Groundwater Research Report
WR17R002

Historic changes in groundwater use by trees in Wisconsin due to high-capacity groundwater pumping and climate variability

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Research Assistant: Dominick M. Ciruzzi, Graduate Student, Geological Engineering Program, Department of Civil & Environmental Engineering, University of Wisconsin-Madison

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Project summary (2 pages):

Depletion of groundwater (GW) resources is a global problem. The availability of GW resources is changing due to compounding drivers including climate-induced variability in recharge and changes in GW use for irrigation, industrial needs, domestic uses, and ecosystem support. In arid and semi-arid environments, tradeoffs are frequently encountered between GW dependent ecosystems and other water users. For example, over-pumping, which is often exacerbated during drought, limits productivity of vegetation that has adapted to using GW to sustain transpiration demand. Conversely, deep-rooted, phreatophytic vegetation uses GW directly and exerts a substantial reduction of available water resources for human use. In fact, under equilibrium conditions, any consumptive use of GW by humans is water that would otherwise have been used directly by ecosystems to support evapotranspiration (ET) of terrestrial systems or baseflow of streams prior to GW development. This interplay among climate, human GW use, and vegetative GW use is more often studied and widely acknowledged in arid and semi-arid environments. However, GW use by forests in wetter, temperate environments, such as in Wisconsin (WI), is underrecognized and GW-forest interactions in the context of climate variability and human water use are unknown in temperate systems.

This research explored tree growth and GW levels in WI. **We detected, quantified, and evaluated the extent to which trees currently use, and have historically used, GW (GW) in two sandy areas of WI.** We hypothesized that the sandy soils in the WI Central Sands and in the Northern Highlands regions do not retain sufficient moisture to meet transpiration demand during times of drought and as a result temperate forests use measurable quantities of shallow GW when accessible to buffer against adverse drought impacts including reduced growth. **To test these hypotheses, we used diurnal water table fluctuations to quantify current GW consumption in forests and relative tree ring chronologies to infer tree growth and historic GW levels.**

To determine how GW levels in WI have changed historically, we focused on the **WI Central Sands region and the Northern Highlands (Northwoods) lake-rich region in Vilas County,** which are two sandy regions of WI which differ drastically in the extent to which GW resources have been developed over the past 80 years. Specifically, climate variability induces year-to-year and decadal fluctuations in lake and GW levels in the Northern Highlands whereas high capacity pumping wells in the WI Central Sands has led to longer-term declines in water levels that are superimposed upon fluctuations due to climate variability. Using field observations from forests in these regions, the objectives of this project were to (1) identify when and where in these landscapes trees currently use GW; (2) quantify current GW use of trees across a range of GW depth; (3) evaluate the role of GW on forest productivity during drought and non-drought conditions; (4) reconstruct historic changes in GW levels from tree growth time series to identify changes in water levels due to pumping and/or climate-induced variability.

Our research had three key findings: (1) Shallow GW resources are used by trees where and when it is available; (2) Tree growth is substantially enhanced in the presence of a shallow water table especially during drought conditions; and, (3) Historic depth to GW time series can be reconstructed from tree cores in shallow GW areas. First, **trees in WI use GW, but not everywhere and not all the time.** When and where a shallow water table is present, our findings highlight another component to the water balance in temperate forests: GW use by trees. We observed diurnal water table fluctuations indicative of GW use by trees in temperate forests. From these fluctuations, we quantified high and more frequent GW use in forested areas with shallow GW (depth to GW (DTG)<2.5 m). Less frequent and smaller observations of GW consumption by trees were observed at intermediate GW depths (DTG between 2.5m and 3m). At deeper GW depths (DTG>4m), 1% of days showed evidence of GW use. These findings indicate that trees in sandy WI forests use GW for evapotranspiration, but not everywhere and not all the time. GW-tree interactions are strongest when and where the water table is within 1m of the land surface. GW-tree interactions decline as the water table deepens to 4m, which we interpret as a transition zone, and these interactions are nearly non-existent past a DTG of 4m. Our interpretation of a transition zone of

GW-tree interactions to a DTG of 4m for GW use is compatible within the maximum rooting depth distributions of temperate tree species of 3.9 $\pm$ 0.4 m.

Next, we found that **trees that access GW are growing up to three times as much per year than trees that lack access to GW.** In areas of shallow GW (DTG<2.5 m), we observed consistently higher tree growth in *Pinus resinosa* trees than trees in areas of deeper GW (DTG>3.5 m) for the past 80 years. This response of the influence of GW on *Pinus resinosa* growth is compatible with reported observations of maximum rooting depths for this species. In particular, *Pinus resinosa* typically produces a taproot extending anywhere between 0.12-3m (Farrar, 1995; Stiell, 1978). We highlight that across all years, tree growth was up to 96% higher in areas of shallow GW than in areas of deep GW, and on average 44% higher. Further, we observed, in general, a greater influence of shallow GW on tree growth during drought than in non-drought conditions. These findings suggest that the presence of a shallow water table substantially increases forest productivity especially during drought.

Lastly, we found that **historic GW level records can be reconstructed from tree ring chronologies.** Our findings highlight a significant relationship between tree growth and depth to GW ($R^2 = 0.65$). Using these relationships, we are able to reconstruct historic depth to GW records for the last 80 years with an average RMSE of 25 cm. In northern WI, we found that historic GW variability was primarily driven by climatic fluctuations. In central WI, we see evidence of historic GW variability driven by climatic fluctuations in areas unaffected by high capacity pumping wells, but in areas of high-density high capacity pumping wells we see evidence of tree growth that indicates a lowering of the water table since the 1970s. This suggests that as the water table deepens due to pumping and/or climate that GW use by trees decreases, which decreases tree growth. These findings highlight that trees can be used as hydrologic sensors in sandy forested environments and cored to obtain site specific information about historic GW levels and how these levels may have changed due to climatic and/or pumping changes. This may be particularly useful to extend GW depth histories at locations where GW level records are sparse or non-existent. Further, GW records derived from tree cores may be able to fill spatial and temporal GW data gaps and lengthen the calibration and validation periods of numerical models simulating GW flow.

