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Growth, survival, and root system morphology of deeply planted *Corylus colurna* 7 years after transplanting and the effects of root collar excavation

Susan D. Day[a,*], J. Roger Harris[b]

[a]*Department of Forestry (mail code: 0324), Virginia Tech, 228 Cheatham Hall, Blacksburg, VA 24061, USA*
[b]*Department of Horticulture, Virginia Tech, 304 Saunders Hall, Blacksburg, VA 24061, USA*

Abstract

Urban trees are frequently planted with their root collars and structural roots buried well below soil grade, either because of planting practices, nursery production practices, or both. These deeply planted structural roots can impair tree establishment and are thought to reduce tree growth, lifespan, and stability, although research has provided few and contradictory results on these questions to date. This study examines container-grown (55 L) Turkish hazel trees (*Corylus colurna* L.), planted either at grade, 15 cm below grade, or 30 cm below grade into a well-drained silt loam soil, over nearly 8 years. Five years after planting, in 2004, remediation treatments (root collar excavations) were performed on two replicates of each below-ground treatment. Subsequently, all trees were subjected to flooding stress by being irrigated to soil saturation for approximately 6 weeks. In 2006, flooding stress was repeated. Trees root systems were partially excavated in 2007, and root architecture was characterized. Deep planting did not affect trunk diameter growth over 8 years. Survival was 100% for the first 5 years; however, one 30 cm below grade tree died after flooding in 2004 and another died after the 2006 flooding. Photosynthesis was monitored during the 2004 flooding and all trees experienced decline in photosynthetic rates. There was an apparent slight delay in the decline for trees with excavated root collars and those planted at grade. Girdling roots reduced trunk taper and occurred primarily on unremediated trees planted 30 cm below grade.

Selected individual roots were excavated and followed from the root ball and were observed to gradually rise to the upper soil regions. Analysis of roots emerging from excavation trench faces indicated that vertical root distribution at approximately 1.25 m from the tree trunks was the same regardless of planting depth. Longterm consequences of planting below grade are discussed.

Keywords: Deep planting; Deep structural roots; Flooding; Girdling roots; Rooting depth; Taper

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Introduction

Planting trees with root collars below soil grade, also known as "deep planting," can inhibit tree establishment and growth (Arnold et al., 2005, 2007), increase girdling root formation (Wells et al., 2006) and has been identified as a possible contributor to reduced structural stability. Nursery practices, mechanical harvesting techniques, and a desire to increase stability at planting, are all potential causes of deep planting. The seriousness of this problem may be considerable. Observations of two planting sites in the United States, one in 1989 and

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[*]Corresponding author. Tel.: +1 1540 231 7264; fax: +1 1540 231 3330.
E-mail address: sdd@vt.edu (S.D. Day).

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one in 2004, indicated that 72% of trees were planted at acceptable depths (0–7.5 cm to the first two structural roots, described by Watson (2005) as "current industry consensus of 'too deep threshold' in average situations" and now described in the form of a best management practice) in 1989, while only 37% were in 2004 (Watson and Hewitt, 2005). Employees of Bartlett Tree Research Laboratories (Charlotte, NC, USA) excavated 363 recently planted trees and found 93% had buried root collars and 16% were showing signs of girdling due to materials (e.g. soil) around the trunk (Smiley, 1991). These surveys, although limited in scope, suggest that buried root collars are a common occurrence.

Direct contact between the trunk and soil on a deep-planted tree is thought to damage the bark and lead to infection from soil-borne diseases such as *Phytopthora* and *Armillaria* root rots in certain situations (Britton, 1990; Smiley, 1992). Drilias et al. (1982) found that *Fusarium* and *Phytopthora* species commonly related to sugar maple decline were also associated with deep-planted trees. These concerns have led, in part, to the widespread use of "root collar excavations" by arborists (Smiley and Fraedrich, 1993). These excavations are performed on trees when no root flare is visible, presumably due to overly deep planting or mulching, fill application, or sedimentation. The procedure removes soil from around the trunk of trees down to where the root flare is visible. Eastern white pine (*Pinus strobus* L.) and sugar maple (*Acer saccharum* Marsh.) are among those thought to especially benefit from these excavations (Smiley, 1992). These species are both sensitive to poor drainage, suggesting that benefits observed after root collar excavations could be related to improved oxygen availability in the soil.

