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Ecosystem Factors Influencing the Success of Riparian Restoration in Whatcom County

Crystal Elliot

Abstract

Riparian corridors are complex and diverse ecosystems that are essential to the maintenance of global health. The total area occupied by riparian ecosystems in the United States has plummeted in the last 200 years to only 20% of its initial size. The recent movement to restore these fragile and complex ecosystems has produced outcomes of variable success. The Nooksack Salmon Enhancement Association's riparian restoration project at Schell Creek in Ferndale, WA provides an example of an effort that exhibits mixed results. Our experiment explored reasons for the variable success of the restoration vegetation and investigated several ecosystem factors that may limit growth of seedlings at this site. These included competition from grasses, low nutrient availability, lack of mycorrhizal associations, and water availability.

In May of 2000, seedlings of red alder (*Alnus rubra*) and Sitka spruce (*Picea sitchensis*) were planted in a full factorial design with treatments consisting of tilling to reduce competition (T), mycorrhizal inoculation (M), and nutrient supplementation in the form of fertilizer (F). Three replicate blocks of each treatment were situated in both the upper (north) and lower (south) reaches of the project, which differed in water availability. We assessed differences between treatment effects by comparing changes in tree heights, total growth, and photosynthetic rates (determined using a LI-COR 6400).

While we had hypothesized that increased water availability in the upper reach helped revegetation success, the excess soil moisture actually appeared to have negative effects on experimental seedlings: waterlogging caused poor growth and mortality in some cases, leading to negligible treatment effects in the upper reach. Reducing grass competition by tilling, which increased the water and nutrients available to experimental trees, had the largest positive effect on alder growth in the south site. Mycorrhizae had a positive effect on spruce growth, although these effected were muddled by interactions with tilling and fertilizer treatments, which have both been shown to have negative effects on the success of mycorrhizae.

Reducing competition is a technique used widely in riparian restoration, a practice whose benefit is bolstered by the observed considerable effect of tilling on experimental trees at the Schell Creek site. As the use of mycorrhizae as a restoration tool is not common procedure, our results suggest that future studies should continue to explore the advantages of this treatment, especially when planting in low nutrient areas. Current restoration recommendations emphasize the importance of assessing abiotic conditions before selecting project sites and restoration vegetation, and we agree given the very different treatment responses of our experimental species and the environmental variability at the site. We believe that further development of these techniques will continue to enhance project success, thereby providing a substantial contribution to the strong movement afoot to reestablish riparian ecosystems in Whatcom County and elsewhere.

Introduction

Riparian ecosystems have been labeled as "the most diverse, dynamic, and complex biophysical habitats on the terrestrial portion of the earth" (Naiman et al., 1993). A riparian zone consists of a stream channel and the surrounding terrestrial landscape interacting with that channel (Naiman et al., 1993). Their additions to global ecological diversity and the ecosystem services they provide are substantial both in number and importance (Alpert et al., 1999; Goodwin et al., 1997; Gregory et al., 1991; Naiman et al., 1993; Simenstad and Thom, 1996; Young, 1996). Riparian habitats contribute immensely to sustaining local water quality and salmon populations by way of their run-off filtering and water-cooling properties (Berg, 1995; Carpenter et al., 1992). These habitats also support other unique wildlife, and both plant and animal species richness in these zones is unusually high compared to other ecosystems (Karr and Chu, 1999; Naiman et al., 1993). For example, studies in Sweden, Finland, the Peruvian Amazon Basin, southern France, and the northwestern United States found that riparian vascular plants exhibited extremely high levels of diversity in all of these areas (Decamps and Tabacchi, 1993; Gregory et al., 1991; Junk, 1989; Kalliola and Puhakka, 1988; Kalliola et al., 1992; Raedeke, 1989; Salo et al., 1986 as cited in Naiman et al., 1993). The ecosystem services provided by these environments, such as detoxifying and purifying water, have been increasingly recognized, and awareness of their considerable significance to humans is continuing to grow (Young, 1996). People also depend on riparian habitats for a variety of industrial and economic activities, as well as deriving sport and recreational utility from the usage of these ecosystems (Carpenter et al., 1992).

The number of riparian and wetland zones in the United States has plummeted in the last 200 years, resulting in a total area less than 20% of its previous amount (Naiman et al., 1993). The majority of this loss has resulted from urban and agricultural development; both caused by the escalating human population (Brussard, 1991; Carpenter et al., 1992; Karr and Chu, 1999; Madsen, 1986). This destruction of riparian ecosystems has had devastating consequences. Water quality and water resources in many areas have been significantly degraded, and wildlife populations have been considerably damaged (Berg, 1995; Burrows et al., 1998; Karr and Chu, 1999; Young, 1996). Pacific Northwest salmon populations have been hit especially hard by the disruption and depletion of riparian corridors (Berg, 1995; Karr and Chu, 1999; Nehlsen, 1997). The number of fish returning to spawning and rearing grounds has dropped dramatically in recent years, due to habitat destruction and the stripping of Large Woody Debris (LWD) from spawning corridors (Berg, 1995; Young, 1996).

A strong movement is afoot to reestablish the vigor of these fragile ecosystems (Malakoff, 1998; Naiman et al., 1993; Young, 1996). Some believe that the solution lies in allowing these wounded riparian zones to heal themselves (Berg, 1995). However, Berg states that this "passive approach leaves damaged ecosystems degraded for decades, perhaps centuries" (1995). An alternative solution, restoring the damaged ecosystems, is an idea that has continued to gain momentum and support in recent years (Goodwin et al., 1997; Malakoff, 1998; Naiman et al., 1993; Streever and Zedler, 2000; Young, 1996). Because riparian zones are such complex ecosystems, the restoration approach demands the cooperation of many scientific disciplines and the consideration of a number of interacting factors (Young, 1996). This makes the restoration of riparian and wetland zones a very collaborative, fragile, and difficult endeavor. Restoration efforts are often rewarded with positive outcomes, but, sometimes these very involved and time-consuming projects turn out to be unsuccessful (Malakoff, 1998; Mitsch and Wilson, 1996). Given these contradicting results, there has been much controversy surrounding riparian/wetland restorations, and numerous studies have been conducted that have tested and challenged the success and reliability of this approach (Mitsch and Wilson, 1996; Mitsch et al., 1998). With the goal of assessing the viability of the resulting constructed ecosystems, these studies have mainly focussed on scrutinizing the overall success of restoration sites. Not many inquiries, however, have focussed specifically on the influence of individual ecosystem factors on the success of a restoration project. Identification of problems with particular ecosystem variables would allow investigators to determine which aspects of a project had failed and which had succeeded. This method, instead of looking only at overall success, would allow for greater "fine-tuning" of restoration efforts in the future, and would reduce usage of the "hit and miss" approach that is currently commonplace.

Vegetation productivity is the main determinant of the success of any given project (Mitsch and Wilson, 1996; Mitsch et al., 1998). With this, great attention is given to plants, namely trees, to promote their establishment. Keeping in mind the complexity of these ecosystems, any number of variables may inhibit seedlings from gaining a foothold in a newly restored riparian environment.

This is the avenue I chose to explore with my experiment: What might limit revegetated plant growth, and therefore limit project success, in a restored riparian ecosystem? The Schell Creek riparian restoration site in Ferndale, WA provided an excellent study location for exploration of this question. The strong presence of grasses on the site indicated that competition would be a likely ecosystem factor to limit the growth of revegetated seedlings. We hypothesized that competition for resources from neighboring plants would have a negative effect on tree establishment. We grew trees in both competitive and non-competitive environments to see if and to what degree seedlings were effected by this factor. In addition, a soil test revealed that the site was deficient in nitrogen, sulfur, and, especially, phosphorus (Table 1), and so it was possible that a lack of nutrients might limit newly planted seedlings. We grew trees with and without a nutrient supplement to test this hypothesis. Absence of the proper mycorrhizal associations was another ecosystem factor that we thought might limit tree growth. Herbaceous pasture grasses, such as those characterizing the Schell Creek restoration site, do not foster ectomycorrhizae (Barbour et al., 1999; Smith and Read, 1997), which are the symbioses exhibited by most temperate tree species (Barbour et al., 1999). Since the site was in an area that had been converted from forest to pasture at least one hundred years ago (Steve Brommers; pers. comm. May 2001), the native mycorrhizal community may have been greatly reduced. Past plowing and disturbance may also have had the effect of decreasing the mycorrhizal population (Cuenca and Lovera, 1992; McGonigle and Miller, 1996). Mycorrhizae are often essential for proper seedling development because they play a significant role in the uptake of nutrients, namely phosphorus, which is vital in the early stages of tree growth (Gange et al., 1990; Raven et al., 1999; Reid and Woods, 1968). This relationship with a fungal partner is the most prevalent symbiosis in the plant kingdom (Molles, 1999). Given the importance of mycorrhizae and the low-phosphorus environment at the Schell Creek site, it was quite possible that a lack of mycorrhizal inoculation would also limit seedling success. We tested this by inoculating some of our trees with mycorrhizae and leaving others untreated. Water availability was a factor that we thought might be limiting the growth of previously established trees at this specific riparian restoration site. There was a distinct difference in productivity between the upper and lower reaches of the site, represented by differences in alder height and vigor. We believed this variation to be caused by a difference in soil moisture, and we explored this idea by taking volumetric soil moisture measurements throughout the summer using Time Domain Reflectometry (TDR).

Methods

Study Site

Experimental plots were established along the bank of Upper Schell Creek in Ferndale, Washington on a riparian site restored recently (1994, 1995) by the Nooksack Salmon Enhancement Association (NSEA), an organization dedicated to the restoration and preservation of native salmon habitat. The property is owned by the City of Ferndale, which donated the use of the land to support salmon restoration. This location experiences a maritime climate with cool, wet winters and mild summers. The growing season in this area extends from approximately March to November (Stevens and Bursick, 1990).

