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Soil Water Depletion and Recharge under Ten Crop Species and Applications to the Principles of Dynamic Cropping Systems

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ABSTRACT

Dynamic cropping systems principles require that farmers consider climatic, market, and ecological factors on an annual basis in making crop choices. Our objectives were to determine variability of seasonal soil water depletion (SWD) and spring soil water recharge (SWR) among crops and to apply results to dynamic cropping systems practice. A 10-species crop sequence project was conducted under no-tillage on silt loam Haplustoll soils in North Dakota. Mid-May to mid-September SWD and following April SWR were determined from 2002 to 2005 by neutron moisture meter to the 1.8-m depth. Crops studied and average SWD amounts (cm) were: sunflower (*Helianthus annuus* L.), 13.5; corn (*Zea mays* L.), 12.6; sorghum [*Sorghum bicolor* (L.) Moench], 11.0; spring wheat (*Triticum aestivum* L.), 10.6; canola (*Brassica napus* L.), 10.0; millet (*Panicum miliaceum* L.), 9.6; buckwheat (*Fagopyrum esculentum* Moench), 9.4; chickpea (*Cicer arietinum* L.), 8.5; lentil (*Lens culinaris* Medik), 8.1; and dry pea (*Pisum sativum* L.), 5.0, with highest and lowest being 29 and 11% of average May soil water, 46 cm. Because the period of the experiment was relatively dry, recharge was less than depletion. Spring soil water was 10 cm greater following pea than following sunflower. Ranking of crops for water storage roughly followed reverse SWD rank, with several exceptions, notably wheat, which had greater water from snow capture. Lower soil water following crops such as sunflower and corn was linked to negative crop sequential effects in this project. Choosing to seed a lower water-using crop in the spring after the occurrence of below-average SWR on land that had a higher water-using crop the previous season illustrates an application of information reported here along with the principles of dynamic cropping systems.

THE U.S. DEPARTMENT OF AGRICULTURE, Agricultural Research Service (USDA-ARS), Northern Great Plains Research Laboratory is developing a dynamic cropping systems approach for sustainable soil–crop management. The dynamic cropping systems concept may be defined as a long-term strategy for sustainable soil–crop management that is implemented by agriculturalists through annual decisions that respond to changing environmental, economic, and agronomic conditions (Tanaka et al., 2002). In Great Plains dryland agriculture there has been a movement away from the wheat-based biennial crop–fallow system toward the planting of crops every year—continuous cropping (Farahani et al., 1998). Continuous cropping makes better use of the precipitation resource and serves to better protect the soil from erosion, but places a greater emphasis on introducing a diversity of crop species (Tanaka et al., 2002). In dryland cropping, soil water availability is often the most limiting resource; farmers can adapt to this limitation by choosing crops based on soil water availability in the spring (Tanaka et al., 2002).

To implement the dynamic cropping systems concept, it is important to have information about the systematics of crop and soil ecology: how one crop species affects subsequent crops through annual effects on the soil and aboveground environment. In a water-limited region, soil water use by one crop affects following crops, and thus, comparative information about seasonal SWD and water use (evapotranspiration, ET: at first approximation ET = SWD + seasonal precipitation) by crops is valuable. Black et al. (1981) reported water use differences for five crops in eastern Montana, showing greater use by safflower and sunflower compared with spring wheat and barley. Nielsen et al. (1999) showed that the relatively high water use by sunflower decreases yields of subsequent crops in eastern Colorado. Observations of water use by crop species in various dryland environments show that longer-season and more deeply rooted oilseed crops such as sunflower have the greatest water use (ET), whereas shorter season crops such as dry pea have the lowest water use. Such were the results of Schillinger and Shelton (1999) for the xeric climate of the Pacific Northwest, and Anderson et al. (2003) for the continental climate of North Dakota.

In a study of water use by seven broadleaf crops, Anderson et al. (2003) found that the longer-season crop soybean [*Glycine max* (L.) Merr.] used 30% more water than dry pea. Root growth was also measured in this study by using minirhizotron technology (Merrill et al., 2002), and it was shown that root growth depths of soybean and dry pea were similar. In a subsequent study of SWD and water use of ten crop species, including the same seven as the Anderson et al. (2003) study, Merrill et al. (2004) concluded that crop season length was a better predictor of water use than rooting depth.

To provide agriculturalists with soil–crop ecological information necessary to implement the principles of dynamic cropping systems, several alternative crop and crop sequence projects have been implemented at the USDA-ARS Northern Great Plains Research Laboratory in Mandan, ND. The Phase I alternative crops project (Anderson et al., 2003) and the Phase II crop sequence project (Krupinsky et al., 2006) have been completed. A user-friendly CD-ROM product has made the Phase II results accessible to agriculturalists and scientists (Krupinsky et al., 2003). In addition, SWD and

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Abbreviations: ET, evapotranspiration; SWD, soil water depletion; SWR, soil water recharge; USD, United States dollar.

water use results for the Phase II crop sequence project have been reported by Merrill et al. (2004).

The purpose of this paper is to report comparative SWD and SWR measurements of ten crop species based on Phase III of the Crop Sequence Project that has included standard, newer, and emerging crops, and to examine principles and factors relating to characteristic differences in SWD and SWR among crop species. A further purpose is to explore how information about SWD and SWR characteristics of crops may be applied to the principles of dynamic cropping systems.

