species with high RGR are also known to have higher ULR (Garnier, 1992) and higher LWR and LAR (Poorter and Remkes, 1990). The objectives of our research were to determine differences in establishment rate of commercially available and experimental zoysiagrass cultivars, and to determine the underlying factors associated with differential growth rates among zoysiagrass cultivars.

Materials and Methods

Establishment Rates

Plant material of commercially available and experimental cultivars of zoysiagrass (Table 2.1) was collected in the fall of 2003 and propagated in the greenhouse (23 ±5 °C) in plug trays with 8 by 8 by 8 cm divisions filled with fritted clay (Turface, Profile Products LLC, Buffalo Grove, IL). Vegetatively established cultivars were planted into trays as plugs or stolons and seeded cultivars were seeded (49 kg ha^{-1}) into trays. Plants in the greenhouse were fertilized monthly with 49 kg ha^{-1} N, 21 kg ha^{-1} P, and 40 kg ha^{-1} K using a soluble fertilizer (18N-7.9P-17.4K) and mowed weekly at 4.0 cm. Plants were transplanted into field plots at the W.H. Daniel Turfgrass Research and Diagnostic Center, West Lafayette, IN. Experimental plots were 1.0 by 1.0 m arranged in a randomized complete-block design with four replications. One vegetative plug (8 by 8 by 8 cm) of zoysiagrass was transplanted into the center of each plot for both seeded and vegetative cultivars on 7 June 2004 and 2005 and irrigated four times daily for the first month to encourage establishment and then irrigated as needed to prevent wilting. Soil type was a Stark silt loam (fine-silty mixed mesic Aeric Ochraqualfs) with a pH of 7.0, 224 kg ha^{-1} P, 808 kg ha^{-1} K and 84 g kg^{-1} organic matter in 2004 and with a pH of 6.8, 224 kg ha^{-1} P, 639 kg ha^{-1} K and 29 g kg^{-1} organic matter in 2005. The areas were fumigated with methyl bromide at 732 kg/ha prior to establishment each year to minimize weed competition. Plots received 49 kg ha^{-1} N from urea (46N-0P-0K) on 1 July and 1 August of each year and weeds were manually removed during establishment.

Digital images of each plot were taken weekly with a Nikon Coolpix 3200 (Nikon, Melville, NY) digital camera mounted on a monopod to insure a consistent height from the lens to the soil surface (1.05 m). Coverage of zoysiagrass was determined using digital image analysis (DIA) (SigmaScan Pro, Systat Software Inc., Richmond, CA) (Richardson et al., 2001). To selectively identify green leaves in the images, the hue range was set from 47 to 107 and the saturation was set from 10 to 100. Richardson et al. (2001) analyzed images with the saturation set from 0 to 100. However, when images taken on our soil with our camera were analyzed with saturation set at 0 to 100, scanning software would overestimate coverage by selecting some of the surrounding soil. To increase accuracy, the lower limit of saturation was raised to 10. Images were taken of a calibration disk and data converted from selected green pixels to zoysiagrass coverage (cm^2). Using a sod staple, stolons and detectable rhizomes reaching the plot border were angled back into the plot to prevent encroachment into adjacent plots and to ensure that all growth from the plug was measured using DIA. Plots were not mown because of the use of sod staples and to avoid cultivar by mowing interactions since each *Zoysia* spp. have different optimum mowing heights (Higgins, 1998; Unruh et al., 2000).

A weather station onsite monitored daily air temperature (Fig. 2.1). The start of winter dormancy (leaf discoloration) occurred 112 and 113 days after plugging (DAP) in 2004 and 2005, respectively, but final coverage is reported only until 91 DAP because establishment rate decreased with decreasing temperatures in autumn and because some cultivars approached complete plot coverage. To determine the rate of establishment, coverage was transformed using the natural logarithm and applied to the linear model [Coverage = (K*DAP) + I], where K is the rate of increase (establishment rate), DAP is days after plugging, and I was equal to the natural logarithm of 64 cm^2 which was the starting coverage for all plots.

At 43 DAP, the length of individual stolons was measured from the edge of the original plug to the tip of the stolon. Additionally, stolon growth was measured over a 7-d interval by marking the growing tip of three stolons in each plot with toothpicks and measuring elongation with a Vernier caliper 7-d later. Stolon growth rate measurements were collected from 57 DAP to 71 DAP in each year of the study and stolon growth rate (mm day^{-1}) determined. Rhizomes were not measured in our study because only non-destructive measurement techniques were used to preserve plots for future measurements of coverage and winter survival. Lastly, leaf blade width was also measured with a Vernier caliper 64 DAP.

Data were analyzed using PROC ANOVA, PROC TTEST, and PROC REG (SAS Institute, Cary, NC). Error variances were homogenous for dependent variables and thus data were combined across years. When differences were examined between species, ‘J-14’ (*Zoysia sinica* Hance) was grouped with *Z. japonica* and ‘Emerald’ (*Z. japonica x. Z. pacifica* Goudsw.) was grouped with *Z. matrella* because of their similarities in color, texture, and density with respective species. Means were separated using Fisher's protected least significant difference (LSD) when *F* tests were significant at $\alpha \leq 0.05$.

Growth Analysis

Based on preliminary results from the field study, one slow-growing and one fast-growing cultivar of both *Z. japonica* and *Z. matrella* were selected for further growth analysis. *Zoysia japonica* cultivars El Toro (fast-growing) and Meyer (slow-growing) and *Z. matrella* cultivars ‘Zorro’ (fast-growing) and ‘Diamond’ (slow-growing) were selected for these experiments. Cultivars were planted in silica sand-filled 2.5 cm diameter Ray Leach cone-tainers (Stuewe & Sons, Inc., Corvallis, OR) using a 1 to 2 cm segment of stolon or rhizome containing a single node and leaf and root tissues. Plants were fertilized daily after planting with half-strength Hoagland’s solution (Epstein and Bloom, 2005). Plants were established in the greenhouse for six weeks (26 July to 6 Sept. 2004 and 20 June to 1 Aug. 2005) at 24 ±6°C. Plants were then transferred to a growth chamber (PGR15, Controlled Environments Inc., Pembina, ND) maintained at 30 ±0.7°C with 70% relative humidity and 14-h photoperiod of 816 $\mu mol\ m^{-2}\ s^{-1}$ photosynthetically active radiation.