Despite the potential for serious ramifications in urban forests, where transplanting large (>2 m tall) trees is the typical means of aforestation (Harris, 2007), relatively little research has been available until recently concerning the effects of deep planting on trees. The long-term consequences, in particular, are not well understood. In the United States, a national working group to address deep structural roots has been formed (Watson, 2005). The American Standard for Nursery Stock (ANSI Z60.1) now directly addresses concerns with deep planting relating to nursery production and dialogue between the nursery industry, arborists, landscape architects, and other stakeholders continues. A Best Management Practice (BMP) for detecting excessively deep structural roots in nursery stock and avoiding planting trees deeply is now available (Watson, 2005). One component of this effort is increased focus on research addressing deep structural root issues, their long-term consequences, and options for remediation.

Establishment of deep-planted trees

Deep planting of small conifer seedlings in reforestation plantings has been considered to aid establishment in dry years, presumably because the lower soil regions will retain more moisture. For example, deep planting in mounds increased survival and growth of spruce in comparison with standard-depth planting in mounds because of improved moisture conditions in the lower portions of the mound (Macadam and Bedford, 1998). However, deep planting of smaller seedlings can decrease survival in some situations (Koshi, 1960). It should be noted that some deep-planted seedlings in Koshi's study that perished were completely buried (including the growing point) by soil after heavy rains. It would require at least 2 m of soil to completely bury most urban tree plantings. This startling thought illustrates how deep planting research with small reforestation seedlings may not be wholly applicable to landscape-sized trees used in urban plantings. Larger trees are also subject to longer establishment periods, and the soil conditions in the immediate vicinity of the planted rootball are often unfavorable for root growth (Harris, 2007). Lower soil regions, where roots of deep-planted trees are located, are generally even less favorable for root growth, especially in urbanized areas where extensive grading and topsoil removal are common. In surface soil, where small seedlings are planted (even when planted deep) water generally has the best opportunity to both infiltrate and drain away, creating moist and well-aerated conditions for root growth. In contrast, lower soil regions may be inundated by high water tables or remain dry when rainfall fails to penetrate to those depths, especially when surface soil is compacted fill (Day et al., 2001). The effects of these unfavorable conditions would be exacerbated when root systems are planted well below grade.

Arnold et al. (2007) found planting small (9.3 L), container-grown trees as little as 7.5 cm below grade decreased survival and growth of all but one of five species after 3 years in a layered soil (a sandy loam underlain at 15–30 cm with a hard clay pan) in Texas, USA. Trees studied included green ash (*Fraxinus pennsylvanica* Marsh.) and sycamore (*Platanus occidentalis* L.), both flood-tolerant species. Growth *increased* in some instances for trees planted above grade, suggesting that minimizing exposure to the clay hardpan may have been beneficial. An earlier study produced similar results, but also found that increased mulch depth reduced growth, apparently because rainfall was unable to adequately penetrate the soil (Arnold et al., 2005). In a short-term (7 months) establishment study with large (~7.6 cm trunk diameter), field-grown live oak (*Quercus virginiana*), tree growth was unaffected by planting by as much as 18 cm below grade. Greater water deficits were experienced by more deeply planted trees (in comparison to trees planted at grade) after a <1 cm irrigation following an extended dry period. As might be expected, this irrigation event was apparently unable to penetrate down to the deep root balls, even in sandy field soils (Gilman and Grabosky, 2004).

These results suggest that the interaction of climate (rainfall, heat, drought) and particular soil properties (bulk density, moisture availability, drainage) at differing depths are primary factors influencing tree survival and growth of deep-planted trees during the establishment period.

Deep structural roots post-establishment

If deep-planted trees survive beyond the establishment period or if an existing tree root system is buried by construction fill, some living roots may remain below the "normal" depth in the soil. The ultimate distribution of such roots under these conditions is likely species and soil dependent (Day et al., 2001). Such roots developed originally at shallower depths and may result in trees being subject to increased physiological stress during very dry or very wet years, when the lower soil regions may become waterlogged or, conversely, very dry. Another concern is the formation of girdling roots, as soil around the trunk makes root growth upwards above the root flare and against trunks possible. The connection between planting depth and girdling roots has not been clearly established however. In a study including red maple (*Acer rubrum* L.) and Norway maple (*Acer platanoides* L.), both species highly susceptible to girdling root formation, planting below grade was not associated with an increase in girdling roots (Watson, 1990). Wells et al. (2006) found that deep planting did increase girdling roots in red maple, but not in Yoshino cherry (*Prunus* × *yedoensis* Matsum.). There is considerable variation among species, however, in root architecture and physiology. Differences in nursery production, soil conditions and length of study may also influence results. Some species readily generate adventitious roots, while others do not. Some species, such as coast redwoods (*Sequoia sempervirens* (D. Don.) Endl.), have been observed to generate entire new root systems that originate from trunk tissue when floods deposit sediment over existing root systems (Stone and Vasey, 1968). Such differences could also influence the formation of girdling roots.

