Soil water and nitrogen dynamics in dryland cropping systems of Washington State, USA

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Abstract

Understanding the fate of soil water and nitrogen (N) is essential for improving crop yield and optimizing the management of water and N in dryland cropping systems. The objective of this study was to evaluate how conventional (CT) and no-till (NT) cropping systems affect soil water and N dynamics. Soil water and N were monitored in 30 cm increments to a depth of 1.5 m for 2 years at growers' fields in two different agroclimatic zones of Washington State (USA): (1) the annual cropping region with a mean annual precipitation of more than 500 mm (Palouse site) and (2) the grain-fallow cropping region with mean precipitation below 350 mm (Touchet site). In each zone, a CT and a NT cropping system were chosen. All sites had an annual cropping system, except for the CT site in the drier area, which was under a traditional winter wheat/fallow rotation previous to the study. At Palouse, the volumetric water content in the top 1.5 m of the soil throughout the year was about $0.05–0.1\,m^3\,m^{-3}$ less under CT as compared to NT, indicating improved seasonal accumulation and distribution of soil water under NT. Cropping systems modeling indicated, that during winter, surface runoff occurred in the CT system, but not under NT. The differences in soil water dynamics between CT and NT were mainly caused by differences in surface residues. Dynamics of NO_3^--N at Palouse were similar for NT and CT. At Touchet, differences in soil moisture between NT and CT were less than $0.05\,m^3\,m^{-3}$. Under NT, high levels of NO_3^--N, up to $92\,kg\,NO_3$-N ha^{-1}, were found after harvest below the root zone between 1.5 and 2.5 m, and were attributed to inefficient use or over-application of fertilizer. In both climatic zones, grain yield was positively correlated with evapotranspiration.
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Keywords: Soil water storage; Tillage methods; Water conservation; Water-use efficiency

1. Introduction

Dryland crop production relies to a large extent on water conservation (Stoskopf, 1985). In the Pacific Northwest of the United States, which includes the eastern part of the state of Washington (Fig. 1), optimal conservation of water is the key for long-term farming sustainability, and can be attained through tillage me-thods that maximize infiltration, soil water retention, and minimize soil erosion (Papendick, 1996; Hammel, 1996). Tillage methods affect soil physical properties and consequently directly influence soil water balance and crop growth. Conservation tillage, especially no-till (NT), can minimize soil erosion and nutrient losses (Shipitalo et al., 2000; Schillinger, 2001), increase water storage (Unger et al., 1988; Malhi et al., 2001), and reduce production costs (Uri, 2000).

Several factors contribute to water conservation under NT. Surface crop residues contribute to water

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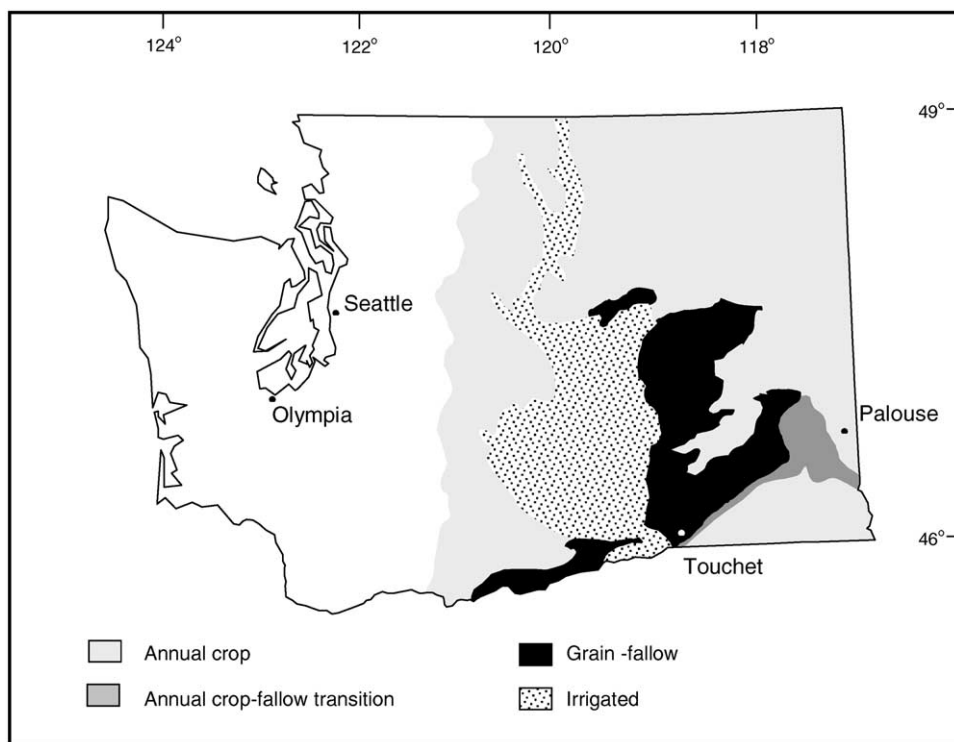*E-mail address:* flury@mail.wsu.edu (M. Flury).

Fig. 1. Agroclimatic zones and location of the field sites, Palouse and Touchet, in the state of Washington (adapted from Douglas et al., 1992).

conservation through multiple effects on the water balance (e.g., Russel, 1939; Duley and Russel, 1939). They reduce evaporation by moderating soil temperatures, and by increasing the resistance of water vapor transfer from soil to the atmosphere (Cornish and Pratley, 1991). Plant residues reduce water runoff and wind erosion by preserving surface soil structure (Addiscott and Dexter, 1994; Papendick and McCool, 1994; McGee et al., 1997), and by providing a physical barrier against erosional forces (Papendick and McCool, 1994), both of which result in enhanced water infiltration.