Eight plants of each cultivar were harvested when plants were transferred to the growth chamber and again every week for five wks. Leaf blades, roots and the remaining fraction that consisted of mainly leaf sheaths, rhizomes and stolons were separated. This third fraction containing leaf sheaths, rhizomes and stolons will be termed ‘stem’. Leaf area was determined using DIA (SigmaScan Pro v. 5.0, Systat Software Inc., Richmond, CA) (Richardson et al., 2001). Leaves were placed on black fabric after harvesting and covered with non-reflective glass.

Digital images (Nikon Coolpix 3200, Nikon, Melville, NY) of leaves were taken immediately after harvest from a set height (33 cm), processed to remove background effects (Adobe Photoshop 6.0, Adobe Systems Inc., San Jose, CA) and DIA was used to determine the number of green pixels per image. To selectively identify green leaves in images, the hue range was set from 47 to 107 and the saturation from 0 to 100. Images were taken of a calibration disk and the data converted from selected green pixels to leaf area (cm^2). Root and stem tissues were washed with water to remove the majority of silica sand and then all tissues were dried separately (at least 72 h at 60°C) and weighed. Root weights were calculated as the difference in dry weight before and after combustion in a muffle furnace (at least 3 h at 600°C) to account for silica sand remaining after washing.

Growth analysis values were calculated using formulae in Table 2.2 and values were then verified using the spreadsheet tool provided by Hunt et al. (2002) which calculates classical growth analysis values. This experiment was conducted in 2004 and repeated in 2005. Error variances were homogenous for dependent variables and data were combined across years. Data were analyzed using PROC MIXED (SAS Institute, Cary, NC). Mean RGR and other growth components were separated using Tukey's test for significant differences when *F* tests were significant at $\alpha \leq 0.05$.

Results and Discussion

Establishment Rates

We observed differences ($p<0.0001$) in coverage among 35 different zoysiagrass cultivars 59 and 91 DAP (Table 2.3). Differences in coverage among cultivars were minimal prior to 59 DAP and thus data is not shown. Coverage ranged from 184 to 959 cm^2 59 DAP, and 425 to

4142 cm^2 91 DAP. Cultivars ‘6186’, ‘DALZ0102’, El Toro, ‘PZB 33’, ‘Chinese Common’, ‘6136’, ‘Companion’, and ‘BMZ 230’ had coverage 59 DAP that was significantly greater than the mean value of 524 cm^2. With the exception of Companion, these cultivars along with ‘Palisades’ also had the greatest coverage 91 DAP compared to the mean of 1943 cm^2. Meyer is considered an industry standard because it is widely used by turfgrass practitioners and researchers and has been available since the 1950’s. Meyer produced significantly less coverage 91 DAP (1203 cm^2) than the mean. Fourteen cultivars had greater coverage than Meyer 59 DAP, whereas Diamond was the only cultivar with significantly lower coverage than Meyer 59 DAP.

Scatter plots of zoysiagrass coverage versus days after planting revealed a non-linear relationship. After a natural logarithm transformation, establishment rate was determined by linear regression with r^2 values ranging from 0.91 to 0.99. Establishment rate [K, $\log_e$ (coverage) d^{-1}] ranged from 0.0191 to 0.0448 for Diamond and 6186, respectively, with a mean of 0.0338. Cultivars 6186, DALZ0102, El Toro, PZB 33, Chinese Common, 6136, Companion, and BMZ 230 had establishment rates significantly greater than the mean value of 0.0338 $\log_e$ (coverage) d^{-1}. Meyer had an establishment rate similar to the mean [0.0307 $\log_e$ (coverage) d^{-1}]. El Toro, Companion and Palisades had the highest establishment rates among commercially available *Zoysia japonica* cultivars. Cultivars Zorro, DALZ0104 and DALZ0101 had the highest establishment rates among *Zoysia matrella* cultivars.

We observed differences ($p<0.001$) in mean stolon length, total stolon length and stolon growth rate among 35 different zoysiagrass cultivars (Table 2.3). Mean total stolon length 43 DAP ranged from 2.6 to 26.2 cm, total stolon length 43 DAP ranged from 11 to 365 cm and stolon growth rate ranged from 1.7 to 11.3 mm d^{-1}. Diamond and 6186 were the lowest and highest, respectively, for all stolon growth parameters measured. DALZ0102, 6186, PZB 33, Chinese Common, 6136, and BMZ 230 had the highest mean stolon lengths 43 DAP, which were greater than the mean value of 11.1 cm. These cultivars along with ‘Companion’ also had the greatest total stolon length 43 DAP, compared to the mean of all cultivars (145 cm). Stolon growth rate was greater than the mean (6.6 mm d^{-1}) for 6186, El Toro, Chinese Common, BMZ 230, Palisades, and ‘J-37’. Stolon length for Meyer was similar to the mean, but total stolon length for Meyer was less than the mean. Stolon growth rate for Meyer (5.0 mm d^{-1}) was similar to the mean and consistent with an earlier report of 4.9 mm d^{-1} (Daniel, 1955). El Toro, also widely used by practitioners and known for its quick establishment rate had a stolon growth rate (9.2 mm d^{-1}) that was among the highest of all cultivars. In general, cultivars with high coverage and establishment rates had the highest stolon growth rates and longest stolons.

Similar to earlier reports (Forbes and Ferguson, 1947; Turgeon, 1991; McCarty, 2001), *Zoysia japonica* cultivars in our study produced more coverage and had a higher establishment rate than *Z. matrella* cultivars (Table 2.4). *Zoysia japonica* cultivars have wider leaves (2 to 4 mm) than *Z. matrella* (< 2 mm) (Anderson, 2000). Leaf width across species was positively correlated with establishment rate ($r^2 = 0.33$, p=0.0003), with wide-bladed cultivars having the fastest establishment rate (Fig. 2.2A). However, interspecific analysis shows that leaf width within species does not significantly influence establishment rate (Fig. 2.2B-C). Therefore, the relationship between leaf width and establishment rate across species indicates that species (genetics) is the most likely cause for differences in establishment rate and not leaf width.