Objectives

The magnitude of the ecosystem services provided by urban trees can be directly tied to canopy size (e.g. Nowak et al., 2006). Therefore, given the large numbers of trees planted deeply, understanding how deep root systems affect tree development and health is fundamental to creating better functioning urban forests.

This study was designed to answer the following questions:

1. Do deep-planted Turkish hazel trees establish as well as trees planted at grade?
2. Is long-term growth affected by deep planting?
3. In a species that does not readily form adventitious roots, will deep planting lead to girdling roots? If yes, how do girdling roots affect trees?
4. Do roots return to "normal" distribution patterns in the soil after deep planting?
5. Does remediation in the form of root collar excavation have any positive effect on deep-planted trees?

Methods

We planted 15 container-grown Turkish hazel trees (*Corylus colurna* L.) into one of three treatments: planted at grade, planted with the root collar 15 cm below grade, and planted 30 cm below grade. Trees had been propagated from seeds, field grown, and planted as bare-root seedlings into 55 L containers where they were grown to approximately 4.5 cm trunk diameter (at 15 cm above soil) in an on-site pot-in-pot production system (Ruter, 1997). Container substrate was industry-standard, semi-composted pine bark. Trees were grown approximately 2 years in the 55 L containers before transplanting into the experimental site. Rootballs were observed to be held intact by well-formed root systems, but were not pot bound. The experiment was installed in a single row, spaced 2 m on center, in a completely randomized experimental design on November 12, 1999 at the Urban Horticulture Center in Blacksburg, Virginia, USA (lat. 37.28°N, long. 80.46°W). Site soil is a well-drained Groseclose silt loam soil (clayey, mixed, mesic Typic Hapludult), pH 6.2 with a 3–5% slope. Trees were hand irrigated to apparent field capacity at planting and micro-spray irrigation installed to provide adequate water supply during the establishment period.

Tree measurements

We measured trunk diameter at 15 cm above the *installed* soil line 1 month after transplanting and every fall thereafter. At harvest, in May 2007, root collars were fully excavated and, in order to characterize trunk taper, a diameter tape was used to measure trunk diameter immediately above the root flare, and at 15 and 30 cm above that first measurement.

Remediation treatments

In May 2004, 5 years after planting, we randomly selected two trees from each of the two deep planting treatments and excavated their root collars with an air excavation tool (Supersonic Air Knife Inc., Allison Park, PA, USA). Soil was removed down to the original root collar (where 1 or more roots $>$ 2 cm diameter emerged from the trunk). After excavation, soil gently sloped up from the excavated pits and returned to the original grade approximately 70 cm from the trunk. Adventitious roots were absent on all trees and original root collars were easily discerned. One root was observed growing upwards and crossing near, but not touching, the trunk. This root was not removed.

Flooding treatment

Water stress, especially soil hypoxia, is thought to be a primary contributor to tree stress from deep planting. Turkish hazel is a Mediterranean species (Whitcher and Wen, 2001) and is not particularly tolerant of poorly drained soils. The experimental site is well-drained. Therefore, to test tree response to increased hypoxic stress, a flooding regime was instituted for approximately 6 weeks in late summer of 2004. Soils were saturated through continuous micro-spray irrigation from July 2 to August 17 and the slowly permeable subsoils of this soil series ensured that soils remained saturated or nearly so during this 6-week period. Photosynthesis was monitored approximately twice a week immediately before, during, and immediately after flooding using a Li-Cor 6400 gas exchange analyzer (LI-COR Biosciences, Lincoln, NE, USA) in order to capture response and recovery to flooding stress. Photosynthesis rates were measured in late morning on each measurement day on two sun-exposed, fully-mature leaves, three to five leaves from branch terminals for each tree and averaged as the photosynthetic rate for that individual tree. Leaves were randomly selected from the middle third of the canopy. By the end of the flooding period, foliage had mostly yellowed or senesced and measurements had to be discontinued. Nearby Turkish hazels still retained healthy green foliage at this time of year.