Nitrogen is a major yield-limiting nutrient in crop production. The fate of N in the soil–plant system depends on a variety of edaphic, climatic, and agronomic factors (Sieling et al., 1998; Malhi et al., 2001). In NT compared with CT, N can become less plant available due to greater microbial immobilization from concentrated crop residues at the soil surface with high C:N ratio. A large C:N ratio is often found in cereal straw

and chaff, and if these plant residues are left in the field after harvest, N-immobilization may occur (e.g., Aulakh et al., 1991; Knowles et al., 1993). Greater denitrification due to higher soil moisture content and the lack of organic matter mixing in the topsoil will also contribute to a lower N availability to plant under NT. Additionally, greater leaching due to higher soil moisture and the presence of preferential flow pathways may contribute to decreased N availability (Shipitalo et al., 2000). However, not all studies show significant differences in N leaching between NT and CT (Granovsky et al., 1993).

There is a wide variety of CT and NT practices, which differ in the type of machinery used, application of herbicides, fertilizers, and techniques of residue management. In addition differences in climatic conditions and soil types among different studies preclude the determination of general conclusions regarding the effects of management systems on the fate of soil water and N. Further information on detailed temporal

patterns of soil water and N are needed to understand the effects of CT and NT under different agroclimatic conditions. The purpose of this study was to: (1) evaluate the temporal dynamics of soil water and N under CT and NT systems in two different agroclimatic zones, and (2) estimate the efficiency of water-use for the two management systems.

2. Materials and methods

2.1. Site selection and characterization

Field studies were conducted in two major dryland agroclimatic zones in Washington State, differing mainly in the amount of annual precipitation: the annual cropping and the grain-fallow cropping region (Fig. 1).

The annual cropping region was represented by a site near Palouse (46°55′N/117°11′W) with Palouse silt-loam soils (fine-silty, mixed, mesic Pachic Ultic Haploxerolls) (Donaldson, 1980). The site was on a mid-slope landscape position with a 2–3% slope and southeastern aspect. Annual precipitation (1940–1997) averages 544 mm and mean annual air temperature is 8.3 °C (Earthinfo, 1995).

The grain-fallow cropping region was represented by a site near Touchet (46°08′N/118°43′W) with very fine sandy loam soils (coarse-silty, mixed, superactive, mesic Calcidic Aploxerolls) (Harrison et al., 1964) and no slope. The mean annual precipitation (1962–1997) is 357 mm and the mean annual air temperature is 10.9 °C (Earthinfo, 1995).

2.2. Cropping systems

In each of the two agroclimatic zones, one CT and one NT field were selected. The CT and NT fields at each location had the same soil series, and were adjacent to each other. The fields were managed by private farmers. The study was conducted during two growing seasons in 1998 and 1999.

2.2.1. Annual cropping region: Palouse

The CT field at this location consisted of a continuous 3-year rotation of soft white winter wheat (SWWW) (*Triticum aestivum* L.)–soft white spring wheat (SWSW) (*T. aestivum* L.)–lentil (*Lens culi-*

naris). The 2-year study occurred during the two cereal crops. Planting and harvesting dates, seeding rates, tillage and fertilization practices are presented in Table 1. Crop residues from the previous crops in CT were incorporated into the soil during the primary tillage operation.

The 25-year NT site was under a 3-year rotation of SWWW–SWSW–lentil, with occasional use of spring barley (SB) (*Hordeum vulgare* L.) in place of SWSW and spring pea (*Pisum sativum* L.) in place of lentil. The SWWW–SWSW portion of the rotation also occurred during the course of this study. For seeding, a 6 m wide NT drill equipped with a double-disk seed opener and a double-disk deep fertilizer applicator was used. Agronomic practices are shown in Table 1.

2.2.2. Grain-fallow cropping region: Touchet

The CT system consisted of over 50 years of traditional winter wheat-fallow where three to four passes of a rod weeder were used during the fallow period. SWWW was planted with a conventional grain drill. However, due to problems with downey brome (*Bromus tectorum*), SWSW was planted in 1998 and 1999 using a Yielder® NT drill (Table 1). After harvest a 2 m wide sweep was used to control Russian thistle (*Salsola iberica*). Crop residues were left in place after sweep operation.

The NT system consisted of 13 years of continuous NT management with hard red spring wheat (HRSW). In 1998, SB was planted in lieu of HRSW. Wheat and barley were planted with a Yielder® NT drill. Seeding and fertilization rates as well as Russian thistle control methods were the same as at the CT site (Table 1).

2.3. Measurement of soil water, soil and plant nitrogen, and crop yield

Two automatic weather stations were installed about five days after planting at Palouse and Touchet. Precipitation and air temperature were measured at standard heights controlled by a data logger (CR10X, Campbell Scientific, Logan, UT). At Palouse, soil temperature was continuously measured at 5 cm depth with copper–constantan thermocouples.

In each of the four fields, volumetric soil water content was measured using 30 cm long, two-rod waveguides connected to a transmission line oscillator (TLO) (GS-615, Campbell Scientific, Logan, UT;

Table 1
Agronomic practices used at the different fields during the course of the study

Crop year	Crop[a]	Planting date	Harvesting date	Seeding rate (kg ha^{-1})	Tillage prior to planting		Main fertilization (kg ha^{-1})	Supplementary fertilization[b] (kg ha^{-1})		
					Primary	Secondary		N	P	S
Palouse CT										
1998	SWWW	November 1997	July 1998	112	None	Field cultivator and harrow	110[c,d]	11[d] 7	6[d] 4	13[d] None
1999	SWSW	April 1999	August 1999	101	Moldboard plow	Field cultivator	90[e,f]	14	8	None
Palouse NT										
1998	SWWW	November 1997	July 1998	112	None	Light harrow	101[c,d]	18	10	16
1999	SWSW	April 1999	August 1999	101	None	None	85[e,f]	18	10	16
Touchet CT										
1998	SWSW	March 1998	July 1998	112	Rod weeder	2 m wide sweep	45[e,d]	18	10	16
1999	SWSW	March 1999	July 1999	112	None	2 m wide sweep	45[c,f]	18	10	16
Touchet NT										
1998	SB	March 1998	July 1998	112	None	2 m wide sweep	45[e,d]	18	10	16
1999	HRSW	March 1999	July 1999	112	None	2 m wide sweep	45[e,d]	18	10	16

[a] SWWW: soft white winter wheat; SWSW: soft white spring wheat; SB: spring barley; HRSW: hard red spring wheat.