Our research clearly demonstrates that trees in temperate forests in WI directly use shallow GW to help meet their transpiration needs and enhance forest productivity. We recommend increasing efforts to map and/or model depth to GW in these environments to determine where GW-forest interactions are the strongest. It is in these locations where GW use by trees may be an important component of the water balance and should be considered in both GW and forest management. The manner in which we manage and use GW requires recognition of forests as users of GW and quantification of the amount of GW consumed by these ecosystems. Furthermore, we recommend that natural resource managers consider the interactions among tree growth, depth to GW, climate, and pumping as they develop forest management plans. In particular, we suggest that trees in areas of shallow GW are less vulnerable to the negative impacts of drought, including water stress and reduced tree growth. Lastly, we suggest that depth to GW time series can be generated from tree core chronologies in sandy temperate forests with shallow GW that would be useful for creating historic records in data-sparse areas to understand long-term trends and variability.

1. INTRODUCTION

1.1 Motivation

Groundwater (GW) is the major freshwater storage reservoir of the hydrological cycle and widespread depletion of GW resources is a global problem (Konikow and Kendy, 2005). The availability of GW resources is changing due to compounding drivers including climate-induced variability in recharge and changes in GW use for irrigation, industrial needs, domestic uses, and ecosystem support. In recent decades the increasing use of GW for human consumption and irrigation has resulted in lower GW levels in large parts of the world (Wada et al., 2012), including the Wisconsin (WI) Central Sands region (Kraft et al., 2012). Predicted climate change will exacerbate these concerns in many parts of the world by changing precipitation regimes and increasing evapotranspiration (ET), both of which may reduce recharge and increase demand for GW withdrawal (Treidel et al., 2012). Many GW resources are non-renewable on meaningful time scales for both human society and ecosystems. Competing demands for GW use, for example GW use for human needs and GW use for vegetation, is well documented in water-limited arid and semi-arid ecosystems (Naumburg et al., 2005). However, the spatial extent, quantity, and history of GW use by vegetation in wetter environments, such as temperate forested ecosystems in WI, remain unclear in the context of changing land-use and climate variability. It is important to fill these knowledge gaps on GW use by vegetation to establish a more robust understanding of when, where, and how much trees use GW under variable climate and increasing GW abstraction for irrigation.

Soil texture is a key variable that drives interactions and feedbacks along the soil-plant atmosphere continuum, influences spatial and temporal patterns of forest productivity, and affects the conditions of when and where trees use GW. Further, soil characteristics affect the distribution of water and nutrients stored in the soil, and these in turn, influence plant distribution (Noy-Meir, 1973), vegetation structure (Fernandez-Illescas et al., 2001), water availability for transpiration (Knoop and Walker, 1985), and the degree of water stress (Porporato et al., 2001). During drought, fast draining, poor retention soils (e.g. coarser texture, sandy soils) have lower soil water availability in the root zone which increases the frequency of drought stress (‘soil drought’) (Fernandez-Illescas et al., 2001). We hypothesized that the sandy soils in the Central Sands and Northern Highlands of WI do not retain sufficient moisture to meet transpiration demand during times of drought and as a result temperate forests use shallow GW when accessible as an adaptation to buffer adverse growth impacts.

1.2 Forest effects on GW and GW effects on forests

Tree growth and water use is sensitive to many environmental factors including temperature, fires, pests, forest structure, and available soil nutrients (Pacala et al., 1996), but water availability is often the strongest driver of forest structure, function, and productivity. This is especially true in water-limited environments, such as in arid and semi-arid ecosystems, where trees have adapted to use GW when and where it is available in order to meet transpiration demand. Phreatophytes are an example of a type of GW dependent vegetation common in arid environments that have evolved with root distributions capable of exploiting GW when present and needed (Meinzer, 1927). Root water compensation is an adaptation through which vegetation, including but not limited to phreatophytes, adjust the depth of root water uptake based on soil water availability, allowing for high rates of root water uptake from the watertable, even when few roots are present at that depth (Verma et al., 2014). Roots also show some plasticity, growing preferentially in soil layers where water is more available (Padilla et al., 2009), enabling them to access the capillary fringe when the watertable is shallow. Individual tree species differ in their ability to capitalize on these adaptations during times of water stress, but several trees common in riparian forests in arid and semi-arid ecosystems (eg. *Salix* spp., *Populus* spp. And *Tamarix* spp.) have been shown to exert substantial controls on local and regional hydrology, such as increasing ET and decreasing baseflow in streams (Doody et al., 2011). Some studies have demonstrated that encroaching non-native deep-rooted vegetation, such as the taxon *Tamarix*, in the semi-arid western U.S. and Australia substantially alter water levels and reduce water resource availability because they directly tap GW during drought (Stromberg et al., 2007). It is clear that GW use by vegetation is an important piece of the water balance in the context of water availability for environmental and human use in arid and semi-arid regions, however little is known regarding GW use by trees in temperate ecosystems during drought and non-drought conditions. Similarly, the role of shallow GW in reducing drought vulnerability is well studied in arid and semi-arid ecosystems but is rarely evaluated in wetter environments which are perceived as less affected; however, drought is becoming more prevalent in temperate ecosystems with potentially severe consequences (Allen et al., 2010). Recent research, though limited, supports the notion that trees in temperate forests access deeper water reserves during periods of water stress. In a temperate forest in northwest Ohio, trees in an oak-dominated forest were able to meet evapotranspiration demand in regions with high soil water storage and shallow GW, in contrast with the water stress observed where GW was deeper (Xie et al. 2014). Similarly, trees were observed to have consistently high evapotranspiration in areas of shallow GW even under dry summer conditions (Zha et al. 2010). Additionally, as temperatures increase trees become reliant on deeper roots to meet greater forest evapotranspiration demand (Teuling et al. 2010). While these studies provide corroborating evidence of continual water use by trees during dry conditions in the presence of shallow GW, the spatial extent and quantities of GW use in temperate forests and its effect on tree growth remain unknown. Our research aims to fill these knowledge gaps of GW-forest interactions in temperate forests by evaluating and quantifying GW use by trees and its role as a mechanism that leads to higher tree growth than trees with no access to GW.