This site was once a native riparian environment through which Schell Creek flowed on its way to meeting the Lummi River (Shannon Moore; pers. comm. September 2000). In order to expand pastureland, the creek was then diverted from its natural course and forced to parallel the property by way of a roadside ditch (Field, 1997 as cited in Burrows et al., 1998; Lookabill et al., 1998). The city of Ferndale then acquired the property and left it as open grassland designated as city park property (Field, 1997 as cited in Burrows et al., 1998).

In the summer of 1994, NSEA constructed a new channel that diverted the creek's flow away from the road on a meandering course through the property; eventually spilling into the Lummi River (NSEA, 1995b). Following new channel construction, riparian vegetation and grasses were planted in the fall for raw bank stabilization. Extensive planting occurred in the spring of 1995 by the North Whatcom Rotary Club and other volunteers (NSEA, 1995b). Among the wide variety of riparian plants that were used for revegetation are *Alnus rubra* (red alder) and *Salix spp.* (willow), which, along with *Typha latifolia* (common cattail) and invasive *Phalaris arundinacea L.* (reed canary grass), now dominate the restoration site. Other native plants used for revegetation in local riparian restoration efforts include *Fraxinus latifolia* (Oregon ash), *Pseudostuga menziesii* (Douglas fir), *Populus balsamifera* (black cottonwood), *Picea sitchensis* (Sitka spruce), *Taxus brevifolia* (Pacific yew), *Thuja plicata* (western red cedar), and *Holodiscus discolor* (oceanspray) (NSEA, 1995a). Currently, the vegetation on the north side of the culvert (referred to as the upper reach) is noticeably more productive than that on the south side of the culvert (referred to as the lower reach).

Experimental Design

Two tree species frequently used by NSEA in local riparian restorations, *Alnus rubra* (red alder) and *Picea sitchensis* (Sitka spruce), were utilized for this project. *Alnus rubra* is a fast-growing deciduous species that is often found in moist, riparian habitats and participates in actinorhizal nitrogen-fixing symbioses (Barbour et al., 1999; Taiz and Zeiger, 1998). *Picea sitchensis* is a native conifer that is restricted to maritime climates and prefers moist soil (Earle, 1999). Seedlings of both tree types were donated by NSEA, who acquired them from the Washington Conservation Commission's Plant Materials Center. We hoped that using both a conifer and a deciduous species for experimentation would ensure more generalized and inclusive results.

Twelve 3.0 x 4.0 m blocks were created: six blocks for spruce and six blocks for alder (six replicate blocks per species). Within each block, two sets of four 1.0 x 1.0 m plots were separated by a 1.0 x 4.0 m buffer strip (Fig. 1).

I used a randomized split-split plot experimental design for a total of eight different treatments in each block (one tree per plot and treatment) (Fig 1). To test individual factors and factor interactions, the three treatment types, mycorrhizal inoculation, tillage, and fertilization, were administered in a full factorial cross--control plots (C); each group alone: tilling (T), mycorrhizae (M), fertilizer (F); all two-way combinations: tilling and mycorrhizae (TM), tilling and fertilizer (TF), mycorrhizae and fertilizer (MF); and the three-way combination: tilling, mycorrhizae, and fertilizer (TMF).

Six experimental plots, three blocks for each species, were established in both the lower and upper reaches of the site (Fig. 1). Block placement was limited by the need to coordinate with NSEA plantings.

Planting occurred on May 8, 2000 with the help of WWU and NSEA volunteers. Plots requiring a tilling treatment were tilled with a Rototiller just prior to planting: trees with tilling treatments were mulched three days after planting to prevent grass regrowth. Periodic weeding and Rodeo® application in following months were used to control the infiltration of weeds into the tilled areas. Those trees receiving mycorrhizae treatment were inoculated at the time of planting with Plant Success Root Dip Gel®, (Mycorrhizal Applications, Grants Pass, OR). Bare-root trees were dipped in the gel immediately prior to planting. The inoculum contained spores from five species of ectomycorrhizal fungi, (*Pisolithus tinctorius,* and four species of *Rhizopogon*) and seven species of endomycorrhizal fungi, (*Glomus mosseae, Glomus intraradices, Glomus clarum, Glomus monosporous, Glomus deserticola, Glomus brasilianum,* and *Gigaspora margarita*). Expandable tubing was also placed around the base of the alder seedlings to protect against vole herbivory. Fertilizer treatments were administered after tree establishment and soil sample collection and analysis by SoilTest (Moses Lake, WA) to determine nutrient deficiencies at the site (Table 1). Using SoilTest's results, the Whatcom Farmers Coop mixed a fertilizer medium meeting the specific needs of our soil. Fertilizer was applied approximately two months after planting on July 13, 2000 and was reapplied approximately a month later on August 22, 2000. Per application, 85 g of fertilizer in pellet form was distributed around the base of the specified trees, resulting in an application of 20.29 g Nitrogen, 12.16 g Phosphorus, and 4.38 g Sulfur, per square meter. Watering on July 20, 2000 (two gallons of stream water per tree) was necessary to dissolve the fertilizer after the first application, but rain following the reapplication eliminated the need for a second watering.

Assessment of Productivity

Height growth, total growth, and photosynthesis rates were measured to determine differences in productivity among treatments. Height measurements were taken on May 23, June 7, June 22, July 5, August 4, and September 6, 2000. Alder heights were taken as the distance from the base of the tree to the apical meristem. Since the apical meristem on the spruce was sometimes difficult to determine, we measured from the base to the greatest vertical extent of the tree. Final height results were then compared to initial measurements to achieve height growth values.

Photosynthetic rates of the alder were measured using a LI-COR 6400 (LI-COR, 1999). Measurements were taken on July 26, 2000. Leaves for measurement were chosen that were mature and receiving full sun (i.e., those leaves most representative of maximum photosynthesis). Measurements were taken for approximately one minute using "survey mode". The chamber environment was set to ambient conditions (LED: 1800 PAR, CO_2 levels: 428 ppm, Relative Humidity: 41%, Flow: set to maintain constant humidity). Two leaves per tree were sampled, and the measurements were averaged to get an average photosynthetic rate for each tree.

Total stem length of each tree was measured on September 6, 2000 to determine total growth. Total stem length included the height of the main stem axis, as well as the length of the branches and sub-branches. This measurement was compared to the initial tree height to get total growth, since branching was minimal in seedlings.

Soil Moisture

We used Time Domain Reflectometry (TDR) to test our hypothesis that the variable productivity of the revegetated trees at the Schell Creek was due to differences in water availability between the upper and lower reaches of the site. TDR is a method that determines the dielectric constant of moist soils by the rate of electromagnetic pulse return and then converts the result to volumetric water content (Cassel et al., 1994; Herkelrath et al., 1991). We used a three-prong method and placed two sets of 30 cm and 60 cm probes in each block, one probe set of each length in both the tilled and non-tilled areas. TDR measurements were taken on June 29, July 13, August 1, August 22, and September 5, 2000.

Statistics

All analyses of variance and regressions were done using the General Linear Model in SYSTAT (SYSTAT, 1999). The dependent variables, height growth, total growth, and photosynthesis rates were analyzed using a factorial model incorporating reach (upper and lower), with and without tilling, with and without fertilizer, and with and without mycorrhizae. The model was described as: variable= constant + reach + block(reach) + fert + myc + till + fert*myc + fert*till + fert*reach + myc*till + myc*reach + till*reach + fert*myc*till + fert*myc*reach + fert*till*reach + myc*till*reach + fert*myc*till*reach. Water availability was determined using the following model: soil moisture = reach + block(reach) + till + reach*till. The block effects were nested within the reach effects for both treatment and water availability analyses, and each measurement date for soil moisture was analyzed separately.

Results

In terms of soil moisture, the upper reach was significantly wetter than the lower reach. At the 30cm depth, soil moisture in the upper reach was significantly greater than that of the lower reach in both the tilled and non-tilled areas of each block throughout the summer (Fig. 2). Upper reach soil moisture values in the tilled areas averaged 35 % saturation, while those in the lower reach averaged 25% saturation. Upper reach soil moisture in the non-tilled areas averaged 21% saturation, while those in the lower reach averaged 14% saturation (Fig. 2). A similar pattern was found at 60cm depth (Fig. 3).

Upper reach soil moisture values in the tilled areas averaged 43% saturation, while those in the lower reach averaged 30% saturation. Upper reach soil moisture values in the non-tilled areas averaged 35% saturation, while those in the lower reach averaged 22% saturation (Fig. 3). Many of the experimental seedlings in the upper reach were waterlogged during the wetter early summer months, leading to mortality in one alder and six spruce.

The alder grew significantly more in height in the lower reach than in the upper reach (Fig. 4). Tilling had a significant positive effect on height growth in the lower reach: the trees that received a treatment with tilling grew significantly more than those without. The other treatments had negligible effects on alder height growth (Fig. 4). The total growth of alder in the lower reach was significantly greater than that in the upper reach (Fig. 5). Tilling also had a significant positive effect on total growth in the lower reach. There was a trend for a fertilizer, mycorrhizae, tilling interaction: fertilizer and mycorrhizae together had a positive effect on total growth, but only in the presence of tilling (Fig 5). Patterns for maximum photosynthesis were similar to those for growth, though not as strong (Fig. 6). Photosynthesis rates for the alder were significantly greater in the lower reach, and there was a trend for a positive tilling effect in the lower reach (Fig. 6).