In summer 2006, a second flooding period was instituted from June 23 to July 17 to create an additional period of hypoxia.

Root architecture

A trench 60 cm deep × 60 cm wide running the full length of the west side of the planted row was dug with a backhoe on May 15, 2007. The near side of the trench was ~1.25 m from the trunks of the trees. The soil surface was gently scuffed and brushed to reveal severed root ends. A 60 cm wide × 45 cm high wire grid with 10 cm wide × 5 cm high cells was centered over the soil by each tree and root ends in each cell counted. An air excavation tool was then used to remove soil from all sides around each trunk down to approximately 5–10 cm *below* the root collar. In addition, individual roots were followed out from the trunks to the trench on all trees to confirm that root end counts did not include roots from adjacent trees.

Statistical analysis

The relationship between girdling roots and trunk taper was determined with regression analysis in SigmaPlot v. 9.01 (Systat Software Inc., San Jose, CA, USA). All other analyses were performed in SAS v. 9.1 (SAS Institute, Cary, NC, USA). Trunk diameter growth was analyzed with multivariate repeated measures analysis of variance within the GLM procedure of SAS. Counts of girdling roots were analyzed by Kruskal–Wallis for overall effect and Wilcoxon Rank Sum test for paired comparisons within the NPAR1-WAY procedure of SAS. Tree mortality was analyzed with Cochran's *Q*-test within the FREQ procedure of SAS. Root distribution and photosynthesis data are presented graphically to reveal overall patterns.

Results

Growth and mortality

Deep planting did not affect establishment or growth after 7.5 years (Fig. 1), but two out of five

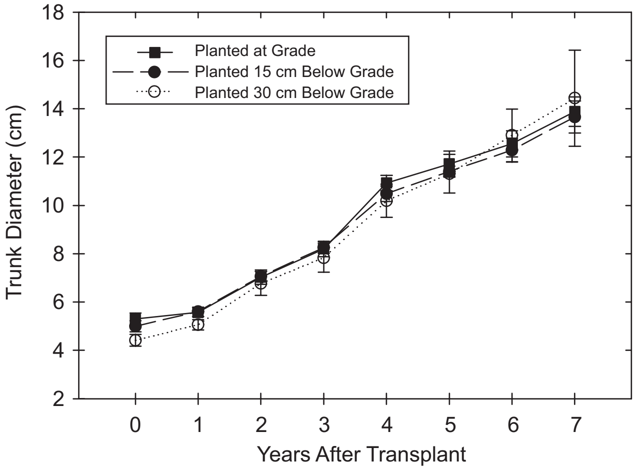

Fig. 1. Mean trunk diameter 15 cm above soil line of Turkish hazel trees planted at grade, 15 cm below grade or 30 cm below grade over 7 years. Bars represent standard error of the means ($N = 5$). $N = 4$ and 3 for 30 cm deep trees in 2005 and 2006, respectively.

Table 1. Survival of Turkish Hazel planted in November 1999 at grade or 15 or 30 cm deep in a well-drained Groseclose silty clay loam

Treatment	Percent survival		
	As of June 2004	As of June 2006	As of May 2007
At grade ($n = 5$)	100	100	100
15 cm deep no excavation ($n = 3$)	100	100	100
15 cm deep excavated[a] ($n = 2$)	100	100	100
30 cm deep no excavation ($n = 3$)	100	100	67
30 cm deep excavated ($n = 2$)	100	50	50

Six week flooding stress tests were applied in July–August of years 2004 and 2006.

[a] Root collar excavations were performed in May 2004.

30 cm below-grade trees died after flooding events (Table 1). All trees appeared vigorous and healthy until flooded in 2004. One remediated 30 cm below-grade tree at the lower end of the slope was observed to be dead in spring 2005, and was removed. A second tree, planted 30 cm below grade with no remediation, died in fall 2006, presumably due to stress imposed by the two flooding regimes. This tree was at the upper end of the slope and was left in place until harvest so that its root architecture could be characterized along with the other trees.