1.3 Research questions, hypotheses, and objectives

In this research, we explored:

Question 1) *Where and how much do trees in temperate forests use GW?* We hypothesize that where available, trees use GW as an additional water supply for transpiration. We expect a gradient of GW use along a depth to GW gradient, where GW use is the highest and most frequent in areas where the watertable is close to the surface to no GW use where the watertable is deep below the root zone.

Question 2) *To what extent and under what conditions does shallow GW influence tree growth in the context of changing GW levels due to climate variability and/or pumping?* We hypothesize that temperate forests with sandy soils, such as in central WI and the northern highlands of WI, do not retain sufficient moisture to meet transpiration demand during times of drought and as a result temperate forests use shallow GW when accessible as an adaptation to buffer adverse growth impacts leading to relatively higher growth than trees in areas of deeper GW. We further hypothesize that the amount of GW use, and therefore influence of GW on tree growth, declines as the water table declines due to drought conditions and/or pumping. We expect strong relationships between the variability in tree growth and shallow GW levels such that GW depth histories may be reconstructed from tree growth time series.

The overall objective of this research is to detect, quantify, and evaluate the extent to which trees use, and have historically used, GW in two sandy areas of WI. Using field observations in forests within the WI Central Sands and the Northern Highlands regions, the objectives of this project are to (1) identify when and where in these landscapes trees currently use GW; (2) quantify current GW use of trees across a range of GW depth; (3) evaluate the role of GW on forest productivity during drought and non-drought conditions; (4) reconstruct historic changes in GW levels from tree growth time series to identify changes in water levels due to pumping and/or climate-induced variability.

2 PROCEDURES AND METHODS

2.1 Field sites and sampling design

Our sampling locations considered two drivers of changing water levels: climate variability and high capacity pumping in two regions of WI. First, we created an ecohydrology observatory in the Northern Highland-American Legion (NHAL) State Forest in the Chippewa River Basin in northern WI. This area has been monitored for GW levels and other ecohydrologic parameters since the 1980s as part of the NSF-sponsored Northern Temperate Lakes-Long Term Ecological Research (NTL-LTER) program, and provides a unique opportunity to investigate changes in both past and present GW use by trees due to climate variability, including historic water stress during a severe recent drought in 2012 and an extended period of drought 2005-2010. There is no substantial pumping occurring in this region.

Second, we monitored trees and GW levels in the WI Central Sands region. On top of climate induced changes in GW levels, GW in this region is tapped for irrigated agriculture by high capacity pumping wells. The general water level decline and record low water levels from 2000-2012 in areas with high capacity pumping wells are consistent with GW depletion resulting from irrigation (Kraft et al. 2012). With these irrigation effects in mind, the WI Central Sands region provides an opportunity to investigate potential impacts of nearby high-density pumping on GW use by trees under both current and historical conditions, which can be contrasted with northern WI forests where GW pumping is minimal.

Our sampling design considered GW-tree interactions across a DTG gradient between 1-9 m. We monitored 15-minute water table fluctuations with HOBO pressure transducers (n = 20 GW wells). We extracted 1-2 radial cores per tree at 1.3m height from red pine (*Pinus resinosa*) trees within 15m of our GW wells, which yielded 5-12 red pine trees per monitoring well site (n = 145 trees).

2.2 Water table fluctuation analysis

To quantify GW use by trees, we analyzed water table fluctuations following methodologies proposed by White (1932) and Loheide et al (2005). To quantify the GW component for evapotranspiration, the following expression was evaluated:

$$ET_G = S_y\left(\frac{\Delta S}{t} + R\right) \qquad \text{(equation 1)}$$

where, ET_G is the rate of evapotranspirative consumption of GW averaged over a 24-hour period [length/time], S_y is the specific yield [dimensionless], ΔS is the daily change in storage [length], R is the net inflow (recovery) rate determined during assumed non-transpiring (night) periods [length/time], and t is the time period (1 day). The subscript G in ET_G is used to emphasize that we are calculating only the component of evapotranspiration that is derived directly from the saturated zone (i.e. GW) and that the vadose zone contribution to evapotranspiration is neglected. While the vadose zone may be the dominant water source for vegetation in many environments including temperate forests, this method will allow us to isolate the times, locations, and GW depth conditions when forests consume GW and quantify GW use. For our analysis, each data pair consists of the quantified daily ET_G and the mean daily GW depth.

2.3 Tree growth processing and analysis

We calculated basal area increment (BAI), the annual increase in cross-sectional area of a tree, from the ring widths in order to estimate annual growth for each tree. BAI is considered a direct measure of wood production as it obviates the need for detrending that is a common processing step in tree-ring chronology construction. BAI is calculated by differencing the computed basal area (BA) between successive years, where BA = $pi(0.5*d)^2$, and d is the tree diameter measured at breast height (1.3 m above the ground). BAI is calculated for each year, t, as: $BAI_t = (BA_t – BA_{t-1})$, where subscript $t – 1$ indicates the previous year (Biondi and Qeadan, 2008).

