DRYLAND CROPPING INTENSIFICATION: A FUNDAMENTAL SOLUTION TO EFFICIENT USE OF PRECIPITATION

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I. INTRODUCTION

Pioneering farmers in the 19th century, frustrated with the erratic yields associated with annual cropping of small grains, began alternating crop with fallow to

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improve yields (on a per harvest basis) and reduce total crop failure and labor. A dryland farming practice known as "summer fallow" soon dominated the North American Great Plains in regions that receive annual precipitation of less than 500 mm. With this practice, no crop is grown during the fallow, and weeds are controlled by cultivation or chemicals to enhance soil-water storage and nutrient availability for the subsequent crop.

Both winter and spring wheat-fallow systems are practiced in the Great Plains. In the central and southern Great Plains, hard red winter wheat (*triticum aestivum* L.) is the dominant dryland crop primarily because of its high-yielding potential (Greb *et al.,* 1979) with limited crop substitutions (Johnson, 1977). In the northern plains, hard red spring wheat is dominant. For winter wheat, the fallow period is approximately 