Journal of Hydrology 483 (2013) 26–38

Contents lists available at SciVerse ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

# Conservation tillage in dryland agriculture impacts watershed hydrology

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ARTICLE INFO

*Article history:*
Received 17 August 2012
Received in revised form 20 December 2012
Accepted 20 December 2012
Available online 12 January 2013
This manuscript was handled by Corrado Corradini, Editor-in-Chief

*Keywords:*
Conservation tillage
No-till
Soil moisture
Runoff
Hydrologic modeling

SUMMARY

Dryland (non-irrigated) crop production in semi-arid regions requires sufficient water storage in the soil profile to ensure adequate plant available water, particularly in areas where the majority of annual precipitation occurs during the non-growing season. Producers can increase soil water storage through the adoption of best management practices (BMPs) for tillage and crop residue management. The objective of this study was to assess our hypothesis that watershed-wide adoption of no-till (NT) farming would decrease winter water losses and increase early growing season plant available water as compared with conventional tillage (CT) methods. We analyzed water storage potential under assumed full-scale adoption of NT and CT cropping practices in the Palouse region of eastern Washington State by applying the Distributed Hydrology Soil Vegetation Model (DHSVM) with modifications to represent the physical changes to infiltration, evaporation, and runoff that result from tillage management.

DHSVM yielded a Nash–Sutcliffe model efficiency (NSE) for streamflow of 0.69 for the watershed-scale simulations over the Palouse River basin, which falls within the NSE ranges reported for DHSVM (0.57–0.91). Surface temperature predictions resulted in an NSE of 0.60, and the model was able to predict the soil state (frozen or unfrozen) 81% of the time. Simulated soil moisture was approximately 50% greater under widespread adoption of CT versus NT management during the majority of the winter months. Predicted volumetric soil moisture content for April 1, 2005 was 29% and 34% under CT and NT management, respectively. This difference in winter and spring soil moisture was caused primarily by decreased evaporation under NT, with minimal effects resulting from changes in infiltration. Two simple crop yield estimation methods indicated that increased spring soil moisture under NT management may result in a 21–26% wheat yield increase.

We concluded that NT has the potential to increase soil water storage of winter precipitation in the root-zone, which may lead to higher wheat yields in the Palouse region. Furthermore, DHSVM was found to be suitable for investigating some watershed-scale agricultural management opportunities and has the potential to address additional questions pertaining to sustainable farming.

## 1. Introduction

Conservation tillage, which includes a variety of reduced- and no-till techniques that leave at least 30% crop residue on the soil surface, has increasingly been adopted as an agricultural best management practice (BMP) to reduce soil erosion. These tillage practices dramatically effect surface hydrologic properties, leading to reduced runoff and increased infiltration, as well as decreased evaporation (Mizuba and Hammel, 2001; Jalota et al., 2006; Singh et al., 2009). In dryland farming areas, such as the Palouse region that encompasses portions of eastern Washington and northern Idaho, it is essential to maintain an adequate and reliable water supply for sustainable crop production. Conservation tillage can also serve as a potential BMP for enhancing water storage in the soil profile. While field studies have demonstrated that conservation tillage strategies may have the ability to increase local soil moisture storage (Hammel, 1996; McCool et al., 2005), there is a need for a more thorough understanding of the implications of a region-wide shift to conservation tillage management.

The potential for conservation tillage to enhance water storage in the soil profile has implications for dryland wheat production in

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*Abbreviations:* BMP, best management practice; CT, conventional tillage; DEM, digital elevation model; DHSVM, Distributed Hydrology Soil Vegetation Model; GIS, Geographical Information Systems; LDAS, Land Data Assimilation Systems; NSE, Nash–Sutcliffe efficiency; NCDC, National Climatic Data Center; NLCD, National Land Cover Database; NRCS, Natural Resources Conservation Service; NT, no-till; PRISM, Parameter-elevation Regressions on Independent Slopes Model; PCFS, Palouse Conservation Field Station; RMSE, root mean square error; SRTM, Shuttle Radar Topography Mission; SWE, snow water equivalent; SSURGO, Soil Survey Geographic Database; USGS, United States Geological Survey; WEPP, Water Erosion Prediction Project.

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http://dx.doi.org/10.1016/j.jhydrol.2012.12.030

arid and semi-arid climates, particularly in regions where precipitation occurs primarily during the non-growing season. Water limitations in the spring can adversely impact spring wheat varieties by delaying seedling emergence and reducing seed germination rates (Hanks and Thorp, 1956; Lindstrom et al., 1976; Noori et al., 1985). Similarly, insufficient plant available water during spring growth ultimately lowers yields of winter wheat varieties (Day and Intalap, 1970; Schillinger et al., 2008). Soil moisture content on April 1st has been shown to be a good predictor of winter wheat yields in the Palouse (correlation coefficient $r = 0.77$; Leggett, 1959). Thus, it is essential to retain as much of the winter precipitation in the cultivated soil as possible.

During the winter, the Palouse is characterized by variable temperatures that cause fluctuations between rain and snow events and pronounced freeze–thaw cycles in the upper soil layers. A single winter in the Inland Northwest will often produce more than 100 freeze–thaw cycles (Hershfield, 1974; McCool et al., 2005), and large runoff events commonly occur due to a combination of snow melt and rainfall on snow or frozen soil (Zuzel et al., 1982; Pikul et al., 1996). A large portion of precipitation during the cold season contributes to streamflow rather than infiltrating into the soil (Davis and Molnau, 1973). The capture and storage of this winter precipitation in the soil profile can increase soil moisture for crop uptake during the summer growing season. Crop residue provides an insulating layer that can help regulate soil temperature (Hammel et al., 1981; Vomocil et al., 1984) by decreasing soil heat losses by up to 40% (Pikul et al., 1986). By increasing winter soil temperature, fields with thicker residue layers experience shallower and less frequent freezes and fewer runoff events (Dowding et al., 1984).