There was a trend for a positive effect of mycorrhizae on spruce height growth in the lower reach (Fig. 7). Other treatments had negligible effects. The total growth of the spruce was significantly greater in the lower reach (Fig. 8). A significant mycorrhizae effect was visible in the lower reach, but this was muddled by interactions with the other treatments. For example, seedlings inoculated with mycorrhizae alone exhibited greater total growth than those receiving mycorrhizae treatments in combination with tilling, fertilizer, or both (Fig. 8).

Note: Mortality was excluded from statistical analyses of treatment effects, however, including values of "zero" for dead trees did not change results.

Discussion

The greater water availability in the upper reach than in the lower reach (Fig, 2 and 3) may explain the difference in productivity of the revegetated tree growth between the upper and lower reaches of the Schell Creek site. Tree cores revealed that the revegetated alder in the upper reach were one to two years older than the trees in the lower reach, but this slight age difference would not account for the large observable difference in productivity. This issue does, however, deserve further investigation. The additional soil moisture in the upper reach would enable the established alder trees to maintain a higher level of productivity throughout the summer months in the past years than those trees in the drier lower reach, therefore leading to overall greater growth in the upper reach (Taiz and Zeiger, 1998).

Whereas increased soil moisture appeared to improve growth of established trees, it had a negative effect on newly planted seedlings. Most of our measurements showed that the experimental trees grew best in the lower reach where there was less soil moisture (Fig. 4,5,6, and 8). The saturated soil conditions in the upper reach created a hypoxic and anoxic root environment, thus limiting aerobic root respiration (Lambers et al., 1998). These conditions caused poor growth in most cases, and prevented the treatments from having much effect on the experimental trees in the upper reach.

The soil moisture inquiry also revealed that the tilled areas were wetter than the non-tilled areas (Fig. 2 and 3). By tilling, we decreased the number of plants absorbing water, thereby decreasing the amount of evapotranspiration (Lambers et al., 1998; Taiz and Zeiger, 1998). As said before, however, this increased soil moisture was not beneficial to experimental trees in the upper reach where water-logging was a problem. In addition, by eradicating grasses, the tilling treatment reduced competition for nutrients. This resulted in more water and nutrients available for uptake by experimental trees in tilled areas, thus improving their productivity. These ideas help explain the alder results, where seedlings exhibited significantly greater growth and photosynthesis in tilled areas (Fig. 4, 5, and 6).

Inoculating with mycorrhizae tended to have a positive effect on spruce growth (Fig. 7 and 8), which was not surprising given Sitka spruce's tendency to engage in ectomycorrhizal symbioses (Harley and Smith, 1983; Smith and Read, 1997) and the site's phosphorus shortage and potential deficiency in the proper mycorrhizae. The alders' lack of response to the treatment was initially puzzling because it has been shown that red alder also exhibit and benefit from mycorrhizae (Harley and Smith, 1983; Molina, 1979; Smith and Read, 1997). After learning that we had been misinformed about the content of the gel inoculum, however, the reasons for this result became clear: the fungal symbionts that have been shown to associate with red alder, *Alpova diplophoeus, Paxillus involotus, Astraeus pteroides, and Scleroderma hypogaeus* (Harley and Smith, 1983; Molina, 1979; Smith and Read, 1997), were absent from the mixture used for the mycorrhizae treatment. *Pisolithus tinctorius*, one of the many mycorrhizal fungi commonly utilized by Sitka spruce (Harley and Smith, 1983), was, on the other hand, present in the inoculum. The mycorrhizae treatment didn't have an effect on either experimental tree species in the upper reach which exhibited increased soil moisture and waterlogging in early summer months (Fig. 3-8). These results are consistent with findings showing that mycorrhizal infection can be reduced in waterlogged habitats (Smith and Read, 1997).

Contrary to our predictions, seedlings receiving a combination of all treatments did not always exhibit the greatest productivity. This idea was illustrated by the spruce total growth results, where mycorrhizae had a significant positive effect alone, but was less effective in combination with the other treatments (Fig. 8). These negative treatment interactions have potential biological explanations. In regard to a fertilizer-mycorrhizae interaction, it has been shown that mycorrhizal fungi may be suppressed or even exhibit parasitic behavior in the presence of abundant phosphorus (Lambers et al., 1998; Marler et al., 1999), a main component of our fertilizer. Mycorrhizal infection has also been found to be hindered in tilled soil (McGonigle and Miller, 1996), which could explain the negative tilling-mycorrhizae interaction.

An interesting finding from this study was that fertilizing had essentially no effect on seedling success. This would suggest that low nutrient availability was not a limiting factor, but the soil test (Table 1) revealed otherwise. And it has been shown that fertilizer treatments, especially nitrogen on spruce and phosphorus on alder, tend to improve growth (Brown, 1999; Chandler and Dale, 1995). This contradiction can perhaps be explained by the tardiness of the fertilizer treatment. The experimental trees were only exposed to the treatment for two months before the final measurements. Following experimental tree productivity in future years may show less ambiguous effects of the fertilizer treatment.

Competition from grasses was found to have the biggest influence on the success of seedling growth, and it was the ecosystem factor most limiting establishment of seedlings, especially alder, on this site. NSEA and other riparian restoration authorities have acknowledged the importance of reducing competition (Durkee-Neuman et al., 1999; Landers, 1997; Olson and Harris, 1997), and methods aimed at this goal have been incorporated into restoration schemes. Common procedures include weedwacking, mulching, and herbicide application (Durkee-Neuman et al., 1999). Mycorrhizal inoculation of restoration vegetation, although it has been utilized to some degree (Smith and Read, 1997), does not seem to be common a practice. Given the positive effect of mycorrhizae on Sitka spruce seedlings at the Schell Creek site, (and potentially on red alder given the proper circumstances), we recommend that future studies explore the advantages of using mycorrhizae as a restoration tool, especially in low nutrient areas. As seen in the mortality data, alder seedlings at Schell Creek were better able to cope with the saturated soil conditions than spruce seedlings, but both species were impaired by the excess soil moisture. Plant species have varying tolerances ranges in regard to water availability and other resources (Barbour et al., 1999; Lambers et al., 1998; Raven et al., 1999). With this as just one among many reasons, we agree with the consensus that it is necessary to assess and consider the complex abiotic conditions of an area when choosing project sites and vegetation for restoration planting (Goodwin et al., 1997; Kershner, 1997; Olson and Harris, 1997). This idea is becoming widely incorporated into riparian restoration recommendations and designs (Kentula, 1997; Kershner, 1997).

Fortunately, riparian restorations are improving in number and success (Goodwin et al., 1997), but as discussed, the convoluted science of riparian restoration is still far from perfected. As natural riparian ecosystems continue to be stressed by the ever-expanding human population, further development of this approach will become increasingly important for preserving these environments. By paying close attention to individual ecosystem factors (such as competition, mycorrhizal associations, and abiotic conditions), scientists will continue to fine-tune their restoration efforts to better accommodate the needs of specific ecosystems, leading to improved sustenance of these fragile habitats that are so vital to global health.

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Table 1. Results of soil test done on soil samples from the upper and lower reaches of the Schell Creek Restoration Site. Interpretation guide shows relative levels of important nutrients, where H=high, M=medium, and L=low in relation to red alder and sitka spruce requirements.

Upper Reach			
Actual Soil Test Results		Interpretation Guide	
Nitrate Nitrogen	2 ppm	Nitrogen	L
Available Phosphorus	2 ppm	Available Phosphorus	L
Potassium	209 ppm	Potassium	H
Sulfur	3 ppm	Sulfur	L
Boron	0.4 ppm	Boron	M
Zinc	2.1 ppm	Zinc	H
Manganese	32.3 ppm		
Copper	3.3 ppm		
Iron	320 ppm		
Calcium	1480 ppm		
Magnesium	546.8 ppm		

Lower Reach			
Actual Soil Test Results		Interpretation Guide	
Nitrate Nitrogen	2 ppm	Nitrogen	L
Available Phosphorus	1 ppm	Available Phosphorus	L
Potassium	87 ppm	Potassium	M
Sulfur	2 ppm	Sulfur	L
Boron	0.3 ppm	Boron	M
Zinc	1.8 ppm	Zinc	H
Manganese	8.5 ppm		
Copper	1.6 ppm		
Iron	157 ppm		
Calcium	1360 ppm		
Magnesium	619.7 ppm		

Figure. 1. Schell Creek Riparian Restoration Site location in Washington, site map, and example block layout with treatments (F=fertilizer, myc=mycorrhizae, till=tilling).

Figure 2. Water content at 30cm depth on five dates during the summer of 2000 in the tilled and non-tilled portions of blocks in both the upper and lower reaches of the Schell Creek Riparian Restoration Site. Measurements made with Time Domain Reflectometry.

Figure 3. Water content at 60cm depth on five dates during the summer of 2000 in the tilled and non-tilled portions of blocks in both the upper and lower reaches of the Schell Creek Riparian Restoration Site. Measurements made with Time Domain Reflectometry.