Zoysia japonica is sold commercially both as seed or vegetative propagules, but *Zoysia matrella* is only available as vegetative propagules. All cultivars were established by vegetative plugs for our field study, and it was found that cultivars with commercial seed availability had an establishment rate similar to cultivars sold as vegetative propagules (Table 2.4). This is similar to Karcher et al. (2005) who found that divot recovery of a two-year-old stand of zoysiagrass was comparable between cultivars established either by seed or vegetative propagules. However, Karcher et al. (2005) also reported seeded cultivars recovered slower than vegetative cultivars during the first year, primarily because seeded cultivars had not yet developed as many rhizomes and stolons as vegetative cultivars. All cultivars were established by eight-month-old vegetative plugs instead of by seed in our study, which may account for why we did not see differences between cultivars with commercial seed availability and those sold as vegetative propagules.

The slow growth of zoysiagrass is possibly its greatest disadvantage, especially compared to bermudagrass which is also adapted to parts of the transition zone (*Cynodon* spp. Rich.) (Busey and Myers, 1979). El Toro is described as the fastest-establishing zoysiagrass cultivar (Gibeault and Cockerham, 1988; McCarty, 2001; Morris, 1998; Shearman and Morris, 1996; Sifers et al., 1992) whereas traditional cultivars like Meyer and Emerald establish slowly (Hall et al., 1998; Morris, 1998; 2004; Shearman and Morris, 1996; Sifers et al., 1992). There is a need to develop zoysiagrass cultivars with faster establishment rates because of its slow growth (Engelke and Anderson, 2003). In our study, experimental cultivars such as 6186, DALZ01012, and PZB 33 had a similar establishment rate to El Toro. Palisades, a newly released cultivar (Engelke et al., 2002), had similar establishment rate and coverage 91 DAP to El Toro. Additionally, 6186 coverage 91 DAP was greater than El Toro. These results indicate that newer cultivars exist with rapid establishment rates.

Though there are few reports comparing establishment among *Z. matrella* cultivars because of their relatively recent release, we found that the newly released *Z. matrella* cultivar Zorro (Engelke and Reinert, 2002) has a greater establishment rate and higher coverage 91 DAP than the older cultivar Emerald (*Z. japonica x. Z. pacifica* Goudsw.) which is similar in color, texture and density to *Z. matrella* (McCarty, 2001). Planting newer cultivars with improved establishment rates could dramatically reduce time, inconvenience, and cost of establishing zoysiagrass.

Plots were not mown in this study, but preliminary evidence from a similar field study in 2006 with five cultivars indicates that mowing at 3.2 cm reduces establishment rate compared to unmown plots (Patton and Reicher, 2006). Although low mowing heights decreased establishment rate, it did not change the relative rankings of cultivars and there were no mowing height × cultivar interactions (Patton and Reicher, 2006). Hall et al. (1998) established six zoysiagrass cultivars by either sprigging or plugging, and found that sprigging generally resulted in faster establishment than plugging, but that planting method did not change the relative establishment rankings of cultivars. Additionally, Karcher et al. (2005) recently examined divot injury recovery among vegetatively propagated zoysiagrass cultivars and found that establishment rate was closely related to recuperative potential. Therefore, our establishment rate results (rankings) should be applicable for approximating the establishment rate by either sprigs or recuperative potential after injury.

Growth Analysis

Analysis of variance indicated differences between the four cultivars for all growth analysis parameters. Trends in CGR among cultivars closely followed trends in establishment rate and coverage 91 DAP in the field study. El Toro had the highest CGR and Diamond the lowest (Table 2.5). The CGR of Diamond is low because individual plants are small and initial mass is not accounted for by CGR. When plant weights are transformed with the natural logarithm allowing for a more equitable comparison, the resulting RGR values indicate that Diamond has the greatest growth efficiency and that El Toro, Zorro and Meyer all have similar RGR values. Unlike previous reports with other plants (Poorter and Remkes, 1990; Garnier, 1992; Atkin and Lambers, 1998), there were no significant correlations between RGR with any of the other growth components (ULR, LAR, SLA, LWR, SWR, and RWR) (Table 2.5), which may be expected because only Diamond had a significantly higher RGR than the other three cultivars.

Dry matter production by leaves was most efficient (ULR) for Diamond (23.6 g m^{-2} d^{-1}) and Zorro (22.1 g m^{-2} d^{-1}), followed by El Toro (17.3 g m^{-2} d^{-1}) and Meyer (12.6 g m^{-2} d^{-1}). High ULR of Diamond and Zorro were likely due to their narrow leaves compared to Meyer and El

Toro. Narrow leaves decrease shading of other leveas and allow for greater production efficiency. Despite Diamond and Zorro having similar ULR values, dry weight was partitioned differently. On a relative basis, Diamond partitions 2.8%, and 4.6% more carbon into leaves (LWR) and roots (RWR), respectively, than Zorro. By comparison, Zorro invests more (7.4%) of its dry weight into stolon and rhizome (SWR) mass than Diamond. This difference in dry matter partitioning may explain why Zorro established more quickly in the field than Diamond. El Toro and Meyer also have similar ULR values, but partition dry weight differently among plant parts. El Toro partitioned 1.6% and 3.6% more dry weight to produce roots (RWR) and stolons and rhizomes (SWR), respectively, than Meyer. Meyer, however, partitioned more dry weight (5.2%) to leaves (LWR) than El Toro.

Within species, cultivars with lower CGR such as Diamond and Meyer have higher LAR and SLA values. More dry matter was partitioned into leaf area (LAR) and for Meyer (7.1 m^2 g^{-1}) than Diamond (5.8 m^2 g^{-1}), El Toro (4.9 m^2 g^{-1}) and Zorro (4.1 m^2 g^{-1}). Similarly, SLA was greatest for Meyer (23.8 m^2 g^{-1}) followed by Diamond (21.5 m^2 g^{-1}), El Toro (19.7 m^2 g^{-1}) and Zorro (16.7 m^2 g^{-1}). Higher LAR and SLA values for Meyer and Diamond indicate that these cultivars are more leafy and that the individual leaves were thinner. Differences in SLA of certain grasses is attributed to higher mineral and organic N-compounds, (hemi)cellulose or lignin content (Van Arendonk and Poorter, 1994). Tissues were not analyzed for differences in chemical or physical composition in our study, so it is unclear what caused differences in SLA.