Remediation treatments

Bark of deep-planted trees appeared unaffected by soil contact and no change in taper or swelling was observed when root collar excavations were made in 2004. No adventitious roots were observed. One root on one 15 cm below-grade tree grew upwards and adjacent to the trunk. This root persisted until harvest, growing radially and eventually forming tight tangential contact with the trunk ("girdling") for 3 cm along the trunk surface.

At the final excavation, all surviving 30 cm below-grade trees that were *not* remediated had pronounced girdling roots that affected trunk taper (Table 2 and Figs. 2–4). The two remediated trees did not have these roots. However, most of the girdling roots did not appear to have developed between 2004 and 2007 – they appeared older (Fig. 3), suggesting that this was a coincidence. Because we were only able to remediate two trees per treatment, no definitive conclusions concerning the relation between remediation and root girdling can be made from these data. Nonetheless, results suggest that further investigation concerning the timing of girdling root development may be useful.

Flooding stress test

Root collar excavations did appear to offer some short-term protection from the stress associated with flooding for both below-grade treatments. Mean photosynthesis rates were higher for remediated trees during the first week of flooding than for non-remediated trees (Fig. 5). All trees eventually defoliated and photosynthesis measurements were therefore suspended. Consequently, no potential differences among treatments in "recovery" from flooding stress could be observed.

Table 2. Presence of girdling roots in Turkish hazel either planted at grade or 15 or 30 cm deep after nearly 8 years

Treatment	Trees with girdling roots	Mean number of girdling roots	Mean contact distance per root (cm)
At grade ($n = 5$)	0	0	n/a
15 cm deep no excavation ($n = 3$)	0	0	n/a
15 cm deep excavated ($n = 2$)	1[a]	1	7.6
30 cm deep no excavation ($n = 3$)	3	2.3	13.1
30 cm deep excavated ($n = 1$)[b]	0	0	n/a

Mean comparisons of number of girdling roots[c]	p-value
At grade vs. 15 cm below grade	0.222
At grade vs. 30 cm below grade	0.037
15 cm below grade vs. 30 cm below grade	0.059

Girdling roots are defined as those in tight tangential contact with the trunk.

[a] Girdling root was observed to be present but not yet in contact with trunk at excavation in 2004.

[b] Other excavated tree in this treatment died after flooding in year 5.

[c] Mean comparisons by planting depth by individual Wilcoxon Rank Sum two-sample tests (one-sided t approximation). Overall p-value for treatment differences = 0.032 ($Pr >$ Chi-square via Kruskal–Wallis).

Root architecture

There was no indication that vertical root distribution approximately 1.25 m from the trunk varied

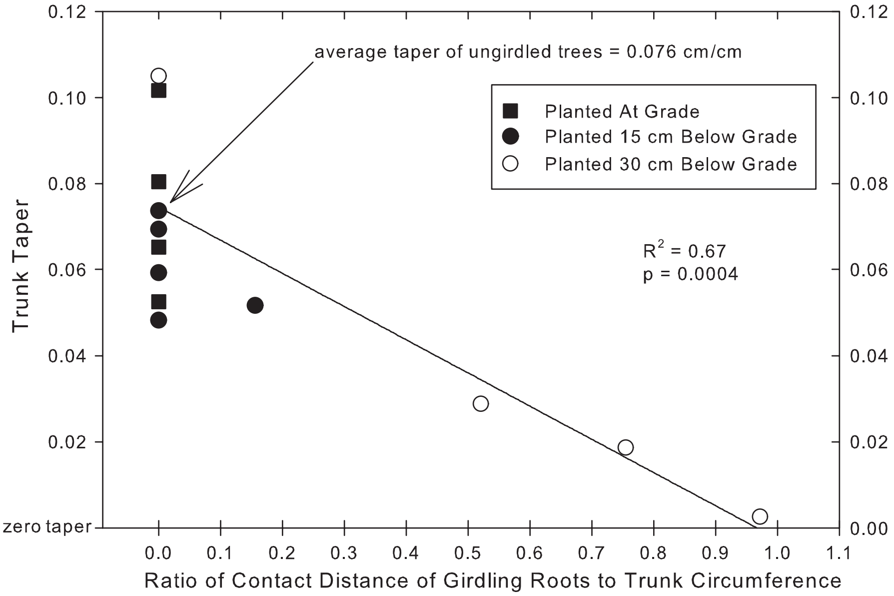

Fig. 2. Relationship between trunk taper in the first 30 cm above the root flare and root girdling for Turkish hazel 7 years after planting either at grade, 15 cm below grade or 30 cm below grade. Trunk taper is defined as (diameter at 0 cm−diameter at 30 cm)/30 cm. Girdling roots are defined as any roots in tight tangential contact with the trunk. Trunk circumference is measured just above root flare (in the vicinity of girdling roots).