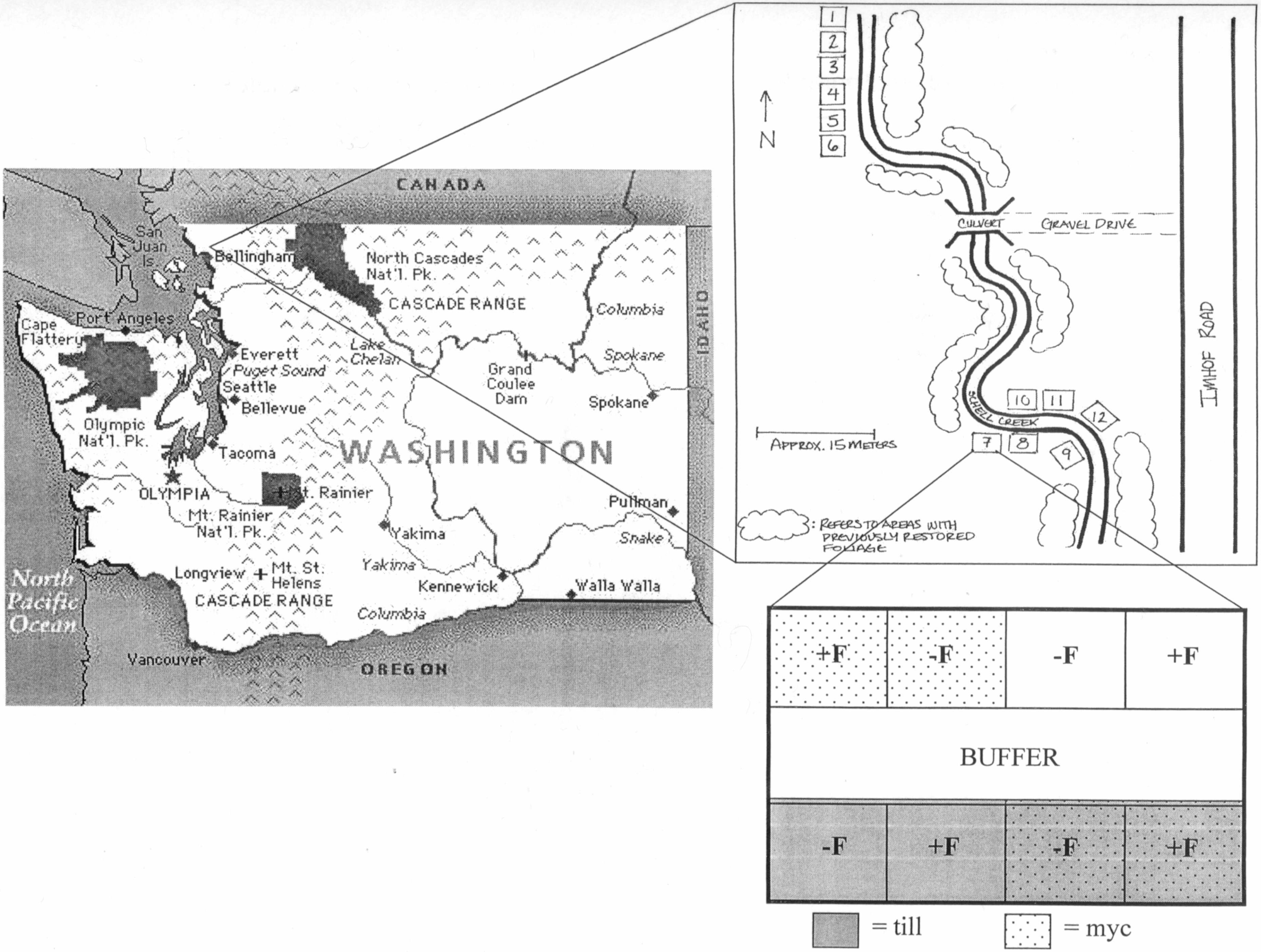
Figure 4. Average height growth of alder receiving eight different treatments (till, myc, fert, t*m, t*f, f*m, t*m*f) in the upper and lower reaches of the Schell Creek Riparian Restoration Site.

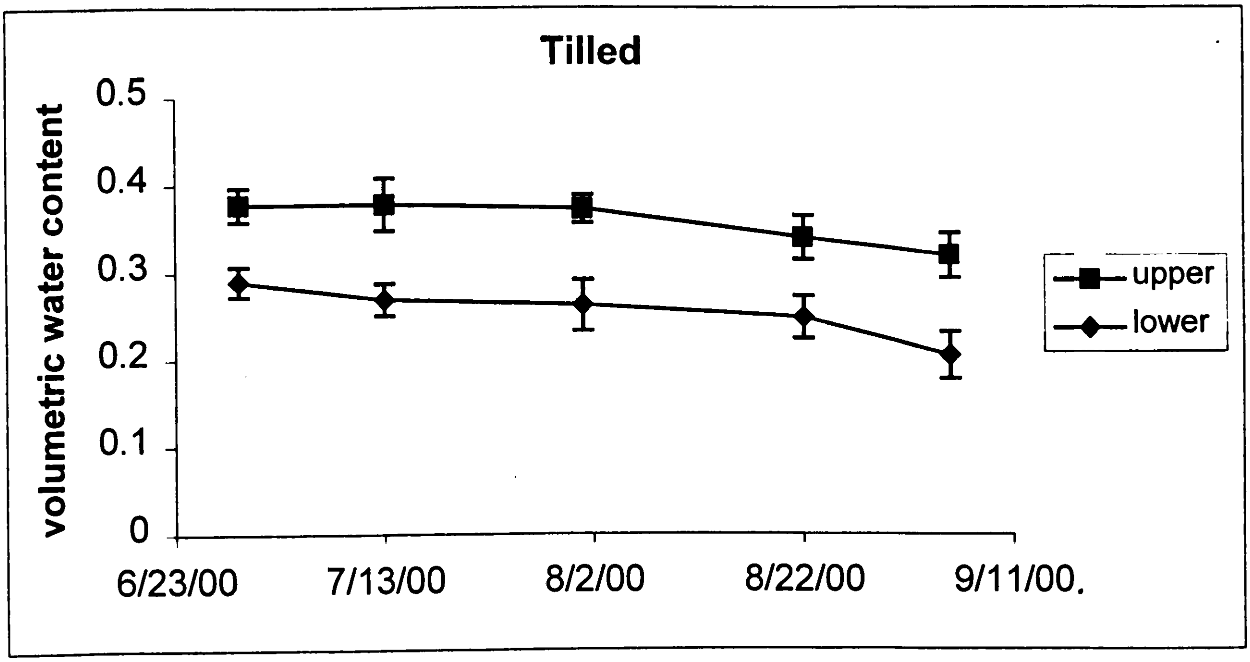
Figure 5. Average total growth of alder receiving eight different treatments (till, myc, fert, t*m, t*f, f*m, t*m*f) in the upper and lower reaches of the Schell Creek Riparian Restoration Site.

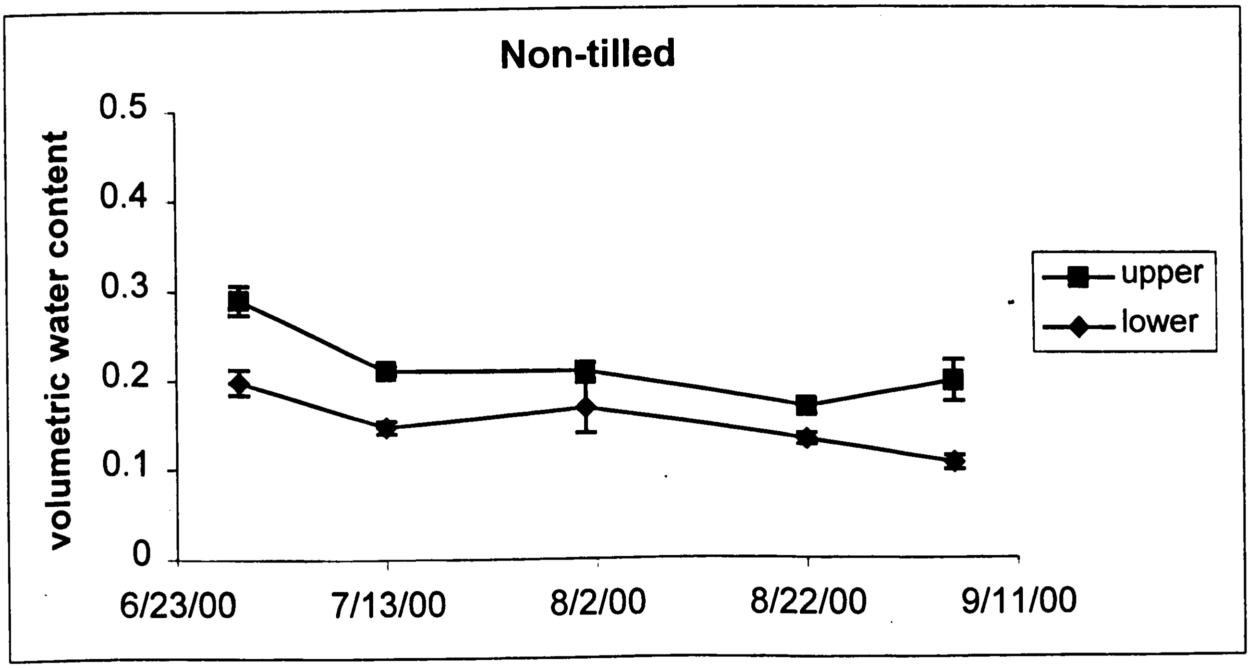
Figure 6. Average photosynthetic rate of alder receiving eight different treatments (till, myc, fert, t*m, t*f, f*m, t*m*f) in the upper and lower reaches of the Schell Creek Riparian Restoration Site. Photosynthesis measured using a Licor LI-6400, and units are in μmol $m^{-2}s^{-1}$.