[b] Commercial solid fertilizer, applied with the seed unless otherwise noted.

[c] Source of N fertilizer: aqua ammonia.

[d] Application in deep band (7.6–10 cm below the seed).

[e] Source of N fertilizer: anhydrous ammonia.

[f] Shanked in prior to planting.

Campbell and Anderson, 1998). Sensors were installed vertically in 30 cm increments from 0 to 1.5 m depth. One TLO sensor per depth and field was used. Volumetric water content was measured once per day at midnight. Gravimetric water contents were measured periodically by soil coring for calibration of the TLO sensors. Particle size distribution was measured in 30 cm depth increments using wet sieving and static light scattering (MasterSizer S, Malvern Instruments, Malvern, UK) after organic matter and carbonates were removed by pretreatment.

For soil N determination, soil core samples were taken in 30 cm increments to a depth of 1.5 m with a 7.5 cm diameter hand auger. At each sampling time, two cores were taken at random locations between crop rows and composited according to depth increments. Sampling started 5 days after planting and continued, from then on, every 15 days until harvesting. For winter wheat, sampling was 5 days after planting and then in 15-day intervals during the postvernalization period. The composite samples were sieved under field moist conditions through a 2 mm screen immediately after sampling. Eight grams of the sieved field moist soil were shaken with 20 ml of 2 M KCl solution for 1 h to extract NO_3^--N (Keeney and Nelson, 1982). Soil NO_3^--N was then determined colorimetrically from extracts using an Alpkem continuous flow analyzer (Alpkem, Clackamas, OR). In addition, at Touchet deep soil cores to 3 m depth were taken in August 1998 and September 1999 with a 3.2 cm diameter hydraulic auger. Samples were treated as described above. To convert gravimetric to volumetric data, bulk density was measured for the different sampling depths using a 5.4 cm diameter core sampler (Blake and Hartge, 1986). Residue cover was determined after planting using the line-transect method, which measures the proportion of ground cover along a continuous strip (Wysocki, 1989). The transects were 30.4 m long and 1 cm wide aligned in a 45° angle to the planting rows. Each transect consisted of 100 equidistant points, where the presence or absence of residues was noted in a binary form. The fractional residue cover (FRC) determined on the transect was then converted to the mass of residues per unit surface area according to Gregory (1982) as

$$WR = -1793.1 \ln(1 - FRC) \qquad (1)$$

where WR is the mass of residue per unit area (kg ha^{-1}). Total plant N was determined periodically during the 1998 growing season by harvesting a 1–2 m long section of a row, replicated four times per field. Plants were subdivided in leaves, stems, and heads, dried at 65 °C for 48 h, and weighed. After completion of the biomass analysis, samples were ground and analyzed for total N with a LECO CHN Analyzer (Leco, St. Joseph, MI). Grain yield was determined by harvesting rows of 10.6 m length replicated four times per field.

2.4. Water balance modeling

Components of the water balance that were not measured in the field were estimated using the cropping systems simulation model CropSyst (Stöckle et al., 1994; Stöckle and Nelson, 1994). CropSyst calculates runoff based on the USDA-SCS curve number approach, where runoff is a function of rainfall, soil water content, soil type, and land use and management (Stöckle and Nelson, 1994). Drainage below 1.5 m depth was calculated using a cascading bucket approach, in which the soil was subdivided into horizontal layers, each of which can hold water up to field capacity, and water in excess of field capacity was routed to the next deeper layer. Field capacity of the soils was estimated from the measured particle size distribution (Saxton et al., 1986). Potential evapotranspiration (ET) was determined with the Priestley–Taylor model (Priestley and Taylor, 1972). Other model parameters needed for CropSyst were either estimated from field measurements or adjusted for cultivar characteristics based on tabulated literature data (Stöckle and Nelson, 1994; Pannkuk et al., 1998). Selected parameters are shown in Table 2.

2.5. Water-use efficiency

Actual ET (mm) was estimated as

$$ET = P + \Delta\theta - R - D \qquad (2)$$

where P (mm) is the precipitation, $\Delta\theta$ the change in water storage (mm) in the top 1.5 m of the soil, R the runoff (mm), and D the subsurface drainage below 1.5 mm depth (mm). This equation was applied for the growing season. Both P and $\Delta\theta$ were obtained

