GROUNDWATER RECHARGE UNDER COMPACTED AGRICULTURALSOILS, PINEAND PRAIRIE IN CENTRAL WISCONSIN, USA

A.M. Radatz, B. Lowery*, W.L. Bland, and A.E. Hartemink

Department of Soil Science, University of Wisconsin-Madison
1525 Observatory Drive, Madison, Wisconsin 53706-1299, USA
*(*Corresponding author: blowery@wisc.edu, 608-692-9210)*

Abstract

The water table in Wisconsin Central Sand Plain (CSP) dropped 1.8 m between 2002 and 2010, and several lakes in the area suffer from low water levels. The lower groundwater level has been attributed to agricultural cropping practices, specifically irrigation, and a reduction in ground-water recharge. Dominant soils in this area are sands (Udipsamments). The objective of our research was to quantify groundwater recharge under (i) irrigated agricultural crops, (ii) prairie, and (iii) a 50-year old pine tree plantation in the CSP. Equipment was installed at five sites to monitor water table elevation, soil water content, and precipitation at 15-minute intervals. It was found that, when the soil was at field moisture capacity, precipitation during the growing season resulted in 1.4 cm more water table rise under a prairie than under irrigated agricultural fields. Agricultural crops used groundwater through irrigation, but natural vegetation relied on soil available water, and capillary rise of water from the shallow groundwater table (1 to 2 m to water table), for daily transpiration. After snowmelt, prairie vegetation yielded greater rise, up to 16 cm, in the water table than agricultural fields. Lack of crop residue on the soil surface of agricultural fields resulted in a continuous layer of frost in the soil profile that extended to about a meter depth. This thick, frozen layer was enhanced by greater soil compaction under irrigated crops compared to limited or no compaction in prairie areas. The key finding was that this deep frost in the soil profile inhibited snowmelt water from infiltrating and recharging the groundwater. Thus, compacted-irrigated agricultural soils in the CSP alter groundwater recharge characteristics during frozen and non-frozen ground periods. Increased crop residues on the surface of agricultural fields might enhance groundwater recharge during winter snow melt periods.

Keywords: compaction, groundwater, water table, prairie

Introduction

Much of the original tall-grass prairie land cover in the United States of America (USA) and the State of Wisconsin has been converted to agricultural crops. Conversion from natural vegetation to agricultural crops reduces the soil carbon stock and affects biodiversity, soil conservation, water resources, and even climate among other things (1, 2). In addition to these, Weisenberger (3) found conversion from tall-grass prairie to row crops results in increased soil compaction.

Vegetative cover impacts water infiltration and drainage to groundwater during the growing season and in the winter in Wisconsin. The vegetation affects water infiltration by interception of precipitation, which later evaporates rather than infiltrate and recharge soil water or groundwater. This is different for different vegetation types. The canopy of mature coniferous forests can intercept up to 48% of precipitation (4), and in addition 47% of throughfall precipitation is trapped by duff layers on the forest floor (5). With greater amounts of precipitation intercepted by plant canopies and residue on the soil surface, less water is available to infiltrate into the soil and recharge groundwater (6). During the winter, soil temperature remains significantly greater when there is at least 90% vegetative cover on the surface than a bare soil surface (7), and this will impact water recharge. Genxu et al. (8) reported that freeze-thaw processes can also be significantly affected by changes in vegetative cover.

Considerable parts of the Wisconsin Central Sand Plain (CSP) are cultivated with potato and other row crops (corn, soybean). Overhead irrigation and heavy machinery are commonly used that has locally resulted in compacted subsoils. A relatively small area in the CSP is under pine forest or under prairie vegetation. The combination of different vegetation covers and soil compaction causes complex soil and groundwater recharge in the CSP. The objectives of this study were to compare the differences between year-long soil water and groundwater recharge under prairie vegetation, pine trees, and irrigated agricultural crops in the CSP.

Materials and Methods

This study was conducted at five sites located on privately owned farmland in Adams County near Grand Marsh, Wisconsin, USA. The CSP of Wisconsin is a deep, uniform sand deposit created by Glacial Lake Wisconsin. This area is underlain by an unconfined sand and gravel aquifer (9). The water table ranges from 1 to 3 m from the ground surface. In the CSP, irrigated land has increased from hundreds to thousands of hectares over the past 70 years. The water table dropped 1.8 m between 2002 and 2010. It has been suggested that the increase in irrigated agricultural production has adversely impacted water resources.

Soil parent material consists of glacial till overlain by glacial outwash. The groundwater is located in an unconfined sand and gravel aquifer. Thus, the groundwater in this area is expected to respond rapidly to changes in surface hydrology, especially water infiltration and drainage, and in some cases water use by deep rooting plants.