We evaluated tree growth over a depth to groundwater (DTG) gradient in northern and central WI by pairing annual BAI with mean growing season DTG and plotting these points over the entire DTG gradient for which we have paired BAI and DTG data. We defined the growing season as May-September. Additionally, we performed a temporal analysis to evaluate BAI time series during drought and non-drought conditions for trees in areas of shallow vs. deep GW. First, we aggregated the average annual BAI time series for all trees in historically shallow GW environments (DTG<2.5m) and aggregated the average BAI time series for all trees in historically deep GW environments (DTG>4m). We defined historically shallow and historically deep GW environments based on the long-term average of GW depths. Second, we calculated a time series of percent differences between tree growth responses in shallow and deep GW environments. We used this time series to quantify the influence and extent to which BAI was enhanced in shallow GW environments compared to deep GW environments during recent and historic times of drought (defined in section 2.4). Years when tree growth was higher in deeper GW sites were interpreted as years with 0% GW influence.

2.6 Defining drought for tree growth analyses in shallow vs. deep GW environments

In order to determine relationships between the influence of GW on tree growth during drought and non-drought years, a drought definition and metric was established. We used the Standard Precipitation-Evapotranspiration Index (SPEI) to analyze tree growth for different drought conditions and GW depths. The SPEI is calculated with a climatic water balance, accumulation of deficit/surplus at an annual time scale, and standardization to a log-log probabilistic distribution. The average SPEI in any SPEI time series is 0 and the standard deviation is 1. A full description of how SPEI is calculated can be found in Vicente-Serrano et al. (2010).

We obtained a time series of SPEI in northern WI using the global SPEI database (spei.csic.es) and the SPEI package in R (Vicente-Serrano et al., 2010). The global SPEI database generates time series (1951-present) of SPEI for ~100x100km grid spacing for most terrestrial ecosystems around the world. Our analysis included averaging and interpreting the percent GW influence on tree growth (Section 2.3) in years for three SPEI categories: (1) Drought years, defined as years with SPEI values less than -1; (2) Non-drought years, defined as years with SPEI values greater than 1, and; (3) Intermediate years, defined as years with SPEI values between -1 and 1.

2.5 Reconstructing depth to GW time series

For this analysis, we removed age-growth trends following a regional curve standardization because typically younger trees grow faster than older trees. We aligned all trees to their biological age and created a smoothing spline response curve across all the trees according to their biological age. We normalized each tree chronology to the average (i.e. expected) growth for that biological age and then realign the time series back to calendar years, which yields time series of the basal area growth index (BAGI). We related BAGI and DTG to reconstruct historic depth to GW time series from tree cores. In northern WI, we used site specific relationships consisting of yearly data pairs between tree growth and depth to GW to reconstruct site specific depth to GW time series. For this model, we used linear relationships to transform yearly tree growth indices into the summer mean GW level. In central WI, we analyzed the BAGI time series in an area unaffected by high-density high capacity pumping wells and in an area affected by high-density high capacity pumping wells. For the central WI analysis, we included a GW depth anomaly (i.e. deviation in water level from the mean) time series for reference from Kraft et al. (2012) at a well unaffected by high-density high capacity pumping wells to determine whether the effects of groundwater pumping could be inferred from tree ring chronologies.

3 RESULTS

3.1 Tree growth along a depth to GW gradient

3.1.1 Spatial variability in tree growth along a depth to GW gradient

The BAI and DTG time series in northern and central WI overlapped for 31 years at 6 sites, 16 years at 3 sites, 2 years at 3 sites, and 1 year at 6 sites (Fig, 1). In general, BAI is up to 3 times higher where GW is shallow (DTG<2.5 m) compared to where the GW is deeper GW (DTG>3.5m).

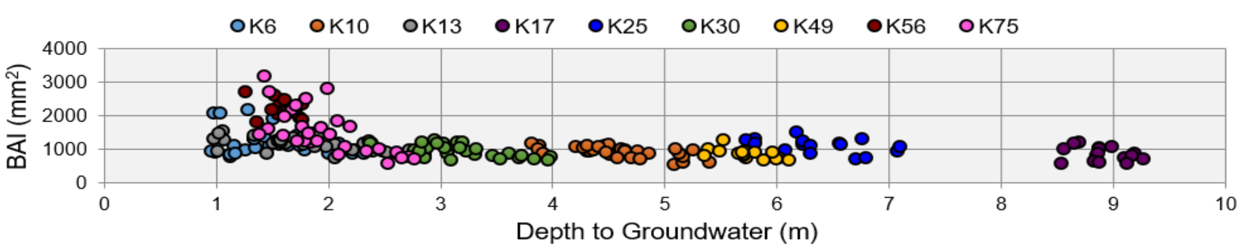

Figure 1. Tree growth response along a DTG gradient. Colors represent different sites.

3.1.2 Temporal variability in tree growth for shallow and deep GW sites

We separated the BAI growth chronologies into two cohorts: (1) trees in areas of shallow GW (DTG<2.5 m, n = 21), and (2) trees in areas of deep GW (DTG>4 m, n = 26). The two cohorts of tree ring chronologies overlapped starting in 1941 until 2015. *Pinus resinosa* trees in areas of shallow GW grew consistently higher than trees in areas of deeper GW (Fig. 2).