Table 2
Selected input parameters used for the calibration of the CropSyst model

	Palouse 1998		Palouse 1999		Touchet 1998		Touchet 1999	
	NT, SWWW[a]	CT, SWWW	NT, SWSW[b]	CT, SWSW	NT, SB[c]	CT, SWSW	NT, HRSW[d]	CT, SWSW
Growth								
Biomass-transpiration coefficient (kPa kg m^{-3})	6.00	5.95	5.80	5.80	5.60	5.30	6.00	6.00
Light to biomass conversion (g MJ^{-1})	3.00	3.00	2.80	2.80	3.00	3.00	3.00	3.00
Actual to potential transpiration that limits leaf area growth	0.20	0.20	0.70	0.70	0.95	0.95	0.80	0.95
Actual to potential transpiration that limits root growth	0.40	0.40	0.50	0.50	0.50	0.50	0.50	0.50
Optimum mean daily temperature for growth (°C)	11.0	11.0	9.0	9.0	10.0	10.0	10.0	10.0
Critical leaf water potential (J kg^{-1})	−1700	−1700	−1670	−1670	−1600	−1600	−1670	−1600
Wilting leaf water potential (J kg^{-1})	−2600	−2600	−2700	−2700	−2700	−2700	−2500	−2500
Maximum water uptake (mm per day)	14	14	15	15	12	12	12	12
Morphology								
Maximum rooting depth (m)	1.6	1.6	1.4	1.5	1.4	1.3	1.3	1.3
Initial green leaf area index (LAI, m^2 m^{-2})	0.03	0.01	0.01	0.05	0.03	0.02	0.01	0.02
Maximum expected LAI (m^2 m^{-2})	8.0	8.0	4.0	4.0	4.5	4.5	4.0	4.5
Fraction of maximum LAI at physiological maturity	0.6	0.6	0.7	0.7	0.8	0.7	0.9	0.7
Stem/leaf partition coefficient	3.2	3.5	2.5	3.5	2.8	2.8	2.8	2.5
Specific leaf area (m^2 kg^{-1})	24.0	24.0	22.0	23.0	22.0	22.0	21.0	23.0
Extinction coefficient for solar radiation	0.60	0.54	0.60	0.60	0.55	0.55	0.48	0.55
ET crop coefficient at full canopy	1.1	1.1	1.0	1.0	1.0	1.0	1.0	1.0
Phenology								
Peak LAI growing degree days (°C days)	1450	1290	700	450	680	650	670	700
Physiological maturity (°C days)	1900	1900	1450	1220	1420	1395	1300	1340
Base temperature (°C)	0.0	0.0	3.0	3.0	3.0	3.0	3.0	3.0
Cutoff temperature (°C)	30.0	30.0	35.0	35.0	30.0	30.0	30.0	30.0

[a] SWWW: soft white winter wheat.

[b] SWSW: soft white spring wheat.

[c] SB: spring barley.

[d] HRSW: hard red spring wheat.

by measurement. Runoff R and drainage D were estimated using the CropSyst model.

Water-use efficiency (WUE) can be defined in different ways (Hillel, 1998), and here we use the agronomic or crop WUE, defined as the amount of grain produced per unit volume of water evapotranspired (Viets, 1962). Thus, we can write the WUE $(kg\,ha^{-1}\,mm^{-1})$ as

$$WUE = \frac{G}{ET} \tag{3}$$

where G $(kg\,ha^{-1})$ is the grain yield.

2.6. Statistical analysis

A linear regression model was used to analyze the WUE using Minitab (Minitab, 1998). For the regression analysis, data from the different sites were pooled. Data from a previous study (Leggett, 1959) were used for comparative purposes. The linear regressions were compared with an analysis of covariance (Snedecor and Cochran, 1989). The residual variances were tested for homogeneity, and the data were transformed by scaling with the residual variances if the test indicated heterogeneity of residual variances.

3. Results and discussion

3.1. Soil water distribution and dynamics

At Palouse, soil moisture was 0.05–$0.1\,m^3\,m^{-3}$ larger under NT than under CT (Fig. 2). The temporal pattern of soil moisture reflects the precipitation events superimposed on ET and deep drainage. In winter, soil moisture under NT was about 5% greater than under CT, possibly due to greater infiltration and retention of water under NT. Surface runoff was nil under NT, but was 35 mm under CT at Palouse (Fig. 3). In summer, moisture difference between CT and NT was less pronounced than in winter, but nevertheless, the decreased evaporation, in part caused by lower soil temperature, under NT kept the soil moister, particularly at the soil surface. A considerable amount of residue was present in the NT system at Palouse (Table 3). Such residues effectively insulate the underlying soil and increase the albedo of the soil

surface, which has been demonstrated in various field studies (e.g., Van Wijk et al., 1959; Unger, 1978).

Water storage in the top 1.5 m of soil, together with other components of the water balance are shown in Fig. 3. Recharge and depletion of soil water were dominated by precipitation and ET; runoff and deep percolation were of minor importance. Runoff and drainage occurred in winter only, when soils were completely recharged. Depletion of soil water storage coincided with maximal plant growth during tillering and harvesting. During the summer soil water storage remained constant despite periodic rainfall. Summer rainfall appeared to be completely lost by evaporation. Changes in soil water storage were calculated based on data shown in Fig. 3 for three different periods: the growing season from planting to harvesting, the postharvest period from harvesting to fall recharge, the fall/winter recharge period from the beginning of recharge to planting, and the second growing season from planting to harvesting (Table 4). During the growing season, the NT system used about 40 mm more water than the CT system in both 1998 and 1999. Water loss in the postharvest season was negligible in both CT and NT. The recharge period, however, accumulated about 20 mm more water in NT than in CT, likely because the soil was initially drier and had a larger capacity to store water.