The five study sites were selected based on their vegetative cover, similar geographic location, and depth to the water table. Soils at the sites are the series Brems loamy sand (mixed, mesic Aquic Udipsamments) and Plainfield sand (mixed, mesic, Typic Udipsamments). The vegetative cover included:
Field 1: irrigated sweet corn: *Zea mays, var. rugosa*
Field 2: irrigated soybeans: *Glycine max*
Pine: red pine plantation: *Pinus resinosa*
Prairie 1: mixed vegetation, grass, bush and oak trees [oak (*Quercus ellipsoidalis*), jack pine (*Pinus banksiana*), and aspen (*Populus tremuloidies* and *Populus grandidentata*)]
Prairie 2: tall-grass prairie [such as switch grass (*Panicaum virgatum*), side-oats grama (*Bouteloua curtipendula*), little bluestem (*Schzachyrium scoparium*) and several other species].

A continuous monitoring system was installed for assessing soil water content and water table elevations using 15-minute recording time intervals. Groundwater monitoring wells were installed at each of the five sites to a depth between 1.2 and 3.5 m below the 2008 spring water table elevation. Monitoring wells were installed using a truck-mounted, hydraulic-driven 7-cm diameter closed-end auger drill unit. At each site, a Campbell Scientific 21X datalogger, Onset RG3 tipping bucket rain gauge, Instrumentation Northwest PS-9805 submersible pressure/ temperature transducer, and Campbell Scientific CS615 water content reflectometer were used for data collection. The rain gauges in the fields collected both amount and intensity of precipitation and irrigation. Rain gauges in the prairies collected only rainfall data. A second rain gauge was installed outside the pine plantation and mixed prairie (Prairie 1) to allow for evaluating the impact of canopy on precipitation. The pressure transducers were installed at a known depth in wells, and measured changes in well water level over time. The reflectometer probes were installed vertically to measure the top 30-cm soil water content using methods described by Ledieu et al. (10) and Cooley et al. (11).

Results and Discussion

Effects of surface cover on water table recharge during the growing season (non-frozen ground)

The water table under the mixed prairie and corn crop responded comparably to recharge events during the 2008 growing season, but the water table elevation under pine plantation increased only after 50 mm of precipitation (Fig. 1). Water table rise beneath the mixed-prairie and corn increased linearly with increasing rainfall, but the water table under the pine did not follow this relationship (Fig. 1). This suggests there is considerable interception of precipitation in the pine trees and less water reaches the ground surface. As a result, there is less soil water recharge since soil water needs to be recharged before the water table can increase.

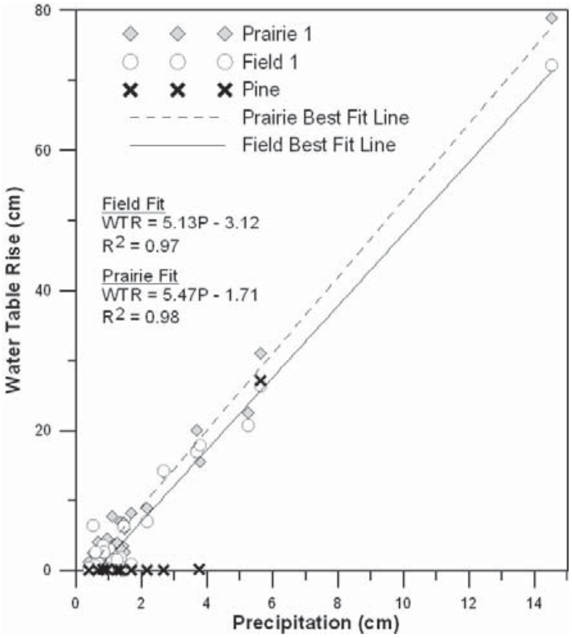

Figure1. Water table rise (WTR) and precipitation (P) for mixed prairie (Prairie 1), corn (Field 1), and pine plantation (Pine).

Interception losses

The canopy of mature trees at both the mixed-prairie and pine sites intercepted a portion of each precipitation event. The amount of precipitation intercepted by the tree canopy increased as the total precipitation increased (Fig. 2). Based on data from rain gauges inside and outside the pine plantation, it was found that the canopy intercepted between 7 to 55% of each precipitation event. Hormann et al. (4) found 9 to 48% of precipitation interception by coniferous forest canopies, whereas McLaren et al. (12) reported that at least 18% of precipitation was intercepted by forest canopy. Precipitation interception by vegetation impacts recharge to the water table under the pine, but produces no observable impact at mixed-prairie, even though the canopy of deciduous trees can intercept half of the precipitation.