Fig. 3. Turkish hazel root collars nearly 8 years after planting at grade (left) or 30 cm below grade (right). Note girdling roots on the tree at right (arrow indicates original root flare).

among planting treatments (Fig. 6). Roots apparently re-established their optimal rooting depth relatively quickly as they extended out into the soil. During final excavation, individual roots were followed from the original root flare and were observed to grow upwards in the soil profile to the point where they were counted in the root grid (Fig. 7). This indicates that roots counted were very likely not simply branching off of roots lower in the soil profile, but that the entire root system returned to its "natural" depth in the course of 1.25 m. Similar results were observed when rooting depth was measured for 24-year-old white oak (*Quercus alba*) 3 years after the root systems were buried with 20 cm of fill soil (Day et al., 2001). However, sweetgums (*Liquidambar styraciflua* L.) subjected to the same treatment did not extend roots into the new soil. This was attributed to the relatively fertile original soil occupied by the sweetgums as well as that species' root foraging patterns.

Planting 30 cm below grade trees increased the development of girdling roots (Table 2). In addition, the greater the degree of root contact with the trunk, the lower the degree of trunk taper evident in the first 30 cm of trunk (Fig. 2), indicating that reduced taper was a result of root girdling, rather than simply the presence of soil. Remediated trees planted 30 cm below grade did not develop girdling roots. Again, however, because remediation occurred after 5 years, it seems unlikely that girdling root formation was prevented by remediation.

Fig. 4. Girdling roots nearly 8 years after planting 30 cm below grade on Turkish hazel. The small root indicated by the white arrow was embedded in the groove shown by the key.

Discussion

Deep planting did not impair establishment of Turkish hazel trees in the well-drained soil of the experimental site. Furthermore, there is no indication that planting below grade had a detrimental effect on tree growth during the nearly 8 years of this study. However, because trees are long-lived organisms, it is critical to note that 40% of the 30 cm below-grade trees died after the imposition of flooding stress (Table 1). There is some slight evidence that this effect was due to depth of planting ($p = 0.13$ via Cochran's Q-test), but mortality cannot be conclusively linked to depth of planting. Because all trees were exposed to flooding, this