At Touchet, the temporal pattern of soil moisture was similar for CT and NT (Fig. 4); however, soil under CT started out with more water storage than under NT, likely because of the previous fallow season under CT (Fig. 5). Soil moisture under CT was slightly, but consistently higher than under NT until planting in 1999. Water soil storage indicated that more water was stored under CT than under NT during the first growing season and the postharvest period. Differences in soil water storage disappeared during the fall/winter recharge period and the following growing season. Due to similar crop rotation and soil management practices under CT and NT during the experimental period (Table 1), residue cover between the two cropping systems was practically identical (Table 3), leading to a similar overall water loss. CropSyst simulations showed that there was no runoff nor deep percolation in CT or NT during the growing seasons (Fig. 5). The CT system had a net water gain of about 6 mm during the postharvest season, whereas the NT system had a net loss of 13 mm (Table 4); however,
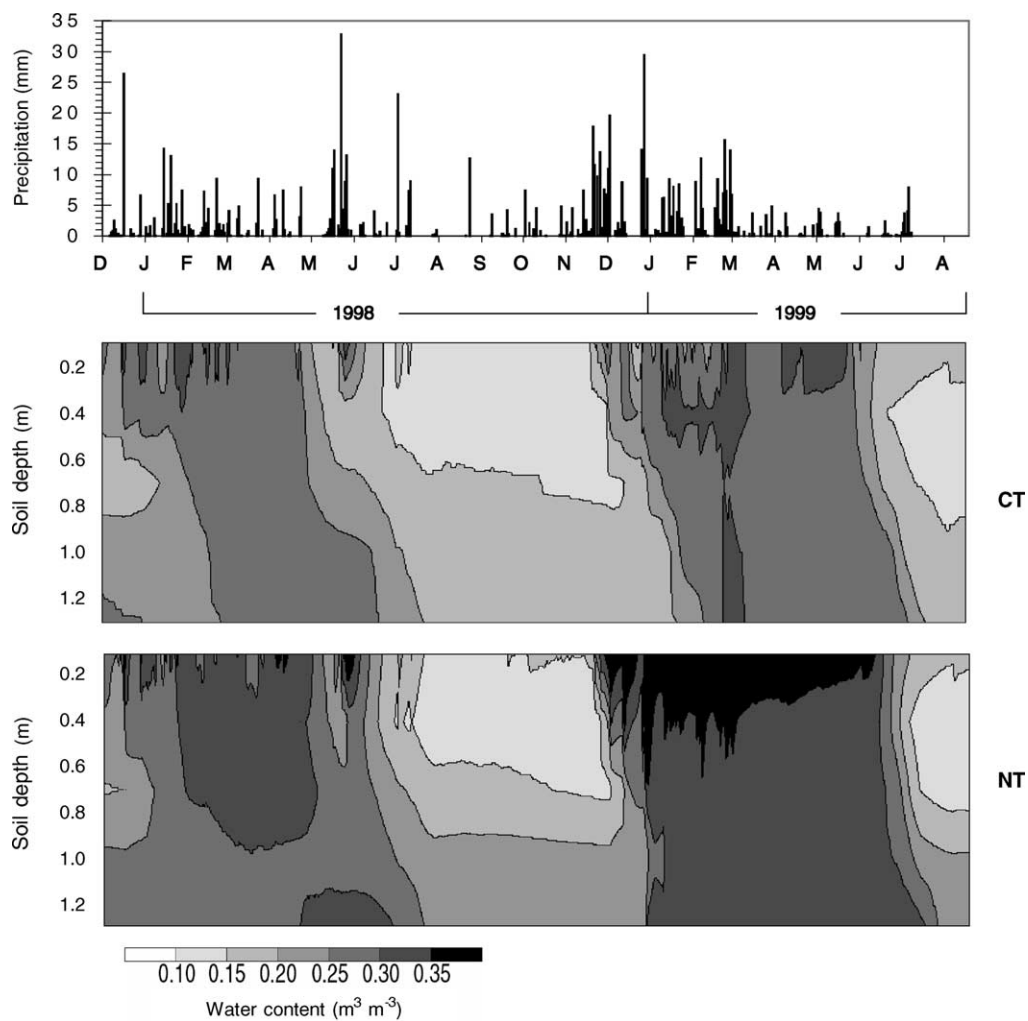
Fig. 2. Daily precipitation and soil moisture pattern at Palouse for CT and NT cropping systems.

Table 3
Crop yields and residues for CT and NT at Palouse and Touchet

Location	Year	CT			NT		
		Crop[a]	Yield (Mg ha^{-1})	Residue (Mg ha^{-1})	Crop[a]	Yield (Mg ha^{-1})	Residue (Mg ha^{-1})
Palouse	1998	SWWW	5.8 (0.7)[b]	0.8 (0.06)	SWWW	8.1 (0.3)	2.4 (0.2)
Palouse	1999	SWSW	4.7 (0.8)	0.2 (0.05)	SWSW	3.8 (1.1)	4.2 (0.1)
Touchet	1998	SWSW	2.5 (0.5)	0.7 (0.05)	SB	3.2 (1.3)	0.8 (0.1)
Touchet	1999	SWSW	1.8 (0.2)	0.9 (0.02)	HRSW	1.2 (0.3)	1.0 (0.2)

[a] SWWW: soft white winter wheat; SWSW: soft white spring wheat; SB: spring barley; HRSW: hard red spring wheat.
[b] Values in parentheses are standard deviations of the mean.
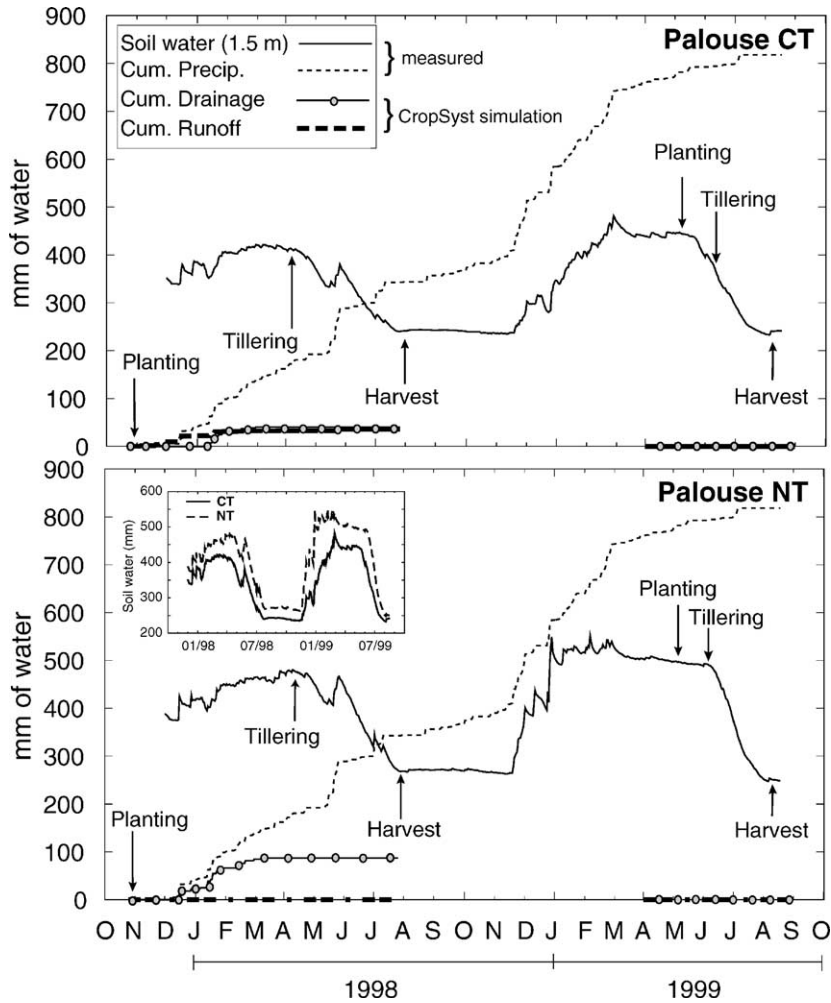
Fig. 3. Daily water storage and cumulative components of the water balance at Palouse for CT and NT cropping systems. The drops of soil water storage in winter 1998 and 1999 are a measurement artifact due to soil freezing. The inset shows the comparison between CT and NT soil water storage in the top 1.5 m.