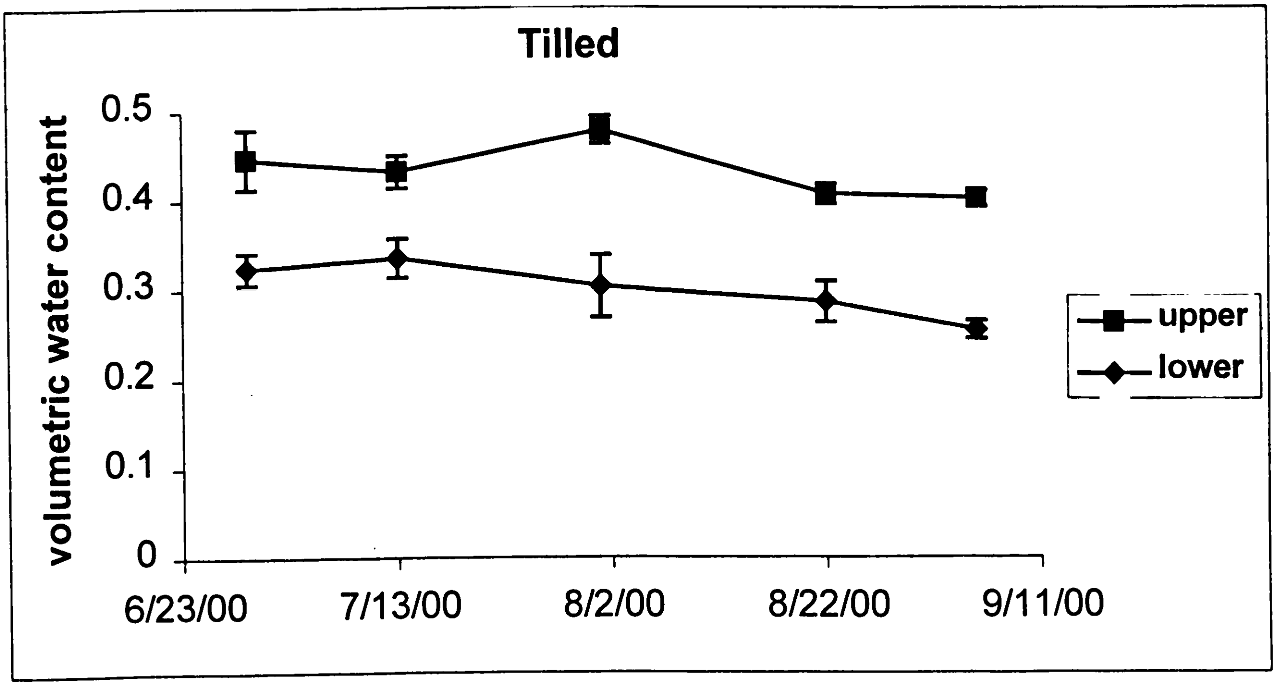
Figure 7. Average height growth of spruce receiving eight different treatments (till, myc, fert, t*m, t*f, f*m, t*m*f) in the upper and lower reaches of the Schell Creek Riparian Restoration Site.

Figure 8. Average total growth of spruce receiving eight different treatments (till, myc, fert, t*m, t*f, f*m, t*m*f) in the upper and lower reaches of the Schell Creek Riparian Restoration Site.

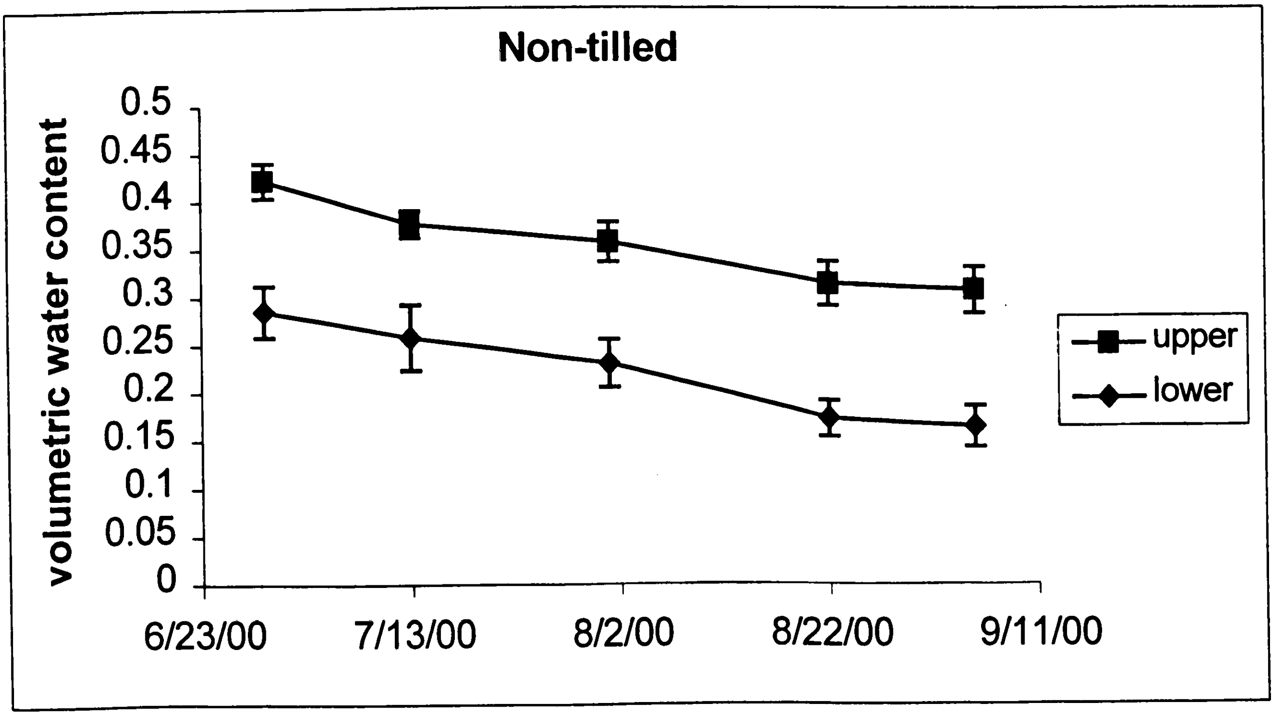

CANADA
San Juan Is.
Bellingham
North Cascades Nat'l. Pk.
CASCADE RANGE
Columbia
IDAHO
Cape Flattery
Port Angeles
Everett
Puget Sound
Lake Chelan
Grand Coulee Dam
Spokane
Seattle
Bellevue
Spokane
Olympic Nat'l. Pk.
Tacoma
WASHINGTON
OLYMPIA
Mt. Rainier
Pullman
Mt. Rainier Nat'l. Pk.
Yakima
Snake
North Pacific Ocean
Longview
Mt. St. Helens
Yakima
Kennewick
Walla Walla
CASCADE RANGE
Columbia
Vancouver
OREGON
1
2
3
4
5
6
N
CULVERT
GRAVEL DRIVE
IMHOF ROAD
10
11
12
SCHELL CREEK
APPROX. 15 METERS
7
8
9
: REFERS TO AREAS WITH PREVIOUSLY RESTORED FOLIAGE
+F
-F
-F
+F
BUFFER
-F
+F
-F
+F
= till
= myc


Tilled
volumetric water content
0.5
0.4
0.3
0.2
0.1
0
6/23/00
7/13/00
8/2/00
8/22/00
9/11/00.
upper
lower

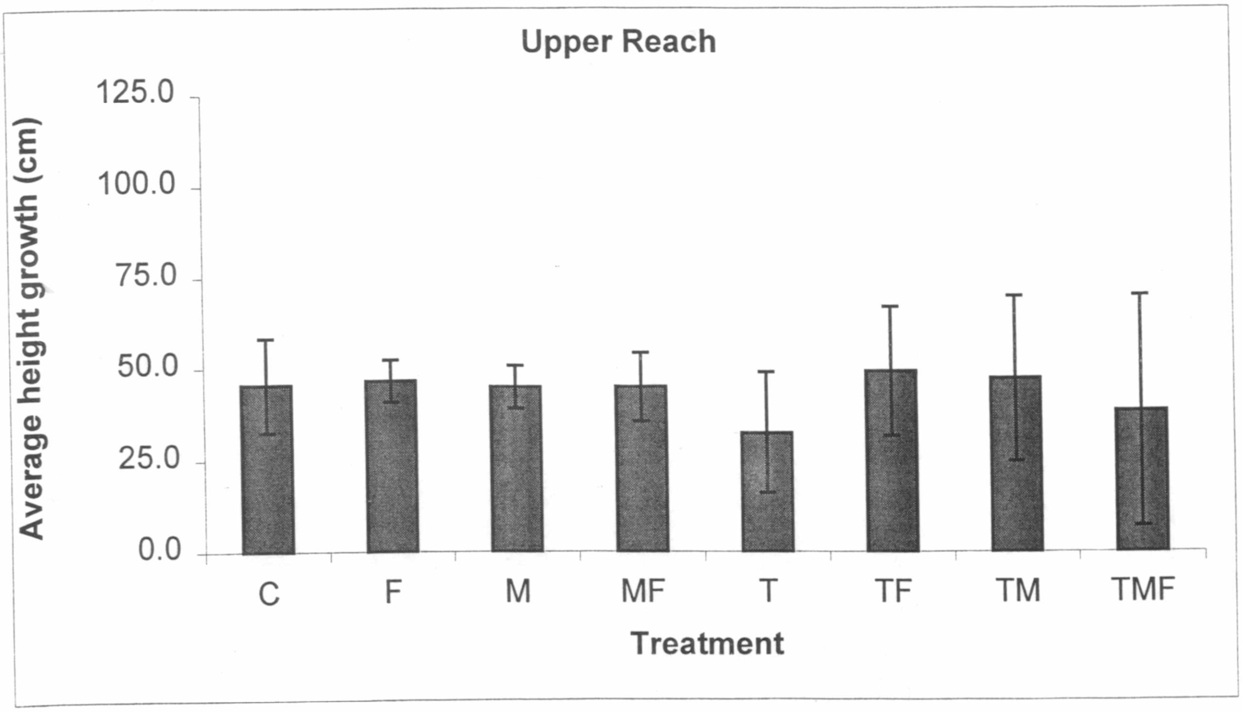

Non-tilled
volumetric water content
0.5
0.4
0.3
0.2
0.1
0
6/23/00
7/13/00
8/2/00
8/22/00
9/11/00
upper
lower