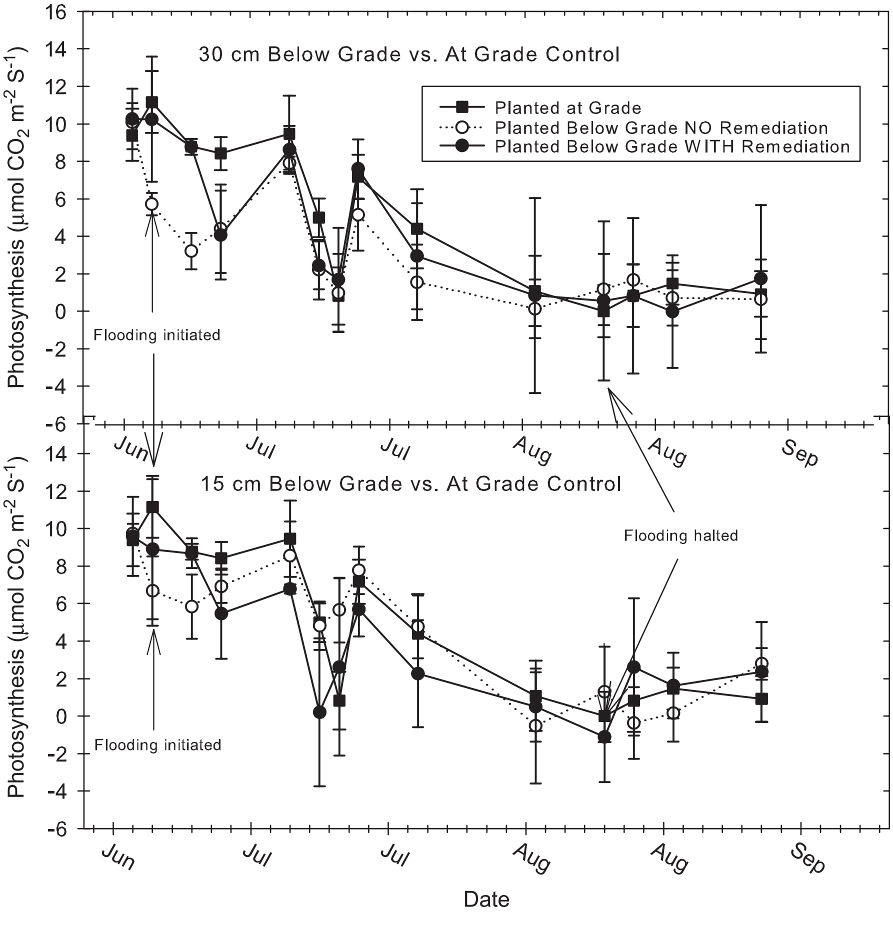

Fig. 5. Photosynthesis response of deeply planted Turkish hazel to flooding and post-flooding periods July–September 2004, 5 years after planting. Each replication is the mean of two measurements (subsamples). For planted at grade, $N = 5$; for planted below grade without remediation, $N = 3$; for planted below grade with remediation, $N = 2$.

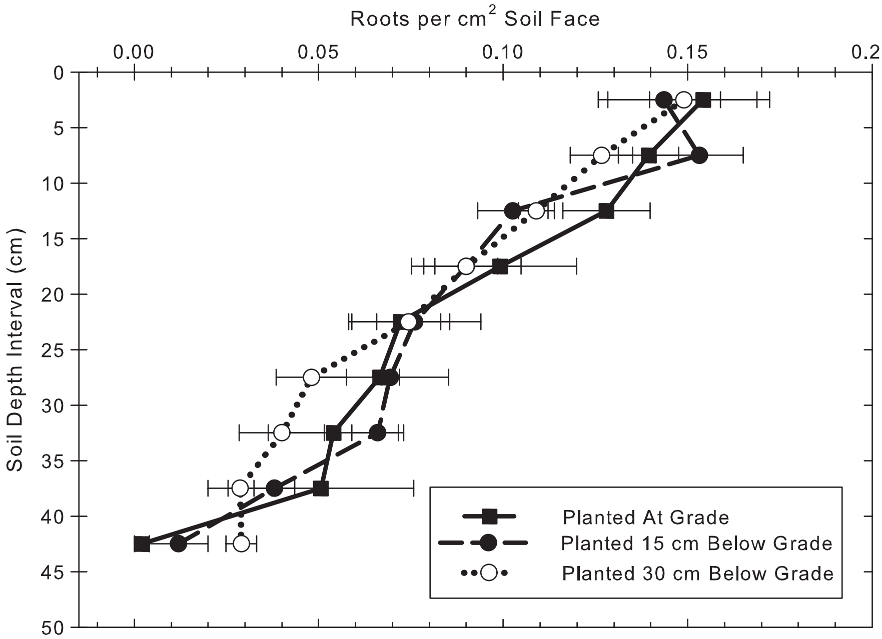

Fig. 6. Mean root count density profile at 1.25 m from tree at nine depth intervals (measurement area = 5 cm deep × 60 cm wide) for Turkish hazel planted at grade, 15 cm below grade, and 30 cm below grade, 8 years after planting. $N = 5$ for planted at grade and 15 cm below grade. $N = 3$ for 30 cm below grade (two trees died).

Fig. 7. Structural root (painted white) is shown emerging from root flare of Turkish hazel nearly 8 years after planting 30 cm below grade. Root rises gradually to the upper 10 cm of soil where root count density was greatest.

result does not constitute a comparison of mortality between flooded and unflooded trees. However, deep planting may predispose trees to suffer from this type of stress by locating their transplanted root systems closer to the water table.