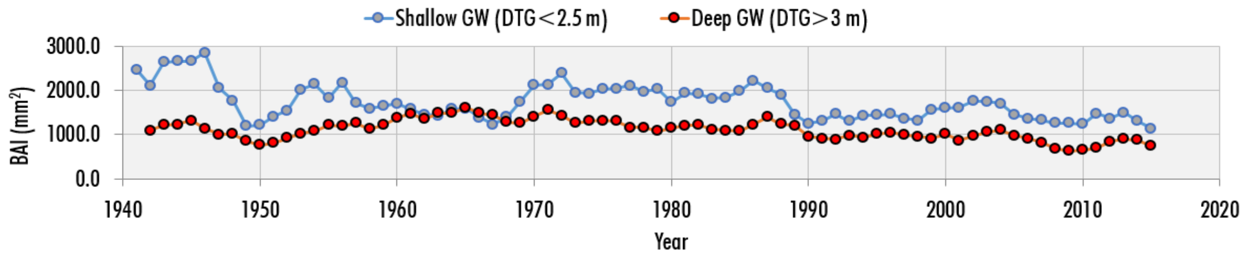

Figure 2. Tree growth in *Pinus resinosa* trees separated into two cohorts based on depth to GW.

3.1.3 Tree growth response to drought in shallow vs. deep GW environments

We interpreted a time series of percent differences in tree growth responses between *Pinus resinosa* in shallow and deep GW environments as the influence of shallow GW on tree growth (Fig. 3). For the entire time series (1941-2015), tree growth in shallow GW environments was on average 44% higher than tree growth in deep GW environments, with a full range of 0-96%.

The yearly SPEI is shown in Figure 3b. From 1951 until 2015 in northern WI, 7 years were classified as non-drought years (SPEI>1), 48 years were classified as intermediate (-1<SPEI<1), and 10 years were classified as drought years (SPEI<-1). In general, the influence of shallow GW on tree growth in *Pinus resinosa* is apparent during non-drought, intermediate, and drought years (Fig. 3c). Though no statistically significant differences were detected among these groups, the percent influence of GW on tree growth was on average higher during drought conditions than during non-drought conditions.

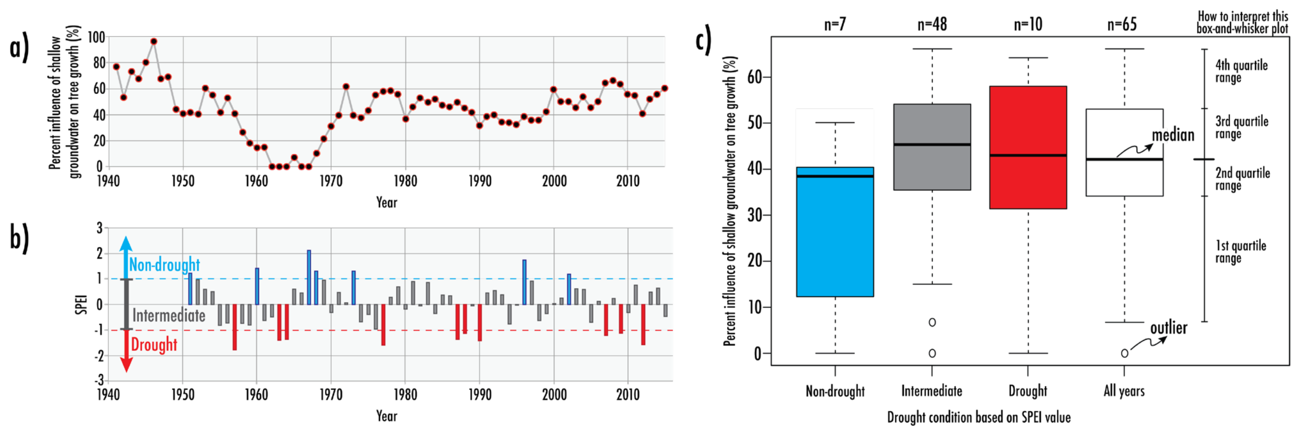

Figure 3. The influence of GW on tree growth during drought and non-drought conditions. (A) The percent influence of shallow GW on tree growth is calculated as the percent difference between tree growth response in *Pinus resinosa* trees in historically shallow (DTG<2.5m) and deep GW (DTG>4m) environments and is presented for the same time series in Figure 2. (B) The SPEI time series was obtained from the global SPEI database. (C) The quartile ranges of the percent GW influence on tree growth, including the median, for the SPEI-generated drought conditions are presented as box-and-whisker plots using a similar color scheme in Fig. 3b.

3.2 GW use along a depth to GW gradient

Along a depth to GW gradient (~1-9m), the GW component of ET (ET_g) was the highest and occurred the most frequently at sites with shallow GW (DTG<2.5 m) across the 4 years we monitored 15-minute depth to GW data (Fig. 4). At shallow GW sites (DTG<2.5m), we detected GW use between 29-67% of the days during the growing season with averages of ET_g ranging between 1.07-3.4 mm/day. We detected GW use in deep GW sites (DTG>4 m) from diurnal water table fluctuations on 1% of days. At intermediate depths (DTG between 2.5 and 4 m), we detected GW use between 7-36% of growing season days, with averages of ET_g ranging between 0.81-0.99 mm/day. For equation 1, we assumed Sy = 0.2.

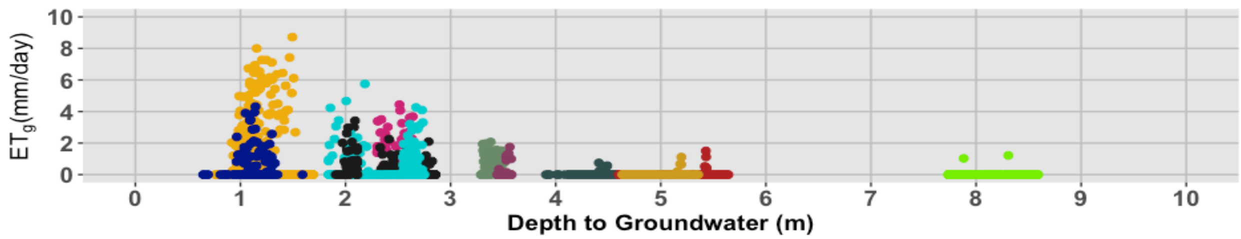

Figure 4. Quantified values of ET_g along a depth to GW gradient.