MATERIALS AND METHODS

The research was conducted at the Area IV Soil Conservation Districts–Agricultural Research Service Cooperative Research Farm, located about 7 km southwest of Mandan, ND. Two sites (Site 1, 46°46′ N, 100°56′ W; Site 2, 46°45′ N, 100°55′ W; elevation 518 m), which were about 2 km apart, were used for the research. Soils at both sites are predominantly classified as Timvik–Wilton silt loams (fine-silty, mixed, superactive, frigid Typic and Pachic Haplustolls). Surface soils, to the ≈0.6-m depth, consist of aeolian-derived materials and are underlain by a transition zone, typically 0.2 m or more thick, consisting of variably coarser-textured materials with lime inclusions. The glacial till subsoils of finer-textured materials are root-penetrable. The climate pattern is continental, with ≈130 to 140 frost-free days, mean annual temperature is 4°C, and daily averages range from 21°C in summer to −11°C in winter. The mean annual precipitation is 412 mm and greatest monthly precipitation generally occurs in June (84 mm average).

Soil water measurements reported here were made in the Phase III crop sequence project. This experiment was performed by seeding 10 crop species in 9-m-wide strips 1 yr, and seeding the same crops in 9-m-wide strips perpendicular to the first set during the following year, creating a crop matrix whereby the results of 100 different crop sequences could be observed. The 91- by 91-m checkerboard-like crop matrix blocks with their 9- by 9-m plots were replicated four times at each site. Crops planted in the first year of crop matrix formation at a site are referred to here as the *residue crops*, and crops planted in the second year of crop matrix formation are termed the *matrix crops*. Residue crops at Site 1 and Site 2 of the Phase III project were seeded in 2002 and 2003, respectively, and matrix crops at Site 1 and Site 2 were seeded in 2003 and 2004, respectively. Spring wheat crops were seeded in the year before formation of the crop matrices, in 2001 and 2002 at Site 1 and Site 2, respectively.

The Phase II crop sequence project (Krupinsky et al., 2006) featured more earlier-seeded species, which are often referred to as cool-season crops. The present Phase III crop sequence project featured more later-seeded species, which are often referred to as warm-season crops. There were four crops in common between the Phase II and Phase III projects: canola, dry pea, spring wheat, and sunflower.

No-till management was used to carry out the experiments (Tanaka et al., 2007). The placement of crop seeding strips within replication blocks was randomized each year. Information on the 10 crop species seeded, their cultivars, and individual crop season dates is provided in Table 1. Seeding of crops other than corn and sunflower was accomplished with a no-till drill (John Deere model 750)[1] in rows 19 cm apart. Seeding of corn and sunflower was accomplished with a no-till row-crop seeder in rows 75 cm apart.

Table 1. List of crops, cultivars, average seeding and harvest dates, and length of season for the period of study, 2002 to 2004. Crops are listed in order of average measured soil water depletion, with the highest (sunflower) first.

Crop	Cultivar	Seeding date (avg.)	Harvest date (avg.)	Season length
				d
Sunflower	63M91	9 June	24 October	137
Corn	TF2183	22 May	25 October	156
Sorghum	DK28E	9 June	25 October	136
Spring wheat	Amidon	1 May	9 August	100
Canola	357RR	10 May	16 August	98
Millet	Earlybird	9 June	20 September	103
Buckwheat	Koto	8 June	18 September	102
Chickpea	B-90	11 May	21 August	114
Lentil	Richlea	11 May	16 August	109
Dry pea	DS Admiral	29 April	30 July	92

Weed control was by preseeding application of glyphosate (N-[phosphonylmethyl] glycine isopropylamine salt) with additional use of postemergent herbicides. Granular fertilizer was applied through the seeder implement at rates of 78 kg N ha^{-1} and 11 kg P ha^{-1}. Leguminous crops (chickpea, dry pea, and lentil) did not receive N fertilization but did receive appropriate *Rhizobium* inoculants at seeding. Canola received sulfur fertilization at 11 kg S ha^{-1}.

Soil water content measurements were taken with a neutron moisture meter (CPN International Inc., model DR503). Readings were made by lowering the active part of the meter into steel access tubes of 40 mm i.d. and 2.7 m length. A single access tube was installed in the center of each plot of interest, and readings were taken to a depth of 2.1 m at 0.3-m intervals every 7 to 14 d during the crop growth season, and at greater time intervals until ambient temperatures were consistently $<0°C$. The particular meter used produced ≈8000 recorded disintegrations per 30-s reading interval in standard, plastic-shielded counting mode. Water content values for 0.3-m intervals were summed over a 1.8-m depth. Moisture meter calibration was achieved through comparison of meter readings with gravimetric water content measurements made on soil samples taken during the previous Phase II crop sequence project. The Phase II project had been conducted on the same soil type as the current project at a site about 1 km distant from Site 1. Gravimetric water contents were converted to volumetric water contents through soil bulk density determinations.