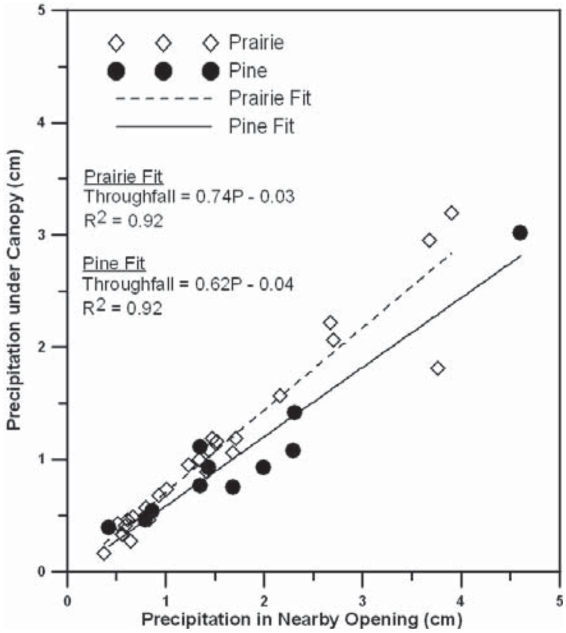

Figure 2. Total precipitation (P) and precipitation interception by tree canopy at mixed-prairie (Prairie) and pine plantation (Pine) sites.

The ground beneath the pine plantation is covered with a 10-cm layer of partly undecomposed litter, including needles and pine cones, which likely intercepted some precipitation as well. Putuhena and Cordery (5) found that the litter layer in mature pine forests intercepts, on average, 47% of throughfall. Such litter layer is not present in the mixed-prairie, which may explain the differences in retention of precipitation between the two vegetation types.

It is likely that precipitation not intercepted by the canopy, and subsequently evaporated is retained by, and evaporated from, the thick layer of pine litter. Water from precipitation that passed through the litter layer on the soil surface likely replenished the severely depleted soil water storage, leading to little or no recharge to the water table underneath the pine plantation during the 2008 growing season (July to October). The water table at the pine plantation only responded to precipitation events during April and May 2009 when the soil water content was greater than field moisture capacity and the precipitation events were between 2 and 5 cm. Soil water content was greater than 0.25 m^{3}m^{-3}when the water table responded to precipitation events. Soil water content during the 2008 growing season was consistently less than 0.10 m^3m^{-3} and did not reach 0.25 m^3m^{-3} even after a sizable precipitation event. O'Brien et al. (6) found that the red pine stand had the lowest daily and monthly drainage to the water table compared to bunch grass and lichen and moss sites.

Effects of surface cover on water table recharge during winter (frozen soil)

Water table elevation data from December 2008 through February 2009 show significant differences in the rise of the water table under mixed and tall-grass prairies and corn and soybean fields following two major snowmelt events. A late December (2008) snowmelt occurred as air temperatures reached approximately 7ºC (Fig. 3). An early February 2009 snowmelt occurred as air temperatures reached 10ºC and approximately 2.5 mm of rain fell in the area. The cropped and prairie areas responded as water from melted snow moved through the soil profile and into the groundwater. The range of water table responses observed was between 3.8 and 21.1 cm (Table 1).

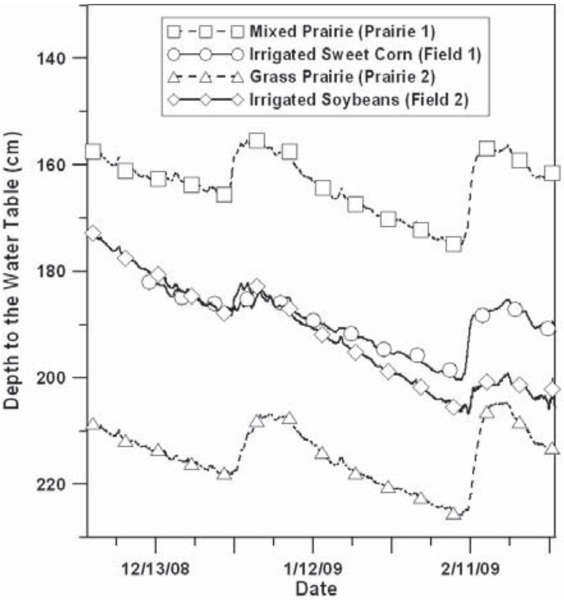

Figure 3. Depth to the water table under prairie and harvested agricultural field sites from 1 December 2008 to 28 February 2009. Symbols plotted every 600 data points.