Table 4
Changes in soil water storage in the top 1.5 m of the soil for different time periods in Palouse and Touchet

Location	Initial water storage (mm)	Changes in water storage			
		Planting to harvest, 1998 (mm)	Harvest to recharge, 1998 (mm)	Recharge to planting, 1998/1999 (mm)	Planting to harvest, 1999 (mm)
Palouse CT	352	−169[a]	−3	209	−205
Palouse NT	389	−206[a]	−4	236	−252
Touchet CT	288	−151	6	47	−92
Touchet NT	268	−142	−14	80	−78

[a] For Palouse, winter crops were grown and data correspond to the time period tillering to harvest.
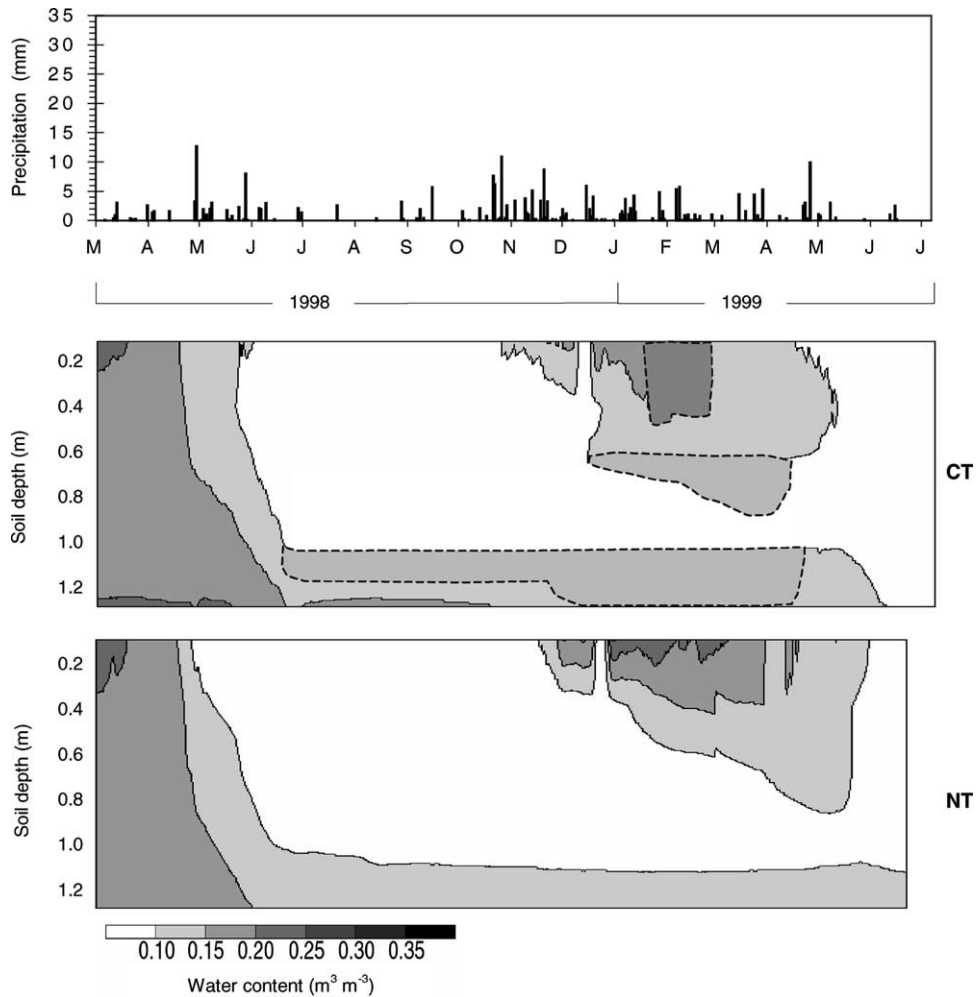
Fig. 4. Daily precipitation and soil moisture pattern at Touchet for CT and NT cropping systems. Dotted lines represent water contents measured by core samples during failure of TLO sensors.

these differences were eliminated by the following recharge period, which equalized the soil water storage in the two systems. The increased water-use in CT compared with NT in the growing season of 1999 may have been due to the different crops grown: SWSW under CT used more water than HRSW under NT.

3.2. Soil N distribution and dynamics

At Palouse, soil NO_3^--N followed similar trends for CT and NT, where N levels were higher earlier in the season and lower towards wheat maturity in June and

July (Fig. 6a). Plants took up a considerable amount of N during the growing season, and the values shown in Fig. 6 correspond to reported values for wheat in the literature (McNeal et al., 1966; Olson and Kurtz, 1982).