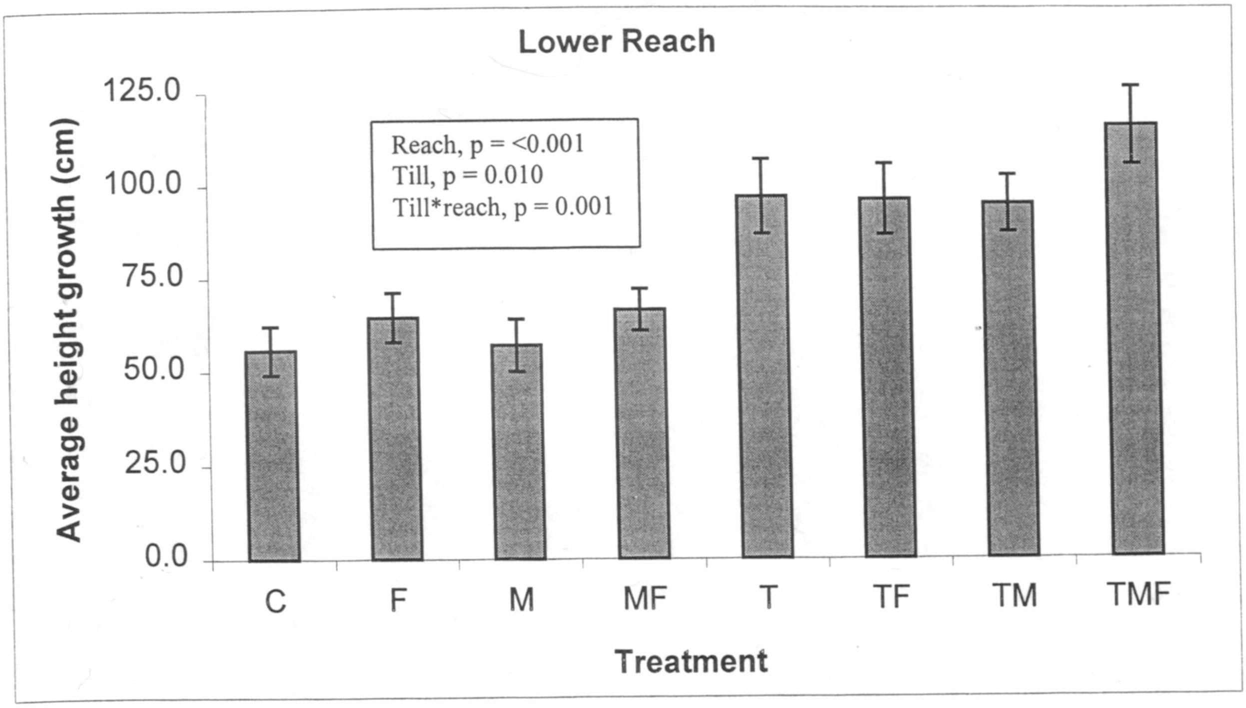


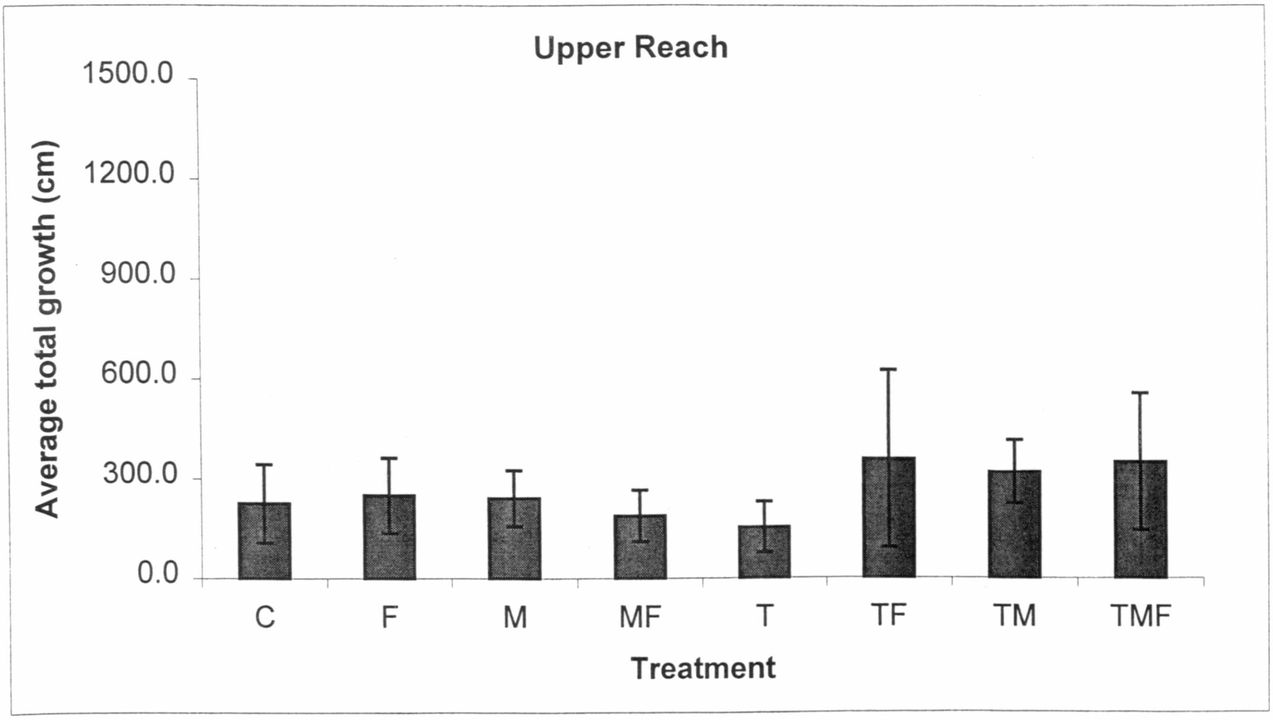
Tilled

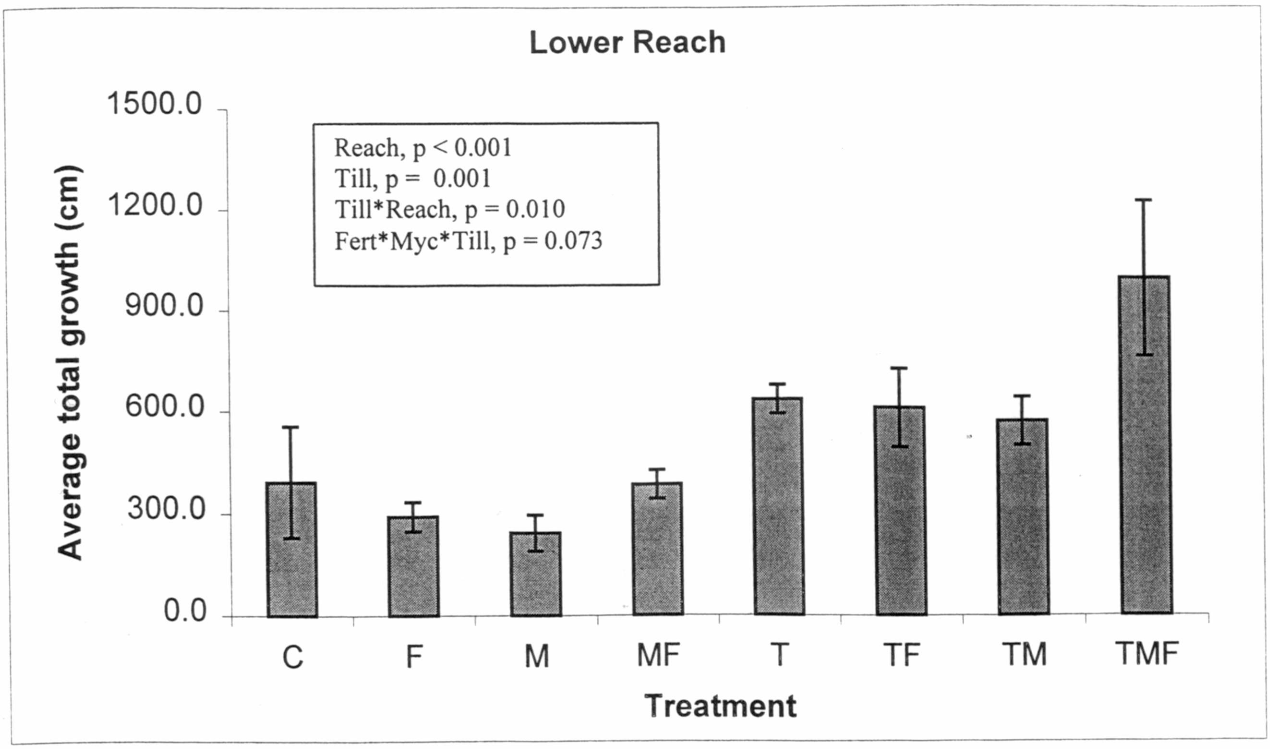


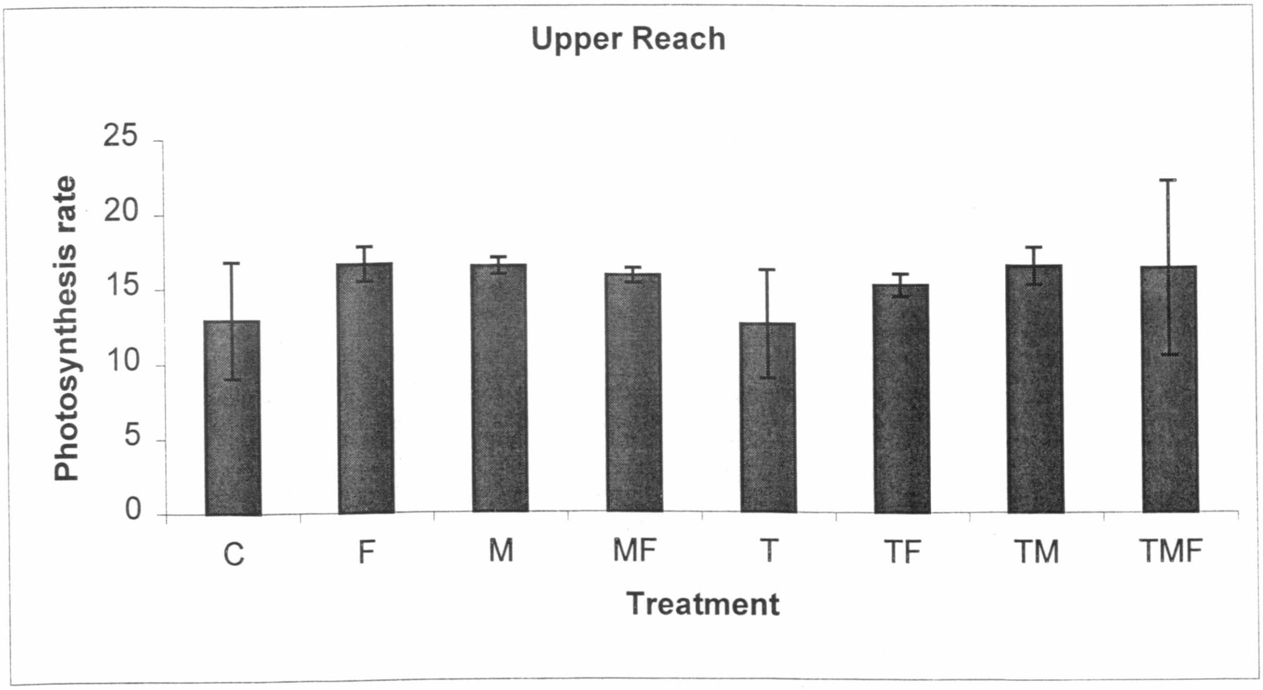
Non-tilled

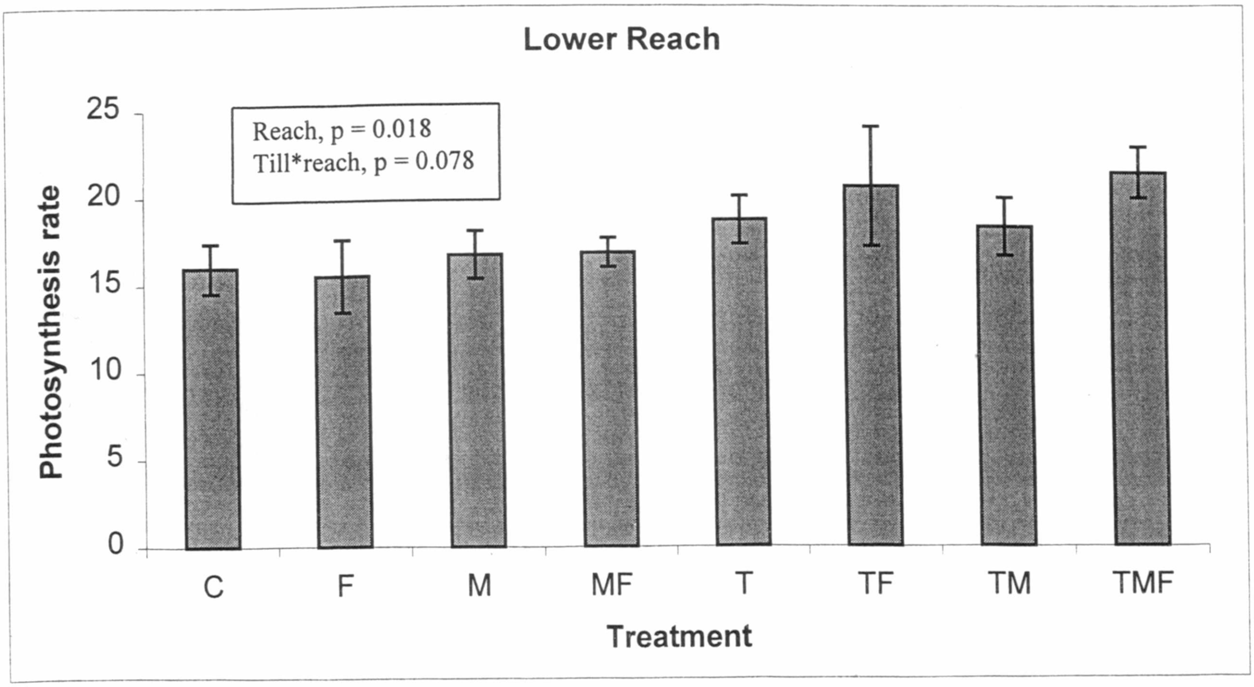

Upper Reach
Average height growth (cm)