Although conservation tillage imparts various agronomic benefits, conventional tillage (CT) practices that generally overturn the top soil layer and bury crop residue are still frequently used in many areas. However, significant efforts continue to promote conservation methods, including the use of no-till (NT) methods that minimally disturb the soil surface. Using the Water Erosion Prediction Project (WEPP) model at the field-plot scale in the Palouse region, Greer et al. (2006) simulated that NT fields generated an average of only 0.3 mm of runoff over a 5-month period compared to 66.0 mm on CT fields during the same time span. Various studies have yielded similar results, demonstrating that NT greatly reduces runoff and increases soil moisture in the Palouse region (Cochran et al., 1982; Papendick, 1996; Fuentes et al., 2003; McCool et al., 2005). Although ∼36% of US cropland used NT practices in 2009 (Horowitz et al., 2010), adoption of conservation tillage in the Palouse has lagged behind the rest of the country, primarily due to economic concerns (Juergens et al., 2004). While portions of the Palouse region have begun to see greater NT implementation, Whitman County, WA, which comprises most of the Palouse River basin, continues to rely heavily on CT management (H. Kok, WSU-UI Conservation Tillage Extension Specialist, personal communication, 2009) and many growers remain hesitant to switching to NT practices.

The objective of this study was to assess our hypothesis that watershed-wide adoption of no-till (NT) farming would decrease winter water losses, by increasing infiltration and reducing evaporation losses, and increase April 1 plant available water as compared with conventional tillage (CT) methods. Although interactions between tillage and the water and energy cycles have been studied on individual field plots (Hammel et al., 1981; Cochran et al., 1982; Vomocil et al., 1984; Papendick, 1996; Fuentes et al., 2003; McCool et al., 2005), watershed-scale examinations have been largely neglected with few exceptions (Tomer et al., 2005, 2006). Furthermore, no known work exists that expands upon field studies of dryland wheat farming to understand the degree to which the watershed-scale water balance is influenced by tillage. It is necessary to quantify the widespread impacts of tillage to encourage well-informed management decisions that will guide the future of sustainable agriculture and water resource management in the Palouse and other water-limited regions.

## 2. Materials and methods

### 2.1. Study area

This study considered the upper section of the Palouse River basin (Fig. 1), which includes the North and South Forks of the Palouse River and overlaps the state border between Washington and Idaho in the northwestern United States. The study area covers 2000 km$^2$ and ranges in elevation from 600 to 1600 m. Land cover in the upper Palouse Basin is primarily agricultural with forest covering approximately one quarter of the area in the northeast section of the watershed. Small urban concentrations exist in the cities of Moscow and Pullman and several rural towns.

The semi-arid climate of the Palouse, a region of eastern Washington and northern Idaho dominated by dryland wheat production, makes water availability a limiting factor for crop establishment and growth. The region receives an average of 500 mm precipitation annually (Daly et al., 1994; PRISM Climate Group, 2009), ranging from 250 mm to 1250 mm. Approximately 70% of the precipitation occurs between November and April, causing the dry summer months to coincide with the period in which crops are maturing and crop water demand is highest.

### 2.2. Description and development of the hydrologic model

The Distributed Hydrology Soil Vegetation Model (DHSVM) (Wigmosta et al., 1994; Storck et al., 1998; Andreadis et al., 2009) is a physically-based, spatially-explicit model developed for use in complex terrains that solves the water and energy balances for every grid cell at every time step. It can be applied over areas from plot to large watershed spatial scales and from hourly to daily timescales. The model includes a sufficient level of detail to represent important processes and feedbacks within the hydrology-vegetation system in a physically-realistic manner. Models such as the Soil Water Assessment Tool (SWAT; Arnold and Fohrer, 2005) and the Water Erosion Prediction Project (WEPP; Laflen et al., 1991a, 1991b) were also considered. DHSVM was chosen because it has a higher degree of complexity than SWAT (Singh and Woolhiser, 2002), particularly in representing distributed soil and vegetation parameters, and because WEPP has predominantly been used for hillslope or small catchment studies.

DHSVM includes a two-layer canopy model for evapotranspiration and interception, an energy-balance model for snow hydrologic processes and snowmelt runoff, a multiple-layer unsaturated soil model, and a saturated subsurface flow model. Inputs required to run DHSVM include a digital elevation model (DEM) with a user-defined spatial resolution and Geographical Information Systems (GISs) grid files representing vegetation, soil type, soil depth, and stream and road networks.

Wigmosta et al. (2009) modified DHSVM to better handle winter infiltration and runoff by adding the Green-Ampt infiltration equation, which uses soil hydraulic conductivity as the basis for predicting infiltration. Their implementation of Green-Ampt incorporated a reduction of hydraulic conductivity due to frozen soils according to the following equation:

$$K_{sef} = c_f K_{se} \tag{1}$$

in which $K_{se}$ (mm h$^{-1}$) is the saturated hydraulic conductivity during normal conditions, $K_{sef}$ (mm h$^{-1}$) is the saturated hydraulic conductivity for frozen soil, and $c_f$ is an adjustment factor. Wigmosta