At Touchet, the seasonal variation of NO_3^--N was similar to the trend observed at Palouse, i.e., high NO_3^--N levels in spring were assimilated by plants during the growing season (Fig. 6b). High concentration of NO_3^--N was detected at deeper layers in the NT site during late May and early June of 1998 and in late April and early May of 1999. In August 1998
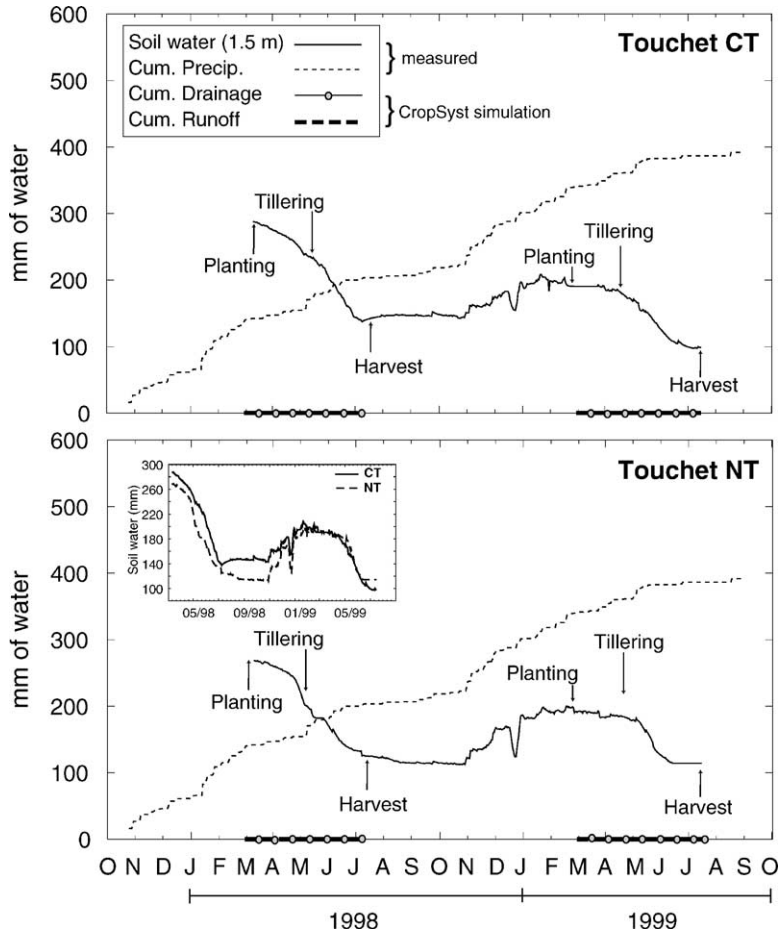
Fig. 5. Daily water storage and cumulative components of the water balance at Touchet for CT and NT cropping systems. The drop of soil water storage in winter 1999 is a measurement artifact due to soil freezing. The insert shows the comparison between CT and NT soil water storage in the top 1.5 m.

a pronounced NO_3^--N peak occurred at 2 m depth (Fig. 7), which likely originated from previous intensive fertilization at the NT site. In 1999, the NO_3^--N peak in NT decreased considerably (Fig. 7). We hypothesize that a large fraction of this NO_3^--N had moved upward and then was removed through assimilation. In fact, the reduction of the N in the soil profile occurred at anthesis when plants usually use a large amount of N for grain filling (Fig. 6b). Distribution of water content in the soils tend to support the hypothesis of upward movement and plant uptake; the soil moisture at >1.2 m depth was consistently wetter, even during winter 1998/1999, as compared to 0.8–1.2 m depth (Fig. 4), suggesting a moisture gra-

dient that could have facilitated upward movement of water. No drainage during this time period was predicted by CropSyst simulations.

3.3. Crop yield

Cereal yield was within the average found in the Pacific Northwest (Papendick, 1996). At Palouse, no consistent difference in yield between NT and CT was found during the experimental period (Table 3). Yield for SWWW in 1998 under NT was within the range of 8–8.5 Mg ha^{-1} given by Cook and Veseth (1991) for an area previously cropped with legumes, whereas yield for CT was below this range. This could
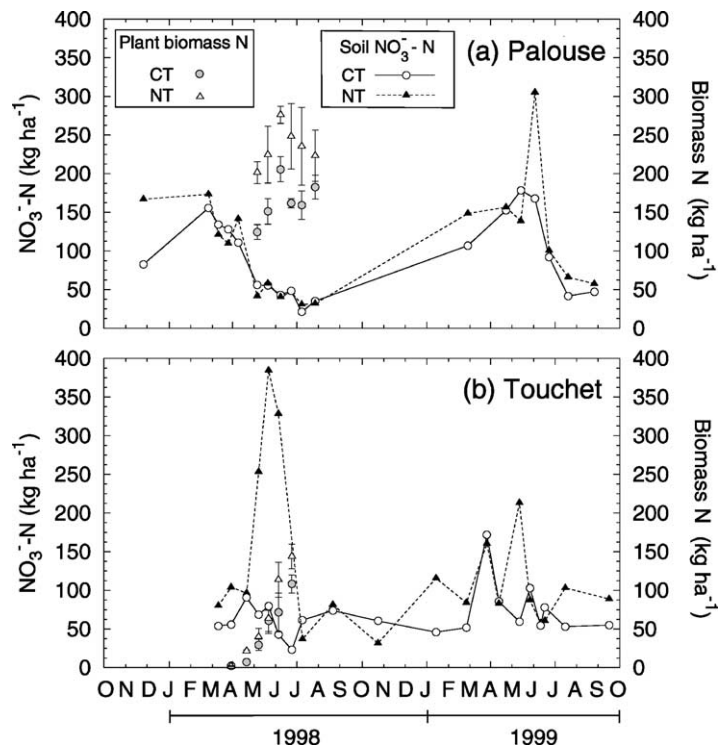
Fig. 6. Soil and biomass nitrogen dynamics at: (a) Palouse and (b) Touchet. Soil NO_3^--N data represent amount of NO_3^--N within the top 1.5 m of the soil. Error bars for biomass in 1998 indicate ± 1 standard error ($n = 4$).
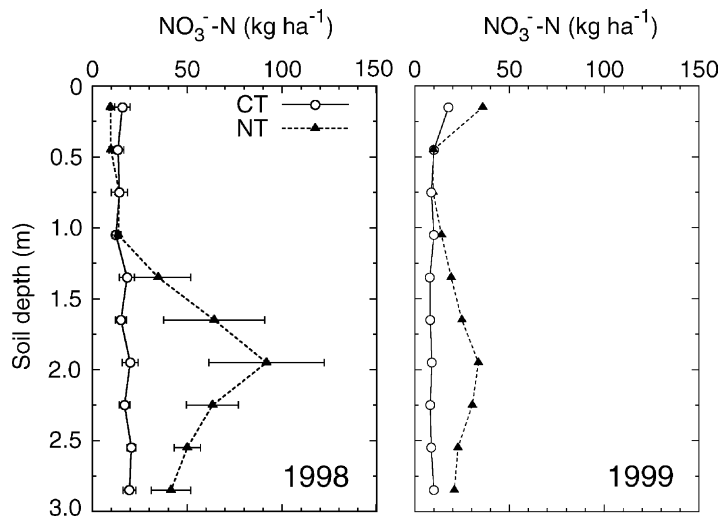