125.0
100.0
75.0
50.0
25.0
0.0
C
F
M
MF
T
TF
TM
TMF
Treatment

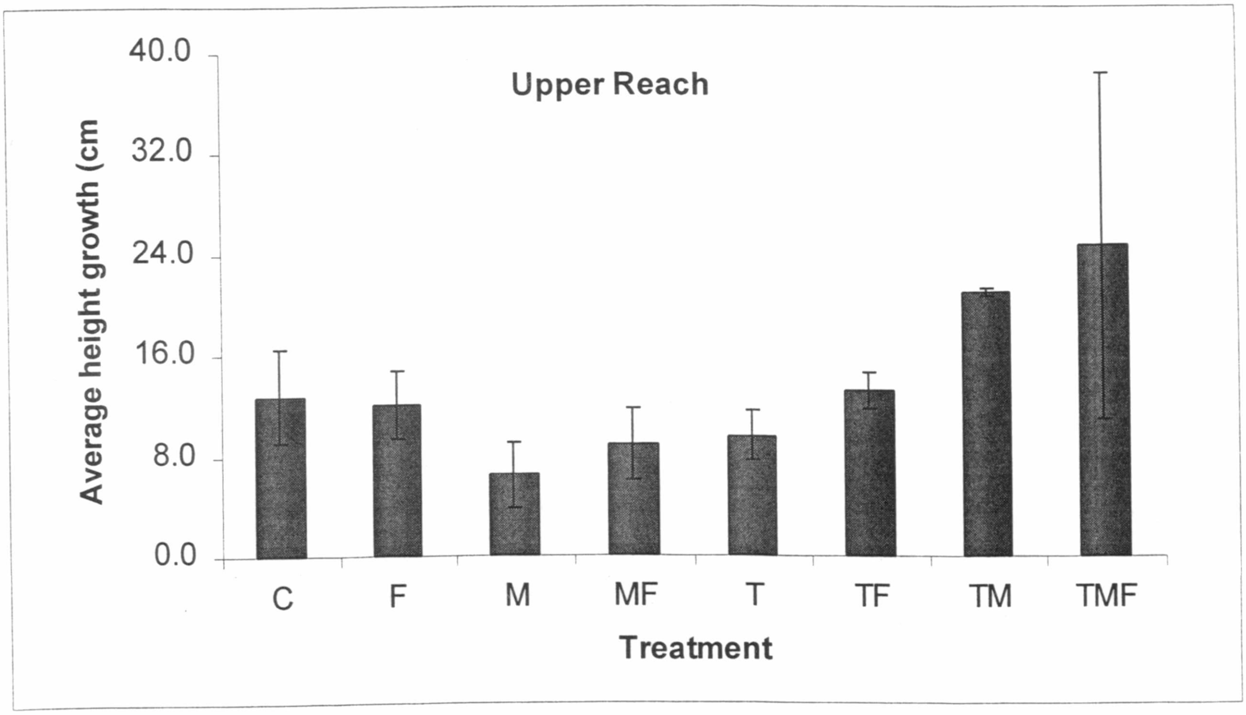

Lower Reach
Reach, p = <0.001
Till, p = 0.010
Till*reach, p = 0.001
Average height growth (cm)
125.0
100.0
75.0
50.0
25.0
0.0
C
F
M
MF
T
TF
TM
TMF
Treatment