The main difference between the agricultural fields and the prairie sites during the winter months was the absence, or varying amounts, of residue from the previous growing season's vegetation. No residue was left on Field 1 (harvested corn field) through winter months, since the plant matter was removed and the field was chisel plowed after harvest. Field 2 (soybean field) was harvested and residue was not removed. According to Burr and Shelton (13), the amount of residue left after soybean harvest can cover as much as 67% of the ground surface. However, this residue cover can be reduced by 18% or more from weathering during winter months. This residue cover is physically different from the prairie residue cover, as it is thinner and extends less than 3 cm above the soil surface. The prairie sites were left undisturbed after the growing season, so the soil surface was totally covered by greater than 15-cm high decaying plant matter.

Table 1. Site, date of detected response to snowmelt, and maximum height of water table rise during event.

Site ID	Event date	Total water table rise
		--cm--
Field 1	25 December 2008	3.83
Field 2	27 December 2008	6.28
Prairie 1	25 December 2008	11.19
Prairie 2	25 December 2008	11.43
Field 1	8 February 2009	15.11
Field 2	10 February 2009	7.52
Prairie 1	8 February 2009	18.89
Prairie 2	8 February 2009	21.07

A snowmelt event during early February 2009 resulted in differences in water table level under the various vegetation types. Prairie 1 again had the greatest total rise in water table compared to Field 1, with 18.9 cm in Prairie 1 versus 15.1 cm in Field 1, (Fig. 3, Table 1). At the soybean site (Field 2), the same pattern was found, as the water table under the Field 2 rose 7.5 cm, while the total height of rise under the Prairie 2 was 21.1 cm (Fig. 3). A site investigation on 10 February 2009 revealed standing water on both agricultural field sites and in many other agricultural fields in the surrounding areas. However, standing water was not observed in the two prairie sites, and it was also noted that melt water had infiltrated into the soil in other prairie sites in the area as well. The differences between the two vegetation covers were found to be the depth of frost and soil compaction.

Test of frozen soil

Differences in frost depth and continuity were tested among sites with different vegetation by driving a 1.2-cm diameter metal rod into the soil with a 12-kg hammer. This proved to be an effective and rapid assessment method.

Corn field (Field 1) – A uniform snow cover of 5 to 10 cm was observed at this harvested agricultural field site. The metal rod could not be driven into the ground. The sweet corn was harvested in August 2008, and the remaining crop residue was plowed under and the field was left fallow throughout the fall and winter. There was no residue cover left on the surface. The lack of vegetative cover left the bare soil vulnerable to extreme freezing temperatures before the first snow fall.

Pine – A uniform 2.5-cm snow cover was present throughout the pine plantation, but 7 to 12 cm of uniform snow cover was observed in the adjacent open field. By driving the rod into the soil, a 25.4- to 30.5-cm frost layer was estimated. The frost zone extended deeper into the soil profile at this site compared to the other naturally vegetated sites (mixed and tall-grass prairies). It is possible that this greater frost is because of the lack of direct sunlight reaching the soil surface under the pine tree canopy. However, the thick layer of decomposing plant matter should have insulated the surface from extreme freezing temperatures.

Tall-grass Prairie (Prairie 2) – Snow cover at this site was not uniform over the entire surface, but rather formed in masses around grass bunches. The snow pack was hard enough to support a 70 kg person’s weight. By driving the rod into the soil, a 10.0- to 15.0-cm frost layer was estimated. Similar to Prairie 1, the surface had almost 100% residue cover from the previous year’s vegetation.

Soybean Field (Field 2) – A uniform snow cover of 5.0 to 10.0 cm was observed over this entire site. It was impossible to drive the rod into the soil at this site. Approximately 50% of the vegetative cover was destroyed at this site in October as the crop was harvested. Approximately 50% of the ground surface was covered by a thin layer of plant matter left on the field after harvest. Because of the nature of the soybean crop, this residue is not as substantial or consistent as the prairie vegetation. This site was not plowed until spring 2009. Freezing temperatures may have created a frost layer early in the winter because of reduced insulating residue cover on the soil surface to prevent heat loss.

Conclusions

During the growing season, vegetative covers such as agricultural crops, prairie, and pine trees impact groundwater recharge. Prairie vegetation had the greatest amount of groundwater recharge per precipitation event, while under pine recharge was lowest. Response by the water table to precipitation events during the 2008 growing season was 1.4 cm greater under the prairie vegetation than irrigated agricultural crops. Recharge to the water table under the pine plantation was minimal (near zero compared to prairie and crop fields) for the 2008 growing season as the forest canopy and litter layer on the soil intercepted much of the precipitation.

During frozen ground period, differences in residue cover on the soil surface and compaction played a significant role in the depth and continuity of frost in the soil under the different vegetation types. Residue on the soil surface of forest and prairies protected soil against extreme freezing temperatures, and this along with less compaction resulted in significant increased recharge to the groundwater aquifer during winter months. Discontinuous and shallow frost in prairie soils allowed snowmelt water to infiltrate and recharge the water table instead of ponding on the surface creating surface water runoff.

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