Overall, growth analysis data suggest cultivars that establish quickly produce a greater proportion of stems (stolons and rhizomes) than leaves compared to slow-establishing cultivars. This is consistent with our field data where cultivars with high establishment rates had longer stolons (Table 2.3). For instance, Meyer and Diamond partition more dry matter into leaf area which is likely why they establish and spread slowly in the field.

There are considerable differences in zoysiagrass growth and establishment rates between species and cultivars. *Zoysia japonica* cultivars generally have higher establishment rates than *Z. matrella* cultivars. Cultivars capable of producing long stolons with high growth rates establish quickly. High stolon growth rate of quick-establishing cultivars is due to a higher proportion of dry weight partitioned to stems instead of leaves. Therefore, breeders could develop cultivars with faster establishment rates by selecting plants that partition more dry matter to stems. Experimental cultivars we tested established as fast or faster than the best-establishing commercially available cultivars. Bermudagrass has a higher establishment and recovery rate than zoysiagrasses (Beard, 1973; Busey and Myers, 1979; Turgeon, 1991), which sometimes precludes zoysiagrass from being used for turf. However, identification of newer cultivars with quicker establishment and recovery than the industry standards of Meyer may make selecting zoysiagrass a more acceptable option to bermudagrass. Practitioners should select available zoysiagrass cultivars with fast establishment and recovery rates to help reduce establishment time, increase revenue and improve course conditions.

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References

Anderson, S.J. 2000. Taxonomy of Zoysia (poaceae): morphological and molecular variation. Ph.D. dissertation. Texas A&M Univ., College Station, TX.

Atkin, O.K., and H. Lambers. 1998. Slow-growing alpine and fast-growing lowland species: A case study of factors associated with variation in growth rate among herbaceous higher plants under natural and controlled conditions. p. 259-288. *In* H. Lambers et al. (ed.) Inherent variation in plant growth: Physiological mechanisms and ecological causes. Backhuys publishers, Leiden, the Netherlands.

Beard, J.B. 1973. Turfgrass Science and Culture. Prentice Hall, Inc. Englewood Cliffs, NJ.

Biran, I., B. Bravdo, I. Bushkin-Harav, and E. Rawitz. 1981. Water consumption and growth rate of 11 turfgrasses as affected by mowing height, irrigation frequency, and soil moisture. Agron. J. 73:85-90.

Borden, P., and R.W. Campbell. 1987. Growth and water use of Meyer zoysiagrass as influenced by five chemical growth regulators. p. 1039[63] *In* Abstracts, Annu. Meet., Am. Soc. Hort. Sci., Orlando, FL. 6-12 Nov., 1987. HortScience 22.

Busey, P., and B.J. Myers. 1979. Growth rates of turfgrasses propagated vegetatively. Agron. J. 71:817-821.

Causton, D.R, and J.C. Venus. 1981. The Biometry of Plant Growth. Edward Arnold, London.

Daniel, W.H. 1955. Emerald Zoysia – A new hybrid turfgrass. p. 34-35. Midwest Regional Turf Foundation Conference Proceedings. West Lafayette, IN.

Dijkstra, P., and H. Lambers. 1989. A physiological analysis of genetic variation in relative growth rate within *Plantago major* L. Functional Ecol. 3:577-587.

Dunn, J.H. 1991. Establishing zoysiagrass. Golf Course Management. 59:38-52.

Engelke, M.C., and S.J. Anderson, 2003. Zoysiagrasses. p. 271-285 *In* M.D. Casler and R.R. Duncan (ed.) Turfgrass Biology, Genetics and Breeding. John Wiley & Sons, Inc., Hoboken, NJ.

Engelke, M.C., and J.A. Reinert. 2002. Zoysiagrass plant ‘Zorro’. U.S. Plant Patent 14130. Date issued: 11 July 2002.

Engelke, M.C., R.H. White, P.F. Colbaugh, J.A. Reinert, K.B. Marcum, B. Rummele, and S.J. Anderson. 2002. Registration of ‘Palisades’ zoysiagrass. Crop Sci. 42:305-306.

Epstein, E., and A.J. Bloom. 2005. Mineral Nutrition of Plants: Principles and Perspective. Sinauer Associates, Sunderland, MA.

Evans, G.C. 1972. The Quantitative Analysis of Plant Growth. Oxford, Blackwell Scientific Publications.

Forbes, I. 1962. Registration of Emerald zoysiagrass. Crop Sci. 2:533-534

Forbes, I., and M.H. Ferguson. 1947. Observations on the zoysia grasses. The Greenkeepers’ Reporter. 15:7-9.

Fry, J.D., and P.H. Dernoeden. 1986. Zoysiagrass competition in two cool-season turfgrasses treated with plant growth regulators. HortScience. 21:464-466.

Fry, J.D., and P.H. Dernoeden. 1987. Growth of zoysiagrass from vegetative plugs in response to fertilizers. J. Amer. Soc. Hort. Sci. 112:286-289.

Garnier, E. 1992. Growth analysis of congeneric annual and perennial grass species. J. Ecol. 80:665-675.

Gibeault, V.A., and S.T. Cockerham. 1988. “El Toro” zoysiagrass. Calif. Turf. Cul. 38:1.

Hall, M.H., R.H. White, J.E. Gaudreau, W.G. Menn, and G.R. Taylor. 1998. Zoysiagrass cultivar study. Texas Turfgrass Research Report. TURF-97-33.

Higgins, J. 1998. Zoysiagrass lawns. Alabama Cooperative Extension System. ANR-1129 (Available online at http://www.aces.edu/pubs/docs/A/ANR-1129/ANR-1129.pdf) (verified 16 May 2006).