Water content determinations were made in each replication block on those plots of the 10 crops where spring wheat had been planted in the year previous to the one in which measurements were made (40 plots per site). Measurements were taken in residue crop plots at Site 1 in 2002, in residue crop plots at Site 2 in 2003, and in matrix crop plots at Site 2 in 2004. Thus, measurements taken in each year were made in a different set of linear crop strips within the field layout and siting of the project. Due to prioritization of work, complete duplicative measurements were not made in matrix crop plots at Site 1 in 2003. However, measurements were made at both sites in 2003 in those spring wheat plots where spring wheat had also been seeded the previous year, and analysis of May to early September SWD showed that there was no significant difference between the sites.

Snow depths were measured at several dates during the winter of 2003–2004. Measurements were taken with a ruler at two randomly chosen points near the center of crop strips in replicate blocks.

[1] Inclusion of branded product information is for the benefit of the reader and does not imply preference nor endorsement by the USDA-Agricultural Research Service.

Although ET is greatest during active crop growth, preseeding or postharvest soil evaporation can be significant. To make valid comparisons of soil hydrology among the various crops, SWD for all the crops was calculated between the same set of dates from about 15 May to about 15 September in a given year. The first date was chosen because it generally represented the seeding dates of the earlier-seeded, cool season crop species, while the later date was representative of harvest dates for crops of the warm-season type. Soil water depletion was calculated to a depth of 1.8 m, and water use (ET) was determined as SWD plus 15 May to 15 September precipitation. This is a practical estimation of ET based on the assumption that there was no redistribution of water by runoff and runon and that no flux of soil water into or out of the bottom of the root zone occurred. Assumption of no net runon or runoff at the scale of moisture meter measurements (<1 m) is based on low land slope under no-till management, and assumption of nil water flux below the root zone is based on observation of low (if any) water content change at greatest depth of observation (2.0 m). Additional soil water content measurements were conducted in mid-April of the year following a given set of measurements to determine overwinter SWR. Multiple comparison with Tukey's Studentized range tests of water measurements were based on ANOVA (PROC GLM, SAS Institute, 1990).

The distribution of SWD with soil depth was analyzed by examining water depletions between the average date of greatest soil water accumulation and the average date of least water in the soil profile. Because SWD in 2004 was relatively low, SWD depth distributions are displayed for only 2002 and 2003. The dates for calculating SWD soil depth distributions were 12 June 2002 and 16 June 2003 for greatest profile water accumulation and 30 Aug. 2002 and 4 Sept. 2003 for lowest soil water. Shorter time intervals were chosen for SWD depth distributions than were used for total SWD (≈2.5 vs. 4 mo) so that periods of substantial within-season recharge by precipitation were not included.

RESULTS AND DISCUSSION

Precipitation during the years of the experiment was considerably less than the long-term average (Table 2). In 2002, April through June precipitation was less than average, but July and August precipitation was average or above average that year. Among the years of the study, 6-mo April through September precipitation was the lowest during 2002. May precipitation was much above average in 2003, but June and especially July and August precipitation amounts were below average. This was a pattern that favored shorter season, earlier-seeded crops (i.e., dry pea and spring wheat) compared with longer season, later-seeded crops (i.e., sunflower). In 2004, spring precipitation for the April through June period was much below average, so that 6-mo April to September precipitation was below average.

Table 2. Precipitation near the two sites of the Phase III crop sequence project.

	2002	2003	2004	Long-term avg. (92 yr)
		cm		
3-mo. (January–March)	2.0	2.1	5.0	3.6
April	2.5	2.1	1.5	3.7
May	1.3	13.2	3.2	5.6
June	3.2	5.3	4.9	8.4
July	6.6	1.2	6.7	6.5
August	4.9	1.0	6.1	4.6
September	0.9	4.1	4.1	3.7
6-mo. (April–September)	19.4	27.0	26.5	32.5
3-mo. (October–December)	2.8	4.0	3.5	4.9
Annual	24.2	33.1	35.0	41.1

Water Use and Soil Water Depletion

The overall pattern of SWD values (Fig. 1), and particularly differences in SWD among years, depended on annual precipitation patterns and mid-May soil water contents. Water stored in the profile in springtime reflects weather patterns operating on the previous year's spring wheat crop and subsequent overwinter SWR. May 2002 soil water contents were moderately high, but succeeding springtime water contents reflect below-