Fig. 7. Deep soil NO_3^--N profiles at Touchet. Error bars are shown for 1998, and indicate ± 1 standard error ($n = 4$). Composite samples were collected for 1999, so no standard errors could be computed.
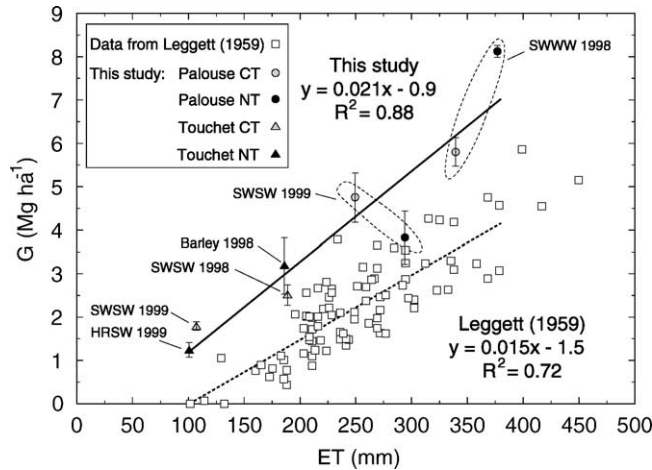
Fig. 8. Grain yield, G versus ET. The bars indicate ± 1 standard error ($n = 4$, except for Palouse NT 1999 where $n = 3$). The lines are linear regressions to data of Leggett (1959) and data of this study, respectively.

be attributed to less available water under CT during spring (Figs. 2 and 3). In 1999, average Palouse SWSW yield was 22% greater for CT than for NT.

Yields for CT and NT could not be compared at Touchet because different crops were grown. The higher yield for SWSW compared to HRSW in 1999 was expected (Stoskopf, 1985). The SWSW yield under CT was 26% greater in 1998 than in 1999, likely due to 23 mm more precipitation in 1998.

3.4. Water-use efficiency

The regression analysis of WUE indicated a significant linear relationship ($P < 0.001$), whereby grain yield increased with ET (Fig. 8). Also shown in Fig. 8 are data collected by Leggett (1959) from different locations in the eastern Washington dryland area. The Leggett (1959) data represent yields for both spring and winter wheat. The slopes of the regression lines were compared and found to be significantly different ($P < 0.01$), indicating a stronger response of the yields with increasing ET in our experiment as compared to the data collected by Leggett (1959). Increased ET of 1 mm increased yield by $0.021\,\mathrm{Mg\,ha^{-1}}$ for our study, but only by $0.015\,\mathrm{Mg\,ha^{-1}}$ in the Leggett (1959) study. Cook (1986) reported a typical yield increase for winter wheat of $0.019\,\mathrm{Mg\,ha^{-1}}$ for every 1 mm of water supply (i.e., ET) in the Pacific Northwest when water

was the only limiting factor for plant growth. This value can vary considerably in different years and at different locations (Cook and Veseth, 1991), so that our value of $0.021\,\mathrm{Mg\,ha^{-1}\,mm^{-1}}$ seems well within expectations. The data reported by Leggett (1959) also indicate that typically in the Pacific Northwest no yield is obtained when the water supply falls below 100 mm; however, our data indicated a yield of $1\,\mathrm{Mg\,ha^{-1}}$ with 100 mm water supply.

4. Conclusions

The eastern part of the state of Washington lies in the rain shadow of the Cascade mountain range and is characterized by a relatively dry climate. Agriculture here is strongly dependent on the efficient use of water. The results of this study show that NT management practices help to conserve soil moisture in the annual cropping region in eastern Washington. This water conservation was mainly due to the effects of residues which limit evaporative water losses and reduce surface runoff.

Little effect of cropping systems on water conservation, however, was found in the grain-fallow cropping region of southeastern Washington, although the specific crop rotations used during the course of this study may have confounded the experimental results. Nevertheless, 1 year of spring wheat following 50

years of winter wheat-fallow appeared to have eliminated the presumed water conservation of the winter wheat-fallow system. There appeared to be little impact of past long-term NT and CT practices on water storage and dynamics when tillage practices were changed.

The N dynamics in the soil were similar between CT and NT, and most of the applied fertilizer N was taken up by the plants during the growing season. Nevertheless, there was NO_3^--N accumulation found in deeper soil layers in the continuous NT cropping system at Touchet, presumably originating from previous fertilization. The increased NO_3^--N content in deeper soil layers was rather unexpected, since NO_3^--N leaching would be usually more of concern in the irrigated rather than the dryland cropping area of Washington State (Ryker and Jones, 1997).

During the 2 years of our study, it appeared that yield was limited by water supply. This is supported by the measured water-use efficiencies, which were consistent with values typically reported for eastern Washington for the case when water supply was the only yield-limiting factor.

Acknowledgements

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