Hunt, R. 1990. Basic Growth Analysis: Plant Growth Analysis for Beginners. Unwin Hyman, London.

Hunt, R. 2003. Growth analysis, individual plants. *In* B. Thomas et al. (ed.) Encyclopedia of Applied Plant Sciences. Academic Press, London.

Hunt, R., D.R. Causton, B. Shipley, and A.P. Askew. 2002. A modern tool for classical plant growth analysis. Ann. Bot. 90:485-488.

Karcher, D. E., M.D. Richardson, J.W. Landreth, and J.H. McCalla Jr. 2005. Recovery of zoysiagrass varieties from divot injury. [Online]. Available at http://www.plantmanagementnetwork.org/ats/. Appl. Turf. Sci. doi:10.1094/ATS-2005-0728-01-RS.

McCarty, L.B. 2001. Best Golf Course Management Practices. Prentice-Hall Inc., Upper Saddle River, NJ.

Morris, K. 1998. National zoysiagrass test-1996. Prog. Rep. Natl. Turfgrass Evaluation Progr. No. 98-4.

Morris, K. 2004. National zoysiagrass test-2002. Prog. Rep. Natl. Turfgrass Evaluation Progr. No. 04-2.

Patton, A.J., and Z.J. Reicher 2006. Mowing height impacts establishment rate of zoysiagrass cultivars. 2006 Annu. Rep. - Purdue Univ. Turfgrass Sci. Progr.

Poorter, H., and R. De Jong. 1999. A comparison of specific leaf area, chemical composition and leaf construction costs of field plants from 15 habitats differing in productivity. New Phytol. 143:163-176.

Poorter, H., and C. Remkes. 1990. Leaf area ratio and net assimilation rate of 24 wild species differing in relative growth rate. Oecologia 83:553-559.

Radford, P.J. 1967. Growth analysis formulae – their use and abuse. Crop Sci. 7:171-175.

Reinert, J.A., and M.C. Engelke. 2001. Resistance in zoysiagrass, *Zoysia* spp., to the tropical sod webworm, *Herpetogramma phaeopteralis* Guenne. Int. Turfgrass Soc. Res. J. 9:798-801.

Richardson, M.D., and J.W. Boyd. 2001. Establishing *Zoysia japonica* from sprigs: Effects of topdressing and nitrogen fertility. HortScience 36:377-379.

Richardson, M.D., D.E. Karcher, and L.C. Purcell. 2001. Quantifying turfgrass cover using digital image analysis. Crop Sci. 41:1884-1888.

Sifers, S.I., J.B. Beard, and M.H. Hall. 1992. Comparative establishment rates and initial performance characteristics of four commercially available zoysiagrass (*Zoysia* spp.) cultivars and four experimental selections for 1988 and 1989. p. 29-31. Texas Agric. Exp. Sta. PR-4986. College Station, Texas.

Shearman, R., and K.N. Morris. 1996. National zoysiagrass test-1991. Final Rep. Natl. Turfgrass Evaluation Progr. No. 96-15.

Turgeon, A.J. 1991. Turfgrass Management. Prentice-Hall, Inc., Englewood Cliffs, NJ.

Unruh, J.B., L.E. Trenholm, and J.L. Cisar. 2000. Zoysiagrass in Florida. Florida Cooperative Extension Service. ENH11 (Available online at http://edis.ifas.ufl.edu/pdffiles/LH/LH01100.pdf) (verified 16 May 2006).

Van Arendonk, J.J.C.M., and H. Poorter. 1994. The chemical composition and anatomical structure of leaves of grass species differing in relative growth rate. Plant Cell Environ. 17:963-970.

White, R.H., M.C. Engelke, S.J. Anderson, B.A. Ruemmele, K.B. Marcum, and G.R. Taylor II. 2001. Zoysiagrass water relations. Crop Sci. 41:133-138.

Youngner, V.B. 1958. Gibberellic acid on Zoysia grasses. Southern California Turfgrass Culture 8:5-6.

Youngner, V.B. 1961. Accelerated wear tests on turfgrasses. Agron. J. 53:217-218.

Table 2.1. Zoysiagrass cultivar and experimental names, species, typical type of establishment method and source of plant material.