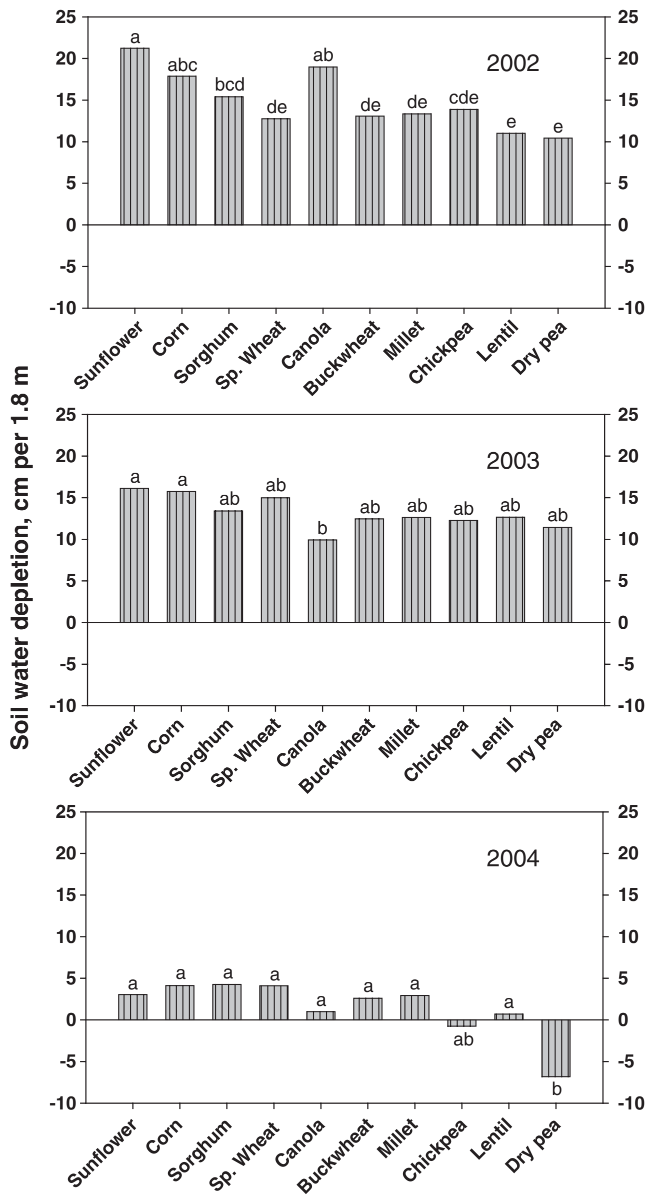

Fig. 1. Soil water depletion from mid-May to mid-September period measured to a soil depth of 1.8 m with a neutron moisture meter. Letters refer to Tukey's Studentized range test at $P < 0.05$.

average precipitation and greater SWD than SWR. Thus, mid-May soil water contents (averaged across crops) for 2002, 2003, and 2004 were 54, 47, and 37 cm, respectively (Table 3).

When crops are listed in descending order of their average SWD values (Table 3), sunflower had the highest and dry pea the lowest values. Corn and sorghum, also longer-season crops, rank second and third in SWD. Millet, another warm-season grass crop, had lower SWD compared with corn and sorghum, but its growing season was 1 mo or more shorter than corn and sorghum (Table 1). Spring wheat, canola, and buckwheat have intermediate SWD values. The three legumes, chickpea, lentil, and dry pea, had the lowest SWD values. These legume crops have relatively shorter growing seasons compared with soybean, which was included in the earlier Phase II crop sequence project (Merrill et al., 2004), and where it showed greater SWD than spring wheat.

During the years of observation, the 2002 SWD values for the various crops had the widest range (Fig. 1). This may be attributed to a relatively dry springtime period that limited SWD values of the shorter season, earlier-seeded crops like dry pea and lentil, and increased differences in depletion between these crops and the longer season crops, like sunflower and corn. In 2003, the springtime period was favorable for growth of shorter-season crops because of high May precipitation (Table 2), but summer precipitation was quite limited, which put stress on longer-season crops like corn and sunflower, lessening the range of SWD values. Two preceding years of below-average precipitation and a dry spring in 2004 greatly limited SWD values, and near-average July precipitation resulted in negative SWD in the cases of dry pea and chickpea.

Four crops, sunflower, canola, spring wheat, and dry pea, were included in the present experiment (crop matrices in 2003 and 2004) as well as the Phase II crop sequence project (crop matrices in 1999 and 2000), which was reported earlier (Krupinsky et al., 2006; Merrill et al., 2004). Despite the considerable difference in climatic conditions between the below-average precipitation of the present crop sequence project and the average to above-average precipitation of the Phase II project, the pattern of SWD results among crop species common to both was similar: sunflower > canola, which was about the same as spring wheat > dry pea. Canola had the greatest variability in year-to-year SWD values, which was also observed in the earlier Phase II crop sequence project. In work conducted at the same research facility, Anderson et al. (2003) found that sunflower had the greatest seasonal water use compared with six other broadleaf crops, and that while dry pea had relatively low water use, canola had even lower water use.

Miller et al. (2002) reported 5 yr of postharvest, fall-measured soil water contents following various crops in Saskatchewan. Such measurements track crop differences in seasonal SWD, and indeed, their results were in agreement with those of the present study: sunflower > spring wheat > chickpea, which was about the same as lentil > dry pea. In another northern Great Plains study, Black et al. (1981) found the ordering of water use to be: sunflower > rapeseed (*Brassica napus* L., agrobotanically similar to canola) > spring wheat. Working in the xeric Pacific Northwest, Schillinger and Shelton (1999) reported that the order of water use among crops was: sunflower > rapeseed > winter wheat > pea. Thus, the relative water use and SWD ordering of sunflower > wheat > pea is well supported by other dryland agriculture experiments.

The length of the active growing season for a particular crop appears to have the greatest predictive power for the comparative amount of water use or SWD that a crop species will exhibit. Fine root growth profiles of most of the species in Phase II of the crop sequence

Table 3. Soil water depletion to the 1.8-m depth during the mid-May to mid-September growth period and overwinter recharge on land seeded to listed crops. Measurements in 2002 and April 2003 were taken at Site 1, and those taken in 2003 through April 2005 were done at Site 2. Also, soil water depletion (SWD) as the percentage of water use (evapotranspiration, ET) and SWD accounting periods.