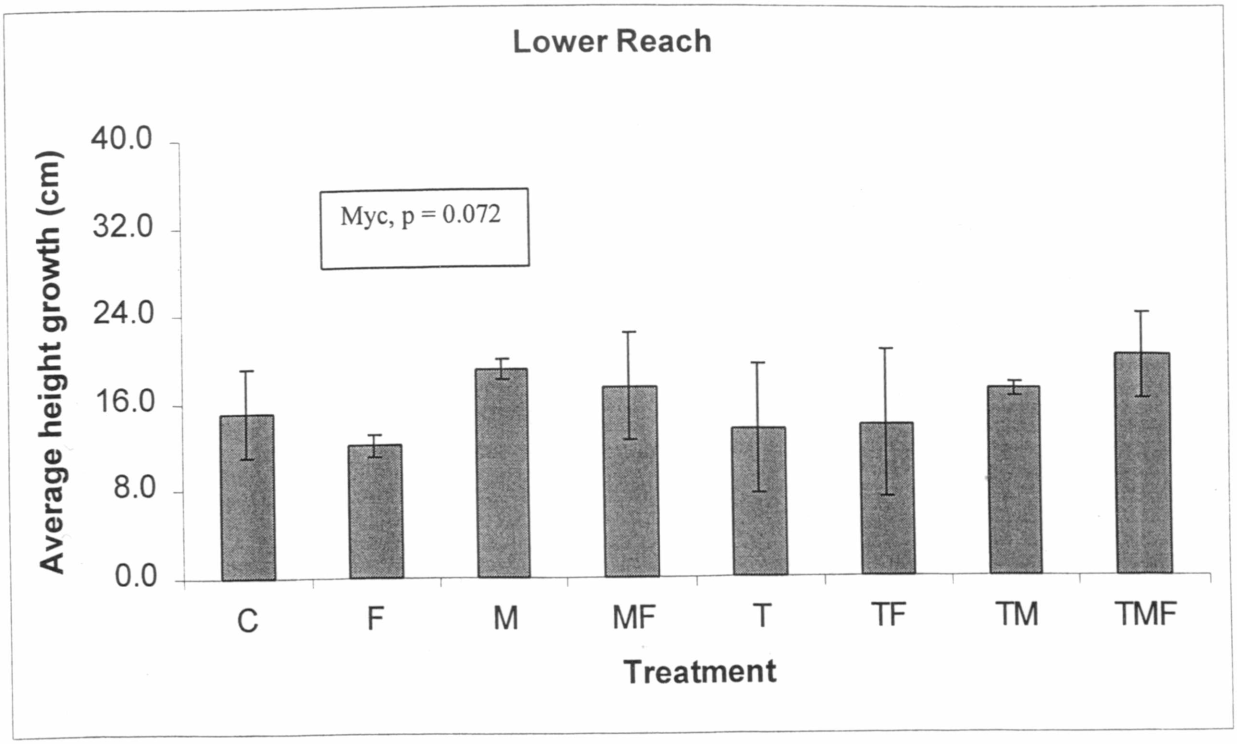

Upper Reach
Average total growth (cm)
1500.0
1200.0
900.0
600.0
300.0
0.0
C
F
M
MF
T
TF
TM
TMF
Treatment

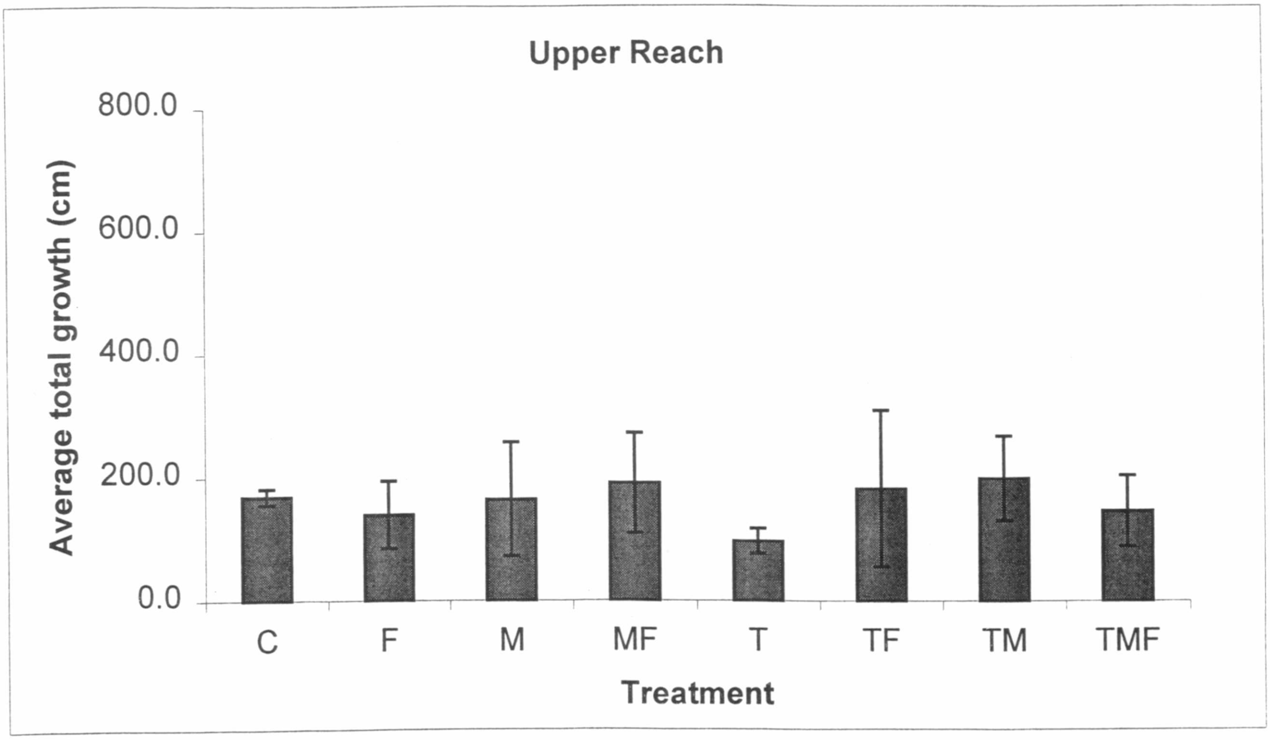

Lower Reach
Reach, p < 0.001
Till, p = 0.001
Till*Reach, p = 0.010
Fert*Myc*Till, p = 0.073
Average total growth (cm)
1500.0
1200.0
900.0
600.0
300.0
0.0
C
F
M
MF
T
TF
TM
TMF
Treatment

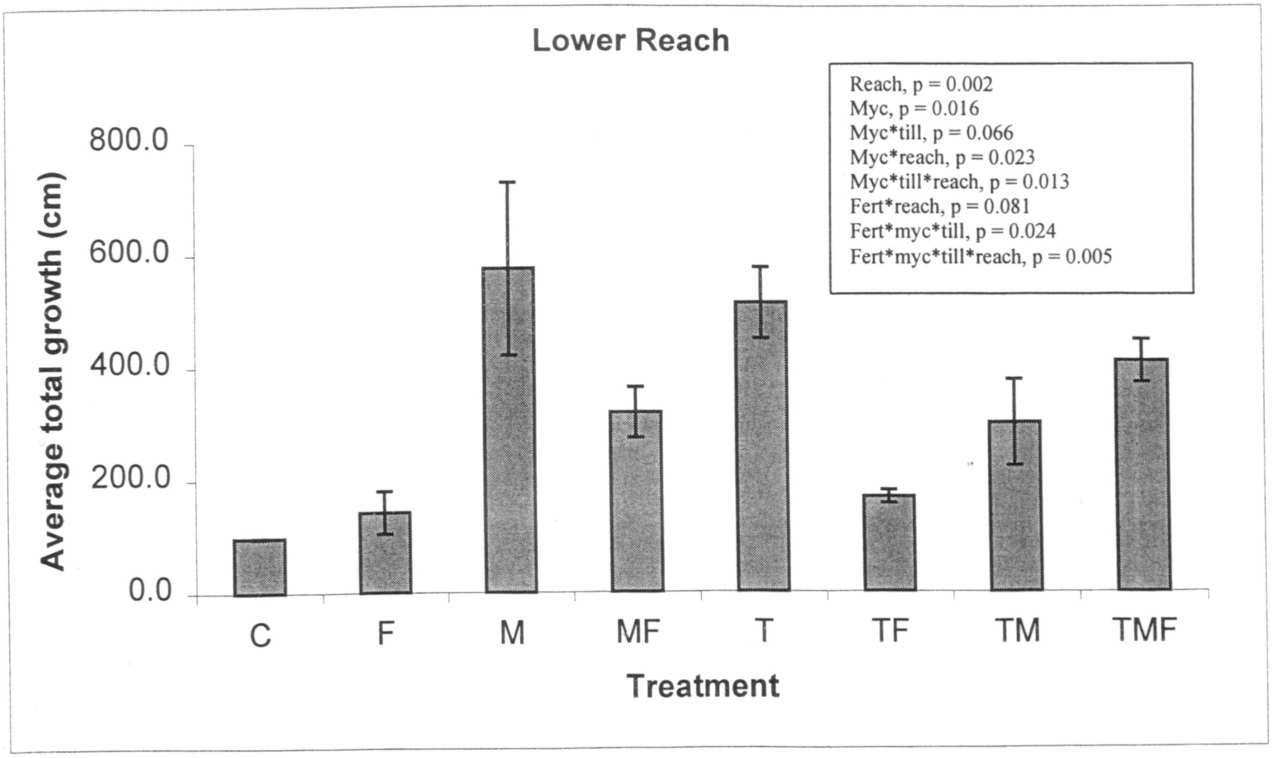

Upper Reach
Photosynthesis rate
25
20
15
10
5
0
C
F
M
MF
T
TF
TM
TMF
Treatment


Lower Reach
Reach, p = 0.018
Till*reach, p = 0.078
Photosynthesis rate
25
20
15
10
5
0
C
F
M
MF
T
TF
TM
TMF
Treatment


Upper Reach
Average height growth (cm
40.0
32.0
24.0
16.0
8.0
0.0
C
F
M
MF
T
TF
TM
TMF
Treatment


Lower Reach
Myc, p = 0.072
Average height growth (cm)
40.0
32.0
24.0
16.0
8.0
0.0
C
F
M
MF
T
TF
TM
TMF
Treatment


Upper Reach
Average total growth (cm)
800.0
600.0
400.0
200.0
0.0
C
F
M
MF
T
TF
TM
TMF
Treatment


Lower Reach
Reach, p = 0.002
Myc, p = 0.016
Myc*till, p = 0.066
Myc*reach, p = 0.023
Myc*till*reach, p = 0.013
Fert*reach, p = 0.081
Fert*myc*till, p = 0.024
Fert*myc*till*reach, p = 0.005
Average total growth (cm)
800.0
600.0
400.0
200.0
0.0
C
F
M
MF
T
TF
TM
TMF
Treatment