3.3 Reconstructing GW levels with tree cores

In northern WI, we related BAGI and GW depth records to create linear models to reconstruct GW depth histories at specific sites (representative reconstruction in Fig. 5a). The average RMSE was 25 cm. In central WI, we show the BAGI time series at two sites: (1) in an area without high-density high capacity pumping wells (blue line in Fig. 5c); and, (2) in an area with high-density high capacity pumping wells (red line in Fig 5c). We also included a GW depth anomaly time series from a reference well 10 miles away from the minimally affected by GW depletion site (black line in Fig. 5c).

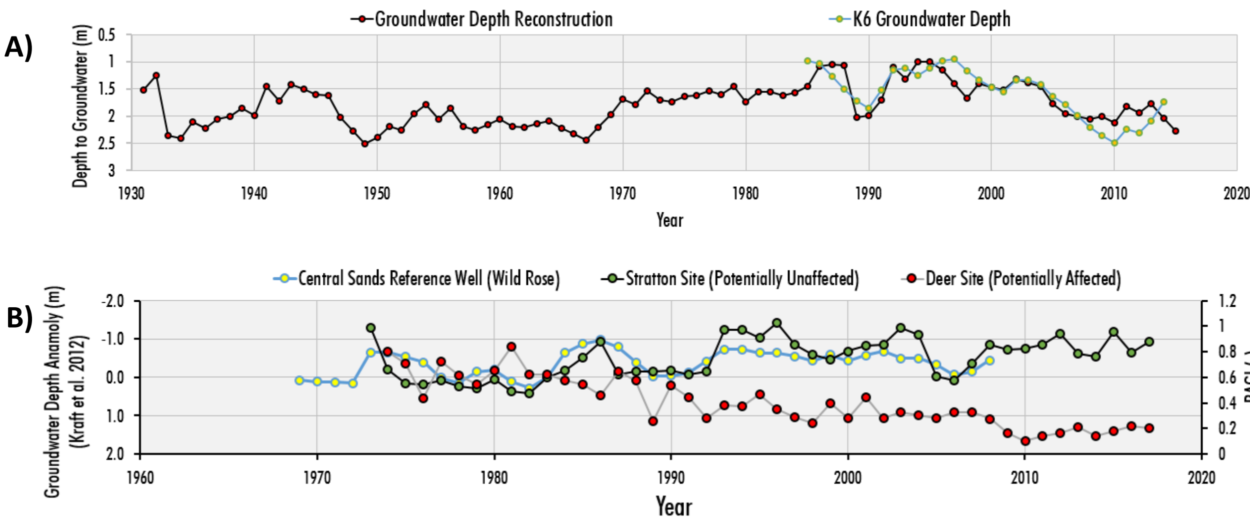

Figure 5. (A) Reconstructed GW depth time series from tree cores in northern WI. (B) Tree growth in central WI (right axis) and a GW depth time series near our potentially unaffected site (left axis). Negative GW depth anomalies are higher than average and positive GW depth anomalies are lower than average.

4 DISCUSSION

4.1 Influence of GW on tree growth in temperate forests

In areas of shallow GW (DTG<2.5m), we observed consistently higher tree growth in *Pinus resinosa* trees than trees in areas of deeper GW (DTG>3.5m) for the past 80 years (Figure 2). This finding is likely due to a transitional response in the influence of DTG on *Pinus resinosa* growth. This indicates substantially enhanced growth in areas where DTG is 1m and lesser of an influence, but still enhanced growth, as the watertable deepens to ~2.5-3m. We did not observe enhanced growth in areas where DTG was deeper than ~3m, which is compatible with the maximum rooting depths of *Pinus resinosa* extending anywhere between 0.12-3m (Farrar, 1995; Stiell, 1978). Further, we observed, in general, a greater influence of shallow GW on tree growth during drought than in non-drought conditions (Figure 3c). These findings suggest that the presence of a shallow water table substantially increases forest productivity especially during drought.

4.2 Influence of trees on GW systems in temperate forests

When and where shallow GW is present, our findings reveal an often underrecognized component to the water balance in temperate forests: GW use by trees. We observed diurnal water table fluctuations indicative of GW use by trees (Loheide et al., 2005; White, 1932) in temperate forests. We found that trees in sandy WI forests use GW for ET, but not everywhere and not all the time. As DTG transitions from 1 to 4m, GW consumed for ET decreases, and becomes non-existent in areas where DTG is deeper than ~4m. Our interpretation of a DTG influence transition at 4m for GW use is compatible within the maximum rooting depth distributions of temperate tree species of 3.9 $\pm$ 0.4 m (Canadell et al., 1996).

4.3 Trees as hydrologic sensors in sandy temperate forests

We reconstructed historic depth to GW time series in northern WI with an average RMSE of 25 cm. In areas of high-density high capacity pumping wells in central WI, tree growth at a shallow GW site appeared to decline since the 1970s and follows a similar trend to that of declining GW levels over the past 60 years. This contrasts with tree growth and GW level variations in an area minimally affected by declining water level trends in central WI, where variations in tree growth and water levels are more indicative of climate-driven responses. These findings highlight that trees in these areas of shallow GW in sandy temperate forests could be used as hydrologic sensors to inform site-specific water level variability where water level records are sparse or non-existent.