	2002 depletion	2002–2003 recharge	2003 depletion	2003–2004 recharge	2004 depletion	2004–2005 recharge	Average depletion	Average recharge	Rank of average recharge
	cm								
Sunflower	21.2a†	5.6a	16.1a	3.3b	3.1a	0.1b	13.5	3.0	10
Corn	17.9abc	6.6a	15.7a	6.8ab	4.1a	2.6ab	12.6	5.3	6
Sorghum	15.4bcd	6.1a	13.4ab	8.2ab	4.3a	3.6a	11.0	6.0	1, 2
Spring wheat	12.8de	5.4a	15.0ab	11.5a	4.1a	1.0ab	10.6	6.0	1, 2
Canola	19.0ab	4.9a	9.9b	8.5ab	1.0a	2.6ab	10.0	5.3	5
Millet	13.3de	5.8a	12.6ab	8.1ab	2.9a	2.7ab	9.6	5.6	3, 4
Buckwheat	13.1de	5.5a	12.5ab	7.7ab	2.6a	3.4a	9.4	5.6	3, 4
Chickpea	13.9de	5.4a	13.3ab	4.2b	−0.8ab	1.3ab	8.5	3.6	9
Lentil	11.0e	3.7a	12.7ab	5.7ab	0.7a	1.6ab	8.1	3.7	8
Dry pea	10.4e	4.4a	11.5ab	6.9ab	−6.8b	0.1b	5.0	3.8	7
Average	14.8	5.4	13.2	7.1	1.5	1.9	9.8	4.8	

	2002	2003	2004
4-mo seasonal precipitation, cm	16.1	14.2	21.4
Depletion, % of water use (ET)	39–57	45–53	−47–13
Avg. depletion, % of water use (ET)	48	48	7
Avg. mid-May soil water, cm	54.2	47.4	37.0
Depletion period	13 May 2002–24 Sept. 2002	15 May 2003–18 Sept. 2003	14 May 2004–17 Sept. 2004
Recharge period	24 Sept. 2002–10 Apr. 2003	18 Sept. 2003–19 Apr. 2004	17 Sept. 2004–08 Apr. 2005

† Entries in a column with the same letter are not significantly different at $P < 0.05$ according to Tukey's Studentized range test.

project were measured with microvideo technique (Merrill et al., 2002). Regression and stepwise discriminate analyses showed that the length of growing season (days from seeding to harvest) was a better predictor of water use and SWD than root growth depth parameters, such as maximum root growth depth or midpoint depth of root length growth profiles (Merrill et al., 2004). The difference between dry pea and soybean is instructive: dry pea has a shorter growing season than soybean, and significantly less SWD and water use, yet dry pea and soybean root growth depths were relatively similar (Merrill et al., 2002).

Changes in precipitation pattern from year to year will affect the percentage of water use (ET) that is made up of SWD. Average seasonal SWD of the 10 crops was 15, 13, and 2 cm for 2002, 2003, and 2004, respectively (Table 3). Average SWD as a percentage of water use was 48, 48, and 7% for the same 3 yr. Low precipitation decreased soil water storage and resulted in water use coming predominately from seasonal precipitation in 2004.

Mid-September to mid-April SWR was less than seasonal SWD in 2002–2003 and 2003–2004 (Table 3). However, May precipitation in 2003 was far greater than average (Table 2), and mid-April to mid-May precipitation largely overcome the difference between SWD and SWR that year. This was not the case in 2003–2004, and excess of SWD over SWR resulted in a low soil average profile water content in mid-May 2004 of 37 cm. Approximate field capacity for this soil is about 56 or more cm in 1.8 m of soil profile.

To examine patterns of SWD distribution over soil depths, water depletions were calculated during periods of time with the greatest SWD, from mid-June to early September. To increase clarity of graphical display, we show data (Fig. 2) for the six economically most important crops for the years 2002 (Site 1) and 2003 (Site 2). Low soil water in spring followed by a wetter summer rendered the 2004 SWD pattern relatively anomalous. Sunflower, which had the greatest overall SWD (Table 3), had SWD values at the greatest or near-greatest level for all soil depth intervals below 0.3 m, and had significantly lower SWD for the 0–0.3 m near-surface zone. The pattern is just the opposite for dry pea, which had the lowest overall SWD (Table 3) and a lower level of SWD at all depths below 0.3 m (Fig. 2).

In 2003, more of the crops had greater amounts of SWD coming from subsoil below 1.2 m depth than in 2002 (Fig. 2), and also had greater percentages of total SWD coming from subsoil in 2003. May 2003 precipitation was far greater than average, facilitating relatively greater subsoil recharge, while July and August, 2003, precipitation was below average. Seasonal precipitation in 2002 was less than in 2003, and below average both years (Table 2). This difference in precipitation pattern evidently fostered more deep SWD in 2003 compared with 2002.

It is evident from Fig. 2 that a greater percentage of SWD was drawn from subsoil below the 1.2-m depth by sunflower compared with lentil and dry pea, with spring wheat and canola being intermediate. This is more evident for 2002 than for 2003. The general relationship between soil depth of SWD and root growth is well known. A study of root growth of alternative crops conducted at the same research facility (Merrill et al., 2002) showed that the rooting depth of sunflower was greater than that of spring wheat and canola, which had greater rooting depth than dry pea.