Cultivar	Experimental	Species	Type†	Source
6186‡	6186	*Zoysia japonica* Steud.	Vegetative	Bladerunner Farms, Inc.
DALZ0102	DALZ 0102	*Zoysia japonica* Steud.	Vegetative	Turfgrass America
El Toro*§	UCR#1	*Zoysia japonica* Steud.	Vegetative	Seedland, Inc.
PZB 33	PZB 33	*Zoysia japonica* Steud.	Seeded	Patten Seed Co.
Chinese Common*		*Zoysia japonica* Steud.	Seeded	Natl. Turfgrass Eval. Progr.
6136	6136	*Zoysia japonica* Steud.	Vegetative	Bladerunner Farms, Inc.
Companion*	ZMB-2	*Zoysia japonica* Steud.	Seeded	Seed Research of Oregon, Inc.
BMZ 230	BMZ 230	*Zoysia japonica* Steud.	Vegetative	Turfgrass America
Palisades*	DALZ 8514	*Zoysia japonica* Steud.	Vegetative	M.C. Engelke, Texas A&M Univ.
PST-R7LT	PST-R7LT	*Zoysia japonica* Steud.	Seeded	Pure-Seed Testing, Inc.
Zenith*	ZNW-1	*Zoysia japonica* Steud.	Seeded	Patten Seed Co.
DeAnza*	Z88-8	*Zoysia japonica* Steud.	Vegetative	West Coast Turf
J-37	J-37	*Zoysia japonica* Steud.	Seeded	Jacklin Seed Division J.R. Simplot
J-36	J-36	*Zoysia japonica* Steud.	Seeded	Jacklin Seed Division J.R. Simplot
GNZ*	ZT-11	*Zoysia japonica* Steud.	Vegetative	Greg Norman Turf
PST-R7ZM	PST-R7ZM	*Zoysia japonica* Steud.	Seeded	Pure-Seed Testing, Inc.
Zorro*	DALZ 9601	*Zoysia matrella* (L.) Merr.	Vegetative	Natl. Turfgrass Eval. Progr.
PZA 32	PZA 32	*Zoysia japonica* Steud.	Seeded	Patten Seed Co.
J-14	J-14	*Zoysia sinica* Hance	Seeded	Jacklin Seed Division J.R. Simplot
DALZ0104	DALZ 0104	*Zoysia matrella* (L.) Merr.	Vegetative	Turfgrass America
PST-R7MA	PST-R7MA	*Zoysia japonica* Steud.	Seeded	Pure-Seed Testing, Inc.
DALZ0101	DALZ 0101	*Zoysia matrella* (L.) Merr.	Vegetative	Turfgrass America
Meyer*	Z-52	*Zoysia japonica* Steud.	Vegetative	Natl. Turfgrass Eval. Progr.
VJ		*Zoysia japonica* Steud.	Vegetative	Bladerunner Farms, Inc.
Cavalier*	DALZ8507	*Zoysia matrella* (L.) Merr.	Vegetative	M.C. Engelke, Texas A&M Univ.
Victoria*	Z88-14	*Zoysia japonica* Steud.	Vegetative	West Coast Turf
PST-R7TH	PST-R7TH	*Zoysia japonica* Steud.	Seeded	Pure-Seed Testing, Inc.
Emerald*	34-35	*Z. japonica x.Z. pacifica* ¶	Vegetative	Natl. Turfgrass Eval. Progr.
DALZ0105	DALZ 0105	*Zoysia matrella* (L.) Merr.	Vegetative	Turfgrass America
Empress*	SS-300	*Zoysia japonica* Steud.	Vegetative	Sod Solutions
Himeno		*Zoysia japonica* Steud.	Vegetative	Zoysian Japan Co.
Zeon*		*Zoysia matrella* (L.) Merr.	Vegetative	Bladerunner Farms, Inc.
Royal*	DALZ 9006	*Zoysia matrella* (L.) Merr.	Vegetative	M.C. Engelke, Texas A&M Univ.
Empire*	SS-500	*Zoysia japonica* Steud.	Vegetative	Sod Solutions
Diamond*	DALZ 8502	*Zoysia matrella* (L.) Merr.	Vegetative	M.C. Engelke, Texas A&M Univ.

† Type of establishment (propagation) method typically used by practitioners for each cultivar. Cultivars available by seed are typically seeded, with other cultivars typically established vegetatively by sprigs, plugs or sod. All cultivars were established by vegetative plugs into field plots for this study.

‡ Cultivars sorted according to establishment rate (Table 2.3).

§ Cultivar names followed by an asterick (*) are commercially available.

¶ Formerly *Zoysia japonica* Steud. *x. Zoysia tenuifolia* Willd. ex Thiele (Forbes, 1962), now *Z. japonica x. Z. pacifica* Goudsw. (Anderson, 2000).

Table 2.2. Growth analysis abbreviations, meanings, units, formulae, symbols and quantities used for *Zoysia* spp. growth rate analysis.

Abbreviation	Meaning	Units	Formulae†
CGR	mean crop growth rate	mg d^{-1}	$(W_2-W_1)/(T_2-T_1)$
RGR	mean relative growth rate	mg g^{-1} d^{-1}	$(\log_e W_2-\log_e W_1)/(T_2-T_1)$
ULR	mean unit leaf rate‡	g m^{-2} d^{-1}	$(W_2-W_1)/(T_2-T_1)*[(\log_e L_{A2}-\log_e L_{A1})/(L_{A2}-L_{A1})$
LAR	mean leaf area ratio	m^2 g^{-1}	$[(L_{A1}/W_1)+(L_{A2}/W_2)]/2$
SLA	specific leaf area	m^2 g^{-1}	$[(L_{A1}/L_{W1})+(L_{A2}/L_{W2})]/2$
LWR	leaf weight ratio	g g^{-1}	$[(L_{W1}/W_1)+(L_{W2}/W_2)]/2$
SWR	stem weight ratio	g g^{-1}	$[(S_{W1}/W_1)+(S_{W2}/W_2)]/2$
RWR	root weight ratio	g g^{-1}	$[(R_{W1}/W_1)+(R_{W2}/W_2)]/2$

Symbol	Quantity
W	total dry weight of the plant
T	time in days
L_A	leaf area
L_W	dry weight of leaf blade
S_W	dry weight of stem
R_W	dry weight of root

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† Formulae from Radford (1967) and Hunt et al. (2002).

‡ Also known as mean net assimilation rate (NAR) by some authors.

Table 2.3. Zoysiagrass coverage, establishment rate, stolon length and stolon growth rate by cultivar. Data were averaged over 2004 and 2005.

Cultivar	59 DAP coverage	91 DAP coverage	Establishment rate†	43 DAP‡ Mean stolon length	43 DAP Total stolon length	Stolon growth rate§
	cm^2	cm^2	$\log_e$ (coverage) d^{-1}	cm	cm	mm d^{-1}
6186¶	959	4142	0.0448	26.2	365	11.3#
DALZ0102	889	3450	0.0433	17.6	238	7.7
El Toro	826	3480	0.0422	13.5	189	9.2
PZB 33	899	2609	0.0418	15.5	300	7.6
Chinese Common	821	2838	0.0410	22.0	307	11.1
6136	732	2986	0.0399	15.8	229	7.8
Companion	779	2417	0.0399	14.3	214	8.5
BMZ 230	704	3028	0.0397	17.8	237	9.5
Palisades	622	2912	0.0380	11.1	117	9.3
PST-R7LT	651	2299	0.0379	13.7	157	6.5
Zenith	677	1679	0.0369	11.0	156	5.8
DeAnza	609	2096	0.0368	11.1	194	4.6
J-37	588	2412	0.0365	11.6	163	9.0
J-36	600	2151	0.0363	12.1	163	8.4
GNZ	528	1915	0.0354	11.6	152	5.1
PST-R7ZM	516	1843	0.0347	10.0	156	6.5
Zorro	469	1931	0.0344	9.2	176	6.6
PZA 32	513	1870	0.0337	11.1	104	7.9
J-14	487	1741	0.0336	11.5	128	8.6
DALZ0104	427	1754	0.0325	9.9	108	3.7
PST-R7MA	450	1502	0.0323	8.0	93	6.1
DALZ0101	395	1562	0.0315	10.0	129	5.2
Meyer	400	1203	0.0307	8.1	68	5.0
VJ	359	1430	0.0306	7.4	43	7.7
Cavalier	358	1384	0.0297	6.6	76	5.7
Victoria	347	1279	0.0294	7.5	73	5.6
PST-R7TH	344	1186	0.0286	8.8	72	5.7
Emerald	353	1171	0.0285	7.9	95	3.8
DALZ0105	317	1403	0.0283	6.0	89	4.4
Empress	321	1053	0.0280	7.5	68	2.4
Himeno	282	1139	0.0274	10.9	165	6.6
Zeon	279	1142	0.0268	6.5	65	6.0
Royal	289	1089	0.0263	8.6	124	6.2
Empire	350	1499	0.0253	5.4	46	5.8
Diamond	184	425	0.0191	2.6	11	1.7
Mean	524	1943	0.0338	11.1	145	6.6
$LSD_{0.05}$	165	636	0.0047	3.6	65	2.3