4.4 Implications for GW-tree interactions in a changing world

Shallow GW (DTG between 0-5m) within the critical zone strongly influences land, water, and energy fluxes (Maxwell and Kollet, 2008), and ecosystem services (Qiu et al., 2019), and exists under vast forested regions, including the temperate forests in WI (Fan et al., 2013). We suggest that temperate forests with shallow GW around the world are underrecognized areas where GW-forest interactions are influencing land, water, and energy fluxes. For example, a recent study by Hain et al. (2015) shows regions where remotely sensed latent heat fluxes exceed land surface model predicted evapotranspiration, including our study forests in WI, which has extensive lake cover and associated shallow GW. From our analyses, there is a strong indication that shallow GW is influencing the energy balance within WI forests and that neglecting GW-forest interactions has caused poor performance of land surface models. We suggest that the underpredicted evapotranspiration in WI and in other regions with shallow GW is at least partially the result of neglecting direct GW consumption by forests and that this GW use is broadly ignored by modelers and GW managers alike. Our findings indicate that as shallow GW levels decline, so does evapotranspiration from trees in areas where DTG is between 1-4m. In order to understand how GW-tree interactions may change in the future due to climate change, we recommend that shallow GW be considered as an ecosystem attribute that influences forest productivity and water and energy fluxes in temperate forests. In particular, climate and ecohydrological models with the ability to test future climate scenarios need to consider GW-tree interactions in temperate forests with shallow GW to accurately simulate water and energy fluxes.

Landuse changes also influence forest and GW resources. In central WI, extensive pumping for irrigation over the past 50 years has emerged as a control explaining long-term decreasing trends in local and regional GW levels. Over a period of about five decades, the water table lowered as much as 1m in areas with a high-density of high-capacity pumping wells (Kraft et al., 2012). Our findings indicate a transitional response in tree growth and GW use in temperate trees along a DTG gradient between 1-4m. We observed GW depths shallower than 2.5m influence tree growth in *Pinus resinosa* and these and other temperate trees use GW as deep as 4m. In historically shallow GW areas, when GW levels are lower than normal, tree growth and GW use by trees are low. If declining GW level trends persist, forested areas currently influenced by GW may become less influenced by GW or lose GW influence entirely. Future work should consider the likelihood that there may already be areas in central WI, and other places with declining water tables in shallow GW environments, where the water table is deepening past or has already deepened below these GW depth transition zones. These forested areas will then become more vulnerable to the adverse consequences of drought, including reductions in productivity and increased risk of disease and mortality in the future.

4.5 Potential implications for management prioritization in the context of drought and pumping

For natural resource managers, we recommend developing spatially explicit forest and water management plans that consider GW-forest interactions. For GW managers, we provide two recommendations in this context: (1) Trees should be considered as GW users when and where the watertable is within ~4m of the land surface; and, (2) Prolonged GW pumping leading to local-to-regional GW level declines is likely to reduce forestry outputs in locations where groundwater had been shallower than 4m. In WI, and other temperate forests, GW consumed by trees is a component of the water balance when and where the watertable is close to the land surface (DTG < 4m). As GW levels decline due to drought and/or pumping, so does GW use by trees and tree growth. In order to sustainably manage shallow GW and tradeoffs involving consumption by forests, DTG should be mapped and/or modeled to understand the extent of GW use by trees.

For forest managers, we provide two recommendations: (1) Trees and forests that have access to GW should be considered in drought management plans; and, (2) Mapping DTG in forests can optimize management prioritization for forestry outputs and improve understanding of the vulnerability to adverse drought impacts. Two best practices for managing impacts of drought are thinning and strategically planting drought resistant tree species. Thinning is used to reduce stand density and adjust species composition, with the goal of reducing or mitigating drought-related stress, which can improve stand resistance and resilience to drought disturbance (D'Amato et al., 2013). In general, we suggest prioritizing thinning in forested areas with deep GW instead of the entire forest, or at least first focusing efforts in these regions. Thinning can also occur in forested areas with shallow GW; for example, during an extreme drought, thinning can be used to avoid cascading secondary impacts of drought over a region, including insect attacks and wildfire. Strategically planting tree species can also mitigate the potential impacts of drought on forests by adjusting the successional trajectory of species composition within a forest stand. In general, we suggest targeting forest stands with deeper GW and planting tree species with more hydraulic diversity, meaning planting trees with a variety of water use strategies and rooting depths. Increasing the hydraulic diversity of a forest stand buffers variations in ecosystem fluxes (water and energy) during dry periods, including prolonged drought conditions (Anderegg et al., 2018). However, these and other recommendations for forest managers are only useful if DTG has been mapped or is understood to some extent in a particular forest stand. In order to prioritize spatially explicit forest and GW management plans based on GW depth, investments should be considered to collect and map the extent of shallow GW depth under temperate forests. Fan et al., (2013) developed a global map that simulates static water depth at ~1km grid spacing; however, this map neglects local complexity and human influence and only captures broad scale variability. GW depths vary substantially both spatially and temporally and depend on a multitude of site specific variables, including soil texture, stratigraphy, land use, topography, and proximity to water bodies (lakes, streams, reservoirs, etc.), among others. While global maps may be useful to identify regions of shallow GW, future work should be done to map local GW depth variability that considers multiple approaches including use of field observations, GW modeling, and taking advantage of remote sensing approaches to map GW influenced ecosystems.