We list all 10 crops in rank of their 2002–2003 overall SWD (Table 3), giving the average percentage of mid-June to beginning of September SWD that occurred below the 0.9-m soil depth, followed by the rank of this deep SWD: (1) sunflower, 27.4%, first; (2) corn, 15.4%, sixth; (3) canola, 19.3%, second; (4) sorghum, 12.5%, ninth; (5) spring wheat, 17.0%, third; (6) chickpea, 15.9%, fifth; (7) millet, 14.3%, seventh; (8) buckwheat, 16.3%, fourth; (9) lentil, 10.5%, tenth; (10) dry pea, 12.6%, eighth.

Rank of overall SWD was within two or less of the rank of deep SWD for seven out of 10 crops, showing their correlation. Both corn and sorghum had higher total SWD rank than deep SWD rank by four and five, respectively, probably due to the relatively long growth seasons of these crops; they ranked first and third, respectively, in cropping season length (Table 1).

Soil Water Depletion and Recharge

The farmer's bottom line in terms of amounts of seasonal water use and subsequent overwinter SWR under various crops is how much water is stored in the soil profile the following spring that is available to support a new crop. This amount depends on how overwinter SWR modifies soil water differentials developed by seasonal SWD. In general, SWD should be expected to be more variable among crops than SWR because it depends on differences in crop phenology that determine differences in ET. Soil water recharge is more dependent on stochastic landscape hydrologic processes resulting in runoff and runon. Other factors that can affect SWR are snow capture by crop residue, weed growth, and soil evaporation.

As shown by snow capture measurements (Fig. 3), only about a quarter of snow trapped by sunflower residue and measured in February remained by early March, a result apparently due to less-durable standing residue leading to greater sublimation. About two-thirds of the snow captured in stubble of the other row crop, corn, remained by early March. Spring wheat was best at capturing and retaining snow, and four other crops were able to capture considerable amounts of snow: canola, buckwheat, millet, and sorghum. The three legume crops—chickpea, lentil, and dry pea—having low-lying and less durable residues, were relatively poor at snow capture. The ranking of average SWR among crops (Table 3) roughly reflects differences in snow capture (Fig. 3). Sunflower had the least amount of recharge (10th ranked) and the three legume crops, chickpea, lentil, and dry pea, were also low ranking: ninth, eighth, and seventh, respectively.

As noted above, the most important thing for farmers about crop differences in SWD and water use is the