† Establishment rate was determined by fitting coverage data across time to the model [$\log_e$ (Coverage) = (K*DAP) + $\log_e$(64)], where K is the rate of increase (establishment rate) and 64 cm^2 is the initial plug coverage.

‡ Days after plugging (DAP)

§ Stolon growth rate was determined by dividing the growth (length) from 57 DAP to 64 DAP and 64 DAP to 71 DAP of each stolon by 7 d.

¶ Cultivars are sorted according to the establishment rate column.

Mean of 48 stolons (three samples per plot with four replications on two sampling intervals over two years).

Table 2.4. Influence of species and establishment type on zoysiagrass coverage 91 days after plugging and establishment rate. Data were averaged over type, species and years.

Species	Type†	91 DAP Coverage	Establishment Rate‡
		cm^2	$\log_e$ (coverage) d^{-1}
Z. japonica	Vegetative	2258 a§	0.0351 a
Z. japonica	Seeded	2046 a	0.0361 a
Z. matrella	Vegetative	1317 b	0.0286 b

† Type of establishment (propagation) method typically used by practitioners for each cultivar. Cultivars available by seed are typically seeded, with other cultivars typically established vegetatively by sprigs, plugs or sod. All cultivars were established by vegetative plugs into field plots for this study.

‡ Establishment rate was determined by fitting coverage data across time to the model [$\log_e$ (Coverage) = (K*DAP) + 4.1589], where K is the rate of increase (establishment rate).

§ Within columns, means followed by the same letter are not significantly different according to LSD ($\alpha = 0.05$).

Table 2.5. Growth analysis mean values of zoysiagrass (*Zoysia* spp.) cultivars grown in a growth chamber maintained at 30°C with 70% relative humidity and 14-h photoperiod of 816 μmol m^{-2} s^{-1} photosynthetically active radiation. In additon to the anova table, correlation coefficients between mean relative growth rate and other growth components were calculated and their significances are given at the bottom of the table.

		Growth Analysis							
Cultivar	Species	RGR †	CGR	ULR	LAR	SLA	LWR	SWR	RWR
		mg g^{-1} d^{-1}	mg d^{-1}	g m^{-2} d^{-1}	-----m^2 g^{-1}-----		-------------g g^{-1}------------		
Meyer	*Z. japonica*	85‡b§	50 bc	12.6 c	7.1 a	23.8 a	0.293 a	0.586 c	0.121 c
El Toro	*Z. japonica*	85 b	90 a	17.3 bc	4.9 c	19.7 c	0.241 c	0.622 b	0.137 b
Diamond	*Z. matrella*	120 a	39 c	22.1 ab	5.8 b	21.5 b	0.267 b	0.570 c	0.163 a
Zorro	*Z. matrella*	90 b	62 b	23.6 a	4.1 d	16.7 d	0.239 c	0.644 a	0.117 c
					ANOVA				
Year (Y)		***	***	***	*	*	NS	**	***
Block (Year)		NS	NS	NS	***	***	***	***	***
Harvest (H)		***	***	NS	***	***	***	***	***
H × Y		***	***	**	***	***	***	NS	***
Cultivar (C)		***	***	***	***	***	***	***	***
C × Y		NS	***	*	***	***	***	***	***
H × C		NS	NS	NS	***	***	***	NS	***
H × C × Y		NS	NS	NS	NS	*	***	NS	***
p (correlation coefficients)			NS	NS	NS	NS	NS	NS	NS

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*,**,*** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively. NS, Not significant ($p > 0.05$)

† RGR, relative growth rate; CGR, crop growth rate; ULR, unit leaf rate: LAR, leaf area ratio; SLA, specific leaf area; LWR, leaf weight ratio; SWR, stem weight ratio; and RWR, root weight ratio.

‡ Means of 80 values (2 experimental replications and 5 harvests at 8 plants per harvest) for CGR, RGR, ULR, LAR, SLA, LWR, SWR, and RWR. Plants were harvested weekly for a total of six weeks per experimental replication.

§ Within columns, means followed by the same letter are not significantly different according Tukey's test for significant differences ($\alpha = 0.05$).