Field observations from GW wells provide ground-truth information and can be implemented at relatively low cost, but may be unrepresentative of the larger scale. Numerical modeling of GW flow and depth can help fill in spatial and temporal gaps, but requires extensive effort and data to parameterize, (i.e. soil parameters, boundary conditions, recharge, and land cover, among others), calibrate, and validate the model. Remote sensing approaches that take advantage of satellite products, such as Landsat, have been used to identify vegetative and hydrological indicators suggestive of GW dependence or influence in dry ecosystems (Barron et al., 2014; Gou et al., 2015), but the extent to which these assumptions are reasonable in wetter environments, like temperate forests, are currently unknown. Therefore, a holistic methodology that considers multiple approaches to map GW depth and/or GW influence in temperate forests would be ideal and more research should be performed on these topics. Given the substantial influence of shallow GW on water and energy fluxes in temperate forests, incorporating plans to monitor and map GW depths in forests would represent progress toward being able to develop spatially explicit forest management plans that consider the buffering effects of GW-forest interactions in the context of a changing climate. We note that using tree cores to reconstruct site-specific historic variability in GW depths could be used in these efforts to map and extend GW level records, and therefore increase the data used in calibration and validation in numerical models simulating GW flow.

5 CONCLUSIONS AND RECOMMENDATIONS

Our research led to three key findings related to GW-tree interactions in temperate forests: (1) Shallow GW resources are used by trees where and when they are available; (2) Tree growth is substantially enhanced in the presence of a shallow water table especially during drought; and, (3) Historic DTG time series can be reconstructed from tree cores areas with shallow GW. We observed trees in areas with shallow GW (DTG<2.5m) had consistently higher growth and consumed more GW than trees in areas of deeper GW (DTG>4m). Further, we observed a stronger influence of shallow GW on tree growth during drought than non-drought conditions. These findings suggest that the enhanced growth in trees in areas of shallow GW is a direct result of frequent GW consumption for evapotranspiration. These relationships between shallow GW and tree growth are strong, and historic depth to GW records can be reconstructed from tree core growth chronologies. We recommend that forest and GW managers consider the interactions among tree growth, depth to GW, climate, and pumping by recognizing forests as GW users and acknowledging that shallow groundwater both enhances forest productivity and provides forest resilience during droughts. In addition, we recommend efforts to map and/or model depth to GW in these environments to determine where GW-forest interactions are the strongest. It is in these locations where groundwater use by trees may be an important component of the water balance and should be considered in both groundwater and forest management. Lastly, we suggest that depth to GW time series and datasets can be generated from tree core chronologies in sandy temperate forests with shallow GW that would be useful for creating historic records in data-sparse areas to understand long-term trends and variability.

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APPENDIX A: **Awards, Publications, Reports, Patents, Presentations, Students, Impact**

Presentations:
Dominick M. Ciruzzi and Steven P. Loheide II (2018). *Evaluating tree growth and groundwater use along a depth to groundwater gradient in sandy Wisconsin forests*. CUAHSI 2018 Biennial Colloquium. Shepherdstown, West Virginia
Number of attendees: 40

Dominick M. Ciruzzi and Steven P. Loheide II (2018). *Evaluating tree growth and quantifying groundwater use in sandy Wisconsin forests*. American Water Resource Association, Wisconsin Section. Appleton, Wisconsin.
Number of attendees: 60

Dominick M. Ciruzzi and Steven P. Loheide II (2018). *Groundwater-forest interactions in the sandy temperate forests of NTL-LTER*. LTER All Scientists Meeting. Pacific Grove, California.
Number of attendees: 50

Dominick M. Ciruzzi and Steven P. Loheide II (2017). *Tree growth response to drought along a depth to groundwater gradient in northern Wisconsin*. AGU Fall Meeting 2017. New Orleans, Louisiana.
Number of attendees: 100

Dominick M. Ciruzzi and Steven P. Loheide (2019). *Trees as hydrologic sensors: Evaluating tree rings to reconstruct historic groundwater levels in central and northern Wisconsin*. AWRA Wisconsin Section. Delavan, WI.
Number of attendees: 60

Awards:
Outstanding graduate oral presentation award,
Dominick M. Ciruzzi and Steven P. Loheide (2019). *Trees as hydrologic sensors: Evaluating tree rings to reconstruct historic groundwater levels in central and northern Wisconsin*. AWRA Wisconsin Section. Delavan, WI.

Publications:
<u>In preparation:</u>
DM Ciruzzi & SP Loheide II. Quantifying groundwater use, tree growth, and influence of drought in sandy temperate forests.

DM Ciruzzi & SP Loheide II. Reconstructing historic groundwater levels using tree growth chronologies in sandy temperate forests.

Students:
Graduate students:
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Patents:
Nothing to report

Impact:
Shallow groundwater and forests are connected resources. Trees use groundwater when and where available as a supplement to soil moisture available after precipitation. In the sandy temperate forests of Wisconsin our research had three key findings: (1) Trees influence the groundwater system by consuming groundwater; (2) Shallow groundwater enhances tree growth especially during drought; and, (3) Tree ring chronologies can be used to reconstruct historic depth to groundwater records. When trees use groundwater, groundwater levels decline based on the amount of groundwater used. Further, as groundwater levels declines, tree growth also declines. Finally, as the water table declines, trees use less groundwater. This relationship between tree growth and depth to groundwater can be used to reconstruct historic groundwater levels at locations where groundwater records are sparse or non-existent. Our findings indicate transitional responses in tree growth and groundwater use in temperate trees along a depth to groundwater gradient. As depth to groundwater deepens past 2.5m, groundwater influence on tree growth diminishes and trees use almost negligible quantities of groundwater when it is deeper than 4m under the conditions studied. Declines in groundwater levels due to climate variability (i.e. droughts) and groundwater abstraction for irrigation may cause forested areas currently influenced by groundwater to become less influenced by groundwater or lose groundwater influence entirely and become more vulnerable to negative consequences of future droughts, including increased water stress, reduced productivity, and mortality. In order to sustainably manage forest and groundwater resources concurrently, these two systems must be considered and managed together.