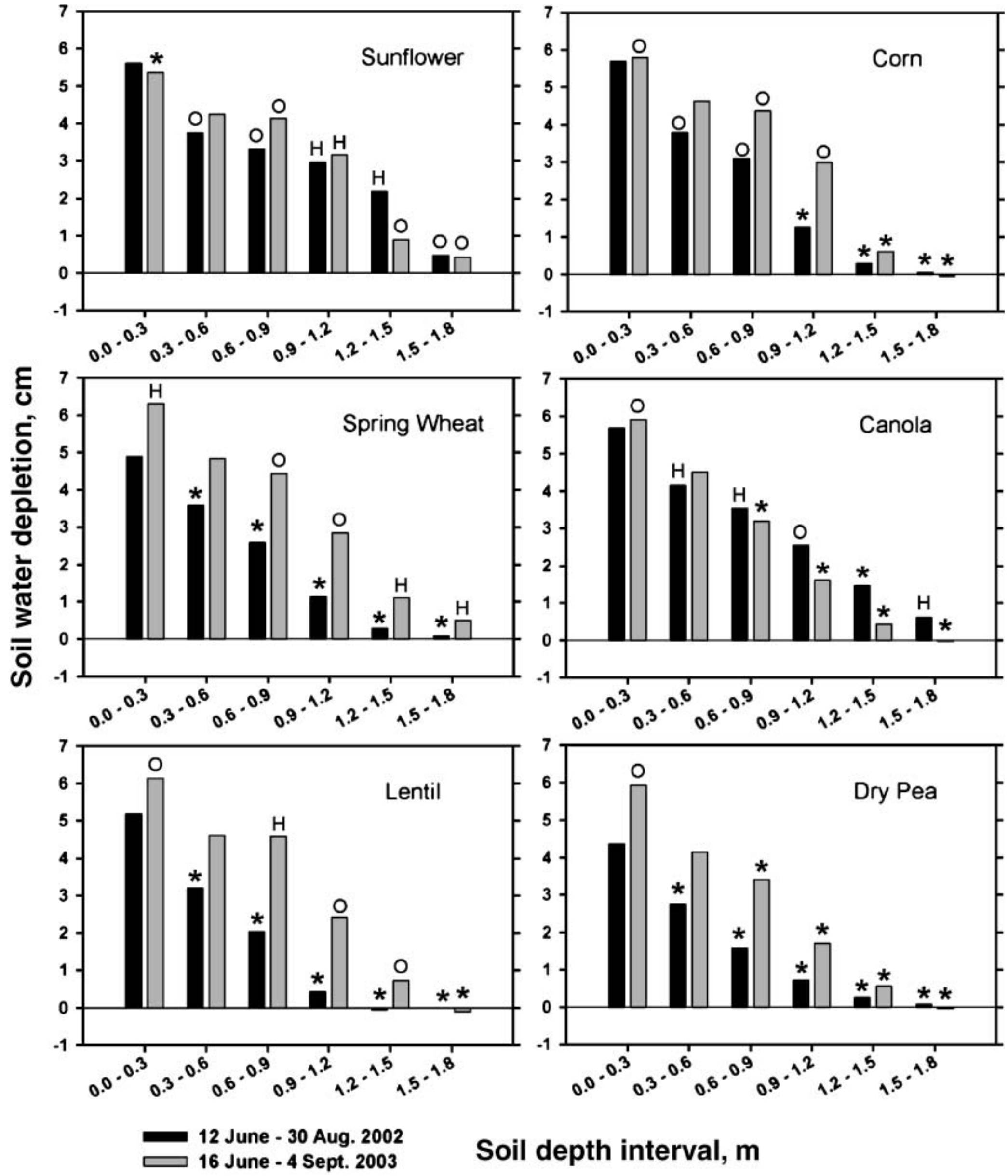

Fig. 2. Depth distributions of soil water depletion for selected crop species measured with a neutron moisture meter for the period between mid-June and beginning of September in years 2002 (Site 1) and 2003 (Site 2). For a given year and soil depth interval, H indicates the highest value, O indicates values not significantly different from the highest value, * indicates values significantly lesser than the highest value, and lack of symbols indicates nonsignificance of main effect (crop) by Duncan's multiple range test at $P < 0.10$.

amount of water stored in the soil profile at spring seeding time. Measurements taken in April following each of the cropping years showed that sunflower, with the greatest average seasonal SWD, left the least amount of water in the soil (Table 4). A ranking of crops by the least amount of soil water stored in the spring roughly follows a ranking of the crops by average SWD. However, April soil water following spring wheat was greater than expected from this ranking, which may be attributed to superior snow capture and retention by this crop.

April soil water contents measured where dry pea had been grown in the previous year were greater than water contents where sunflower had been grown by 11, 9, and 11 cm in 2003, 2004, and 2005, respectively (Table 4). The average difference between soil water following spring wheat compared with soil water following sunflower was slightly less, 10 cm. These values are not far from comparable soil water content values measured in the earlier Phase II crop sequence project in April 2001 showing dry pea vs. sunflower and spring wheat vs. sunflower differences of 9 and 5 cm, respectively (Merrill et al., 2004). The growing season in 2000 before these measurements had near-average precipitation. Such large differences between lower and higher water-using crops can exert considerable effects on succeeding crops, and implies potential for significant on-field and off-field landscape hydrological effects.

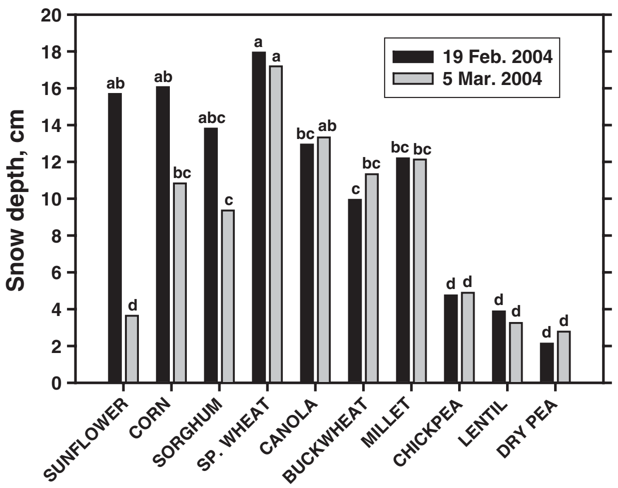

Fig. 3. Depths of snow entrapped in residue structures measured on two dates in 2004. Letters refer to Tukey's Studentized range test at $P < 0.05$ applied to dates separately.

Applications of Results

The potential risk of heavy water-using crops affecting the yield of subsequent crops is well known to farmers and researchers in dryland agriculture portions the Great Plains. Information concerning this issue often focuses on sunflower. In Kansas, Norwood (2000) showed that spring soil water amounts following sunflower and soybean were lower than those following corn and sorghum. Nielsen et al. (1999) showed that sunflower in eastern Colorado used more water than millet or corn, and this was linked to lowered winter wheat yields following sunflower.

The direct economic cost of spring wheat production that may be lost in the year after growing sunflower under drought conditions can be estimated (Merrill et al., 2004). Bauer and Black (1991) reviewed regional literature and found that every additional centimeter of effective soil water evapotranspired beyond the point of zero seed yield will produce, on average, 130 kg ha^{-1} of spring wheat yield. If it is assumed that the average seasonal difference in water use between sunflower and dry pea reported here, 10 cm, is attenuated 20% during overwinter recharge (there was 20% attenuation of SWD differences overwinter in 2000–2001, but less in 2002–2003), dry pea land will have 8 cm more water the following spring than sunflower land. Under critical water limitation, this difference translates into a gross return differential of 136 to 174 United States dollars (USD) ha^{-1} for spring wheat prices of 0.129 to 0.165 USD kg^{-1} (3.50 to 4.50 USD bu^{-1}), respectively.