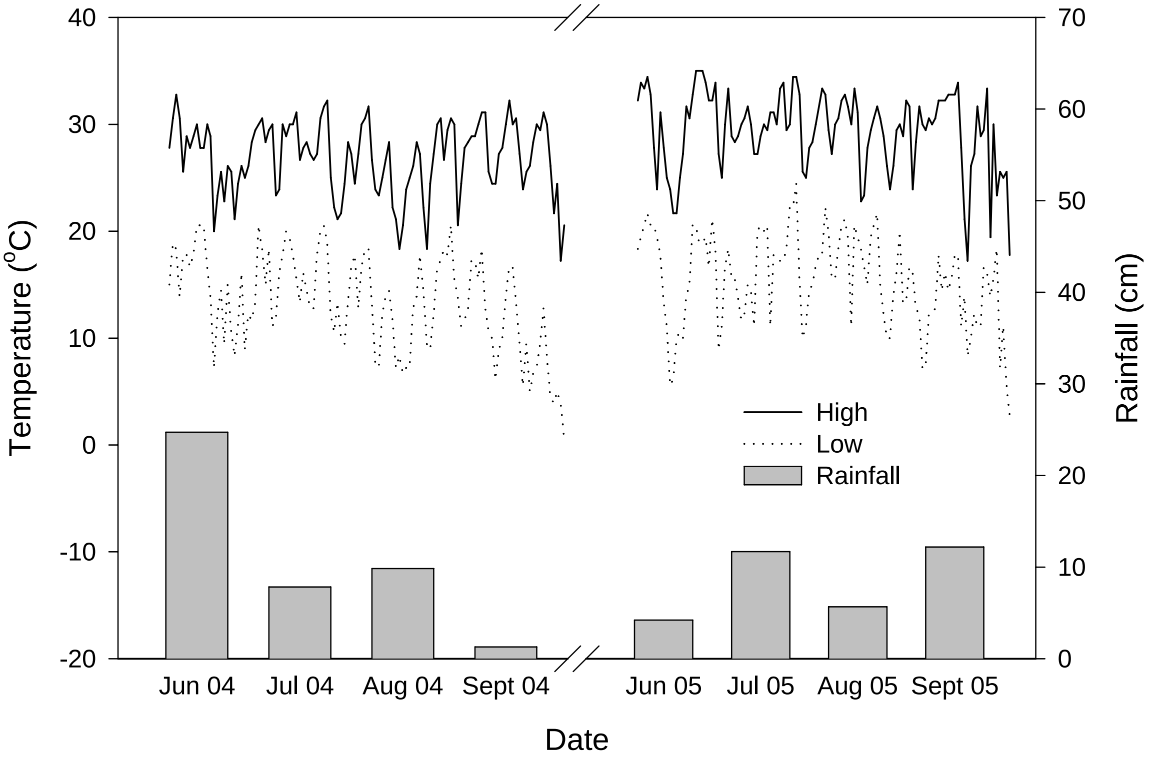

Figure 2.1. Maximum and minimum daily temperatures and monthly rainfall during 2004 and 2005.

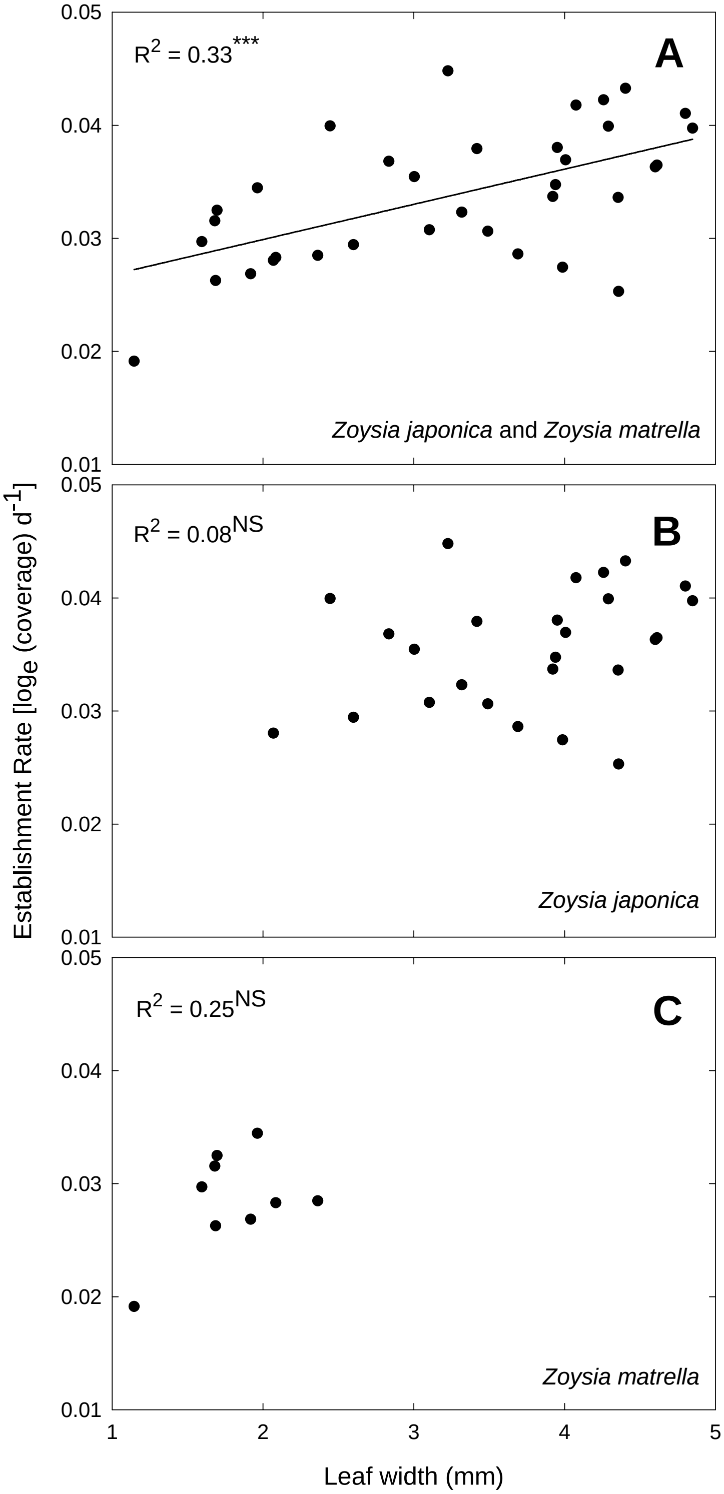

Figure 2.2. Relationship between leaf width and establishment rate for both species (A), *Zoysia japonica* (B) and *Zoysia matrella* (C). Establishment rate was determined by fitting coverage data across time to the model [$\log_e$ (Coverage) = (K*DAP) + $\log_e$(64)], where K is the rate of increase (establishment rate). Significant at $P < 0.001$ level (***) or not significant (NS).