All trees were clearly stressed by the flooding episodes. Turkish hazel is reputed to be intolerant of hypoxic soils, and all trees, in fact, were mostly defoliated after the prolonged flooding in 2004. Trees also appeared stressed during and after flooding in 2006. There are numerous Turkish hazels from the same production year planted about the research plot area, which provided a convenient visual comparison. The first tree to die was in the lower part of the experimental plot suggesting that wet soils brought about by the combination of deep planting and flooding increased mortality in Turkish hazel. Even conditions that occur rarely on a given site (for example, heavy rains, or prolonged drought) can be highly detrimental to the survival of long-lived organisms, such as trees, if they are predisposed to damage from these conditions. Depending upon the specific soils and specific tolerances of tree species, soil conditions in the lower regions may be either wetter or drier. Surface soils are more likely to receive water rapidly from rainfall and to drain water freely, providing more suitable conditions for tree root growth. In our study, however, roots returned to surface levels relatively quickly. Wells et al. (2006) determined that root systems of deep-planted trees remained significantly deeper than those of their at-grade counterparts at approximately 41 cm from the trunk. This suggests that roots closer to the trunk may remain at deeper levels after deep planting, at least in the short-term and for some species. Adventitious roots can replace entire root systems when soil level changes (Stone and Vasey, 1968). The Turkish hazels in this experiment, however, did not form adventitious roots and roots in the vicinity of the original root ball were observed to remain at their original planting depth before rising to the surface soils zones farther from the trunk (Fig. 7).

Root collar excavations may confer some benefit to deeply planted trees. However, the present experiment indicates such benefit is slight and does not address soil drainage issues that may be affected by placing roots in deeper soil layers. Because only four trees were remediated, firm conclusions cannot be drawn from these data. Further research is needed focusing on when root collar excavation could best prevent girdling root development. In addition, we observed no alteration in bark tissue after nearly 8 years of burial. However, our experimental site is well-drained and Turkish hazel does not readily form adventitious roots. Other species and sites may give other results and raise additional research questions, such as if adventitious roots should be removed.

Although planting below grade resulted in increased root girdling in our study, the ultimate effect of girdling roots on trees is a question unanswered by research. Watson (1990) observed that girdling roots did not appear to persist in many species and decline could not be attributed to girdling roots except in the case of Norway maple. Hudler and Beale (1981) observed that xylem was severely compressed by tightly wound roots on Norway maples and may have caused or contributed to decline. However, Norway maple is notorious for its propensity to form tightly twisted root systems and is not representative of other species. In our study, increased contact distance of girdling roots with the trunk was associated with reduced trunk taper. This may have implications for long-term stability since reduced taper can increase the likelihood of stem breakage (Petty and Swain, 1985) in some circumstances and the possibility of uprooting in others (Peltola et al., 2000). These studies look at the effect of whole-tree taper (diameter/height), however, rather than a zone of reduced taper. In our study we measured taper in the first 30 cm of the trunk. The remainder of the trunk appeared to taper normally across treatments, but we did not measure total tree taper.

Conclusions

When this experiment was initiated in 1999, little was known about the effects of planting below soil grade. The recent resurgence of research in this area has provided new insights and we believe the scope of BMPs for buried trees will continue to be expanded in the next several years as our understanding continues to evolve. For Turkish hazel, a species that does not readily form adventitious roots and is intolerant of flooded soils, planting up to 30 cm below grade did not affect growth over nearly 8 years and root distribution returned to normal within 1.25 m of the trunk. Forty percent of trees planted at 30 cm below grade, however, died after flooding episodes were introduced, while no trees planted at 15 cm below grade died. Trees planted 30 cm below grade also had more girdling roots – roots in tight tangential contact with the trunk. The distance of contact with these roots was directly related to reduced trunk taper in the first 30 cm of trunk above the root flare. These results suggest that in many cases trees may establish and grow well even when planted below grade. However, their long-term survival and health may ultimately be affected – if, for example, a period of heavy rains exposes them to prolonged hypoxia, or if girdling roots do not senesce and ultimately restrict growth or cause tree instability. More research is needed to assess probable long-term outcomes.

Development of a BMP for existing deep-planted trees is much needed. No firm conclusions could be drawn from the present work concerning the benefit of root collar excavation as a remediation treatment, but the possibility that they might lessen stress from wet periods of short duration or reduce the development of girdling roots should be further explored. Roots of trees planted below grade attained the same vertical distribution as roots of control trees within 1.25 m of trunks. As trees mature, this should lessen the percentage of the root system exposed to lower soil regions. Although we did not observe any effects of soil contact on trunk tissue in Turkish hazel, this is likely both site and species dependent.

Acknowledgments

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