A number of different types of crop sequential effects can occur in soil–crop production systems, such as those involving soil biology and plant diseases, weed growth interactions, or crop water use differences. An interaction among the different types of crop sequence effects was observed in the Phase II crop sequence project (Krupinsky et al., 2006), which was performed under average to above-average precipitation conditions. Sunflower showed overall positive crop sequential effects on other species during the crop matrix years, and had positive effects on spring wheat crops that were seeded after the crop matrices. The spring wheat results of this project were interpreted as showing that greater water use by sunflower helped lessen plant diseases that flourished with continuous wheat crops (Krupinsky et al., 2006). In contrast, crop sequential effects of sunflower were negative during the currently reported Phase III crop sequence project (Tanaka et al., 2007), which was conducted under precipitation conditions that were considerably below average as already noted.

Understanding the management of dynamic cropping systems requires application of the key principles of dynamic agriculture (Tanaka et al., 2002). These principles are adaptability, diversity, environmental awareness, information awareness, multiple enterprises, and reduced input costs. A farmer using information about comparative water use effects for making cropping decisions about an upcoming season would illustrate application of several of the principles. Choosing a low water-using crop species for the year following a higher water-using one would demonstrate application of the principle of adaptability, and putting in a crop choice that would change agrobotanical family type to lessen disease risk demonstrates application of the principle of diversity.

For practical application of the information in this paper and similar information, farmers should carry out

Table 4. Soil water amounts measured to a depth of 1.8 m in mid-April of the year following the growth of indicated crops during the previous year. Measurements taken in 2003 were done at Site 1, and those taken in 2004 and 2005 were done at Site 2.

Previous crop ranked by seasonal SWD†	Mid-April soil water amount 2003	2004	2005	Avg.	Difference from annual mean 2003	2004	2005	Avg.	Rank by lowest average difference from mean
	cm								
1 sunflower	38.3c‡	34.4c	32.4b	35.0	−6.40	−6.93	−4.92	−6.08	1
2 corn	44.1abc	39.6abc	35.2ab	39.6	−0.62	−1.86	−2.16	−1.58	3
3 sorghum	44.7abc	40.8abc	37.2ab	40.9	0.01	−0.61	−0.13	−0.25	4
4 spring wheat	45.4ab	46.6a	43.2a	45.1	0.68	5.16	5.89	3.91	9
5 canola	41.1bc	46.4a	36.4ab	41.3	−3.58	4.98	−1.00	0.13	5
6 millet	46.0ab	42.8abc	35.9ab	41.5	1.34	1.34	−1.42	0.42	6
7 buckwheat	47.3ab	42.4abc	35.2ab	41.6	2.62	0.96	−2.16	0.47	7
8 chickpea	44.6abc	37.4bc	35.0ab	39.0	−0.09	−4.04	−2.36	−2.16	2
9 lentil	46.6ab	40.2abc	39.7ab	42.2	1.95	−1.20	2.37	1.04	8
10 dry pea	49.1a	43.6ab	43.2a	45.3	4.39	2.22	5.89	4.17	10
Mean	44.7	41.4	37.4						

† SWD, soil water depletion.
‡ Values in a column followed by the same letter are not significantly different at the 0.05 level according to Tukey's Studentized range test.

monitoring of the soil water status of their land, especially in springtime. The choice of higher-water-using crops, such as sunflower or corn, would best be indicated when springtime soil water is known to be sufficiently high and the prior crop was not a heavy water user. If the prior crop had been a lower producer of soil coverage by residue, like dry pea or lentil, then spring wheat, canola, or millet would be better choices than sunflower because they provide better protection against soil erosion through superior residue coverage (Krupinsky et al., 2007). Consideration of such a soil conservation issue in making crop choices illustrates application of the dynamic agriculture principle of environmental awareness.

Our results showing differences in water depletion and recharge among crop species derives from an experiment with traditional replicated land block design, which is useful for observing crop ecological effects on soil hydrology at subfield or point scales. The considerable differences in water use among crop species reported here will have effects at larger scales, as for example where excess water can have negative effects on equipment trafficability at lower landscape positions. At greater, off-field scales, crop water use differences will impact fluxes of sediment, nutrients, and water into wetlands and drainages. To apply information about soil and crop hydrology gained at lower scales through traditional agronomic experiments to the higher soil and land scales that farmers and ranchers actually deal with, we need new scale-bridging observation and experimentation schemes, and new theories and models to generate such science and put it into practice.

A key scale-bridging scientific practice is that of remote sensing. Through remote sensing, it is possible to delineate patterns of plant growth activity and interaction of managed plant communities with the soil and land through, for example, determination of plant C/N ratio (Phillips et al., 2006) and mapping of landscape ET pattern (Bastiaanssen et al., 2005). The higher scale hydrological consequences of differential crop water use effects, such as those reported in this paper, are observable at multiple scales through remote sensing of the dynamics of ephemeral and small water bodies (Phillips et al., 2005). Traditional, field plot-scale soil hydrology information must be integrated with higher, multiscalar information provided by remote sensing and allied technologies. An immediate, necessary research action toward achieving this goal is to link time-series measurements at point- and plot-scales, such as those by neutron moisture meter as in the present project, to remotely sensed plant growth and ET spatial pattern observations and to other current and emerging land survey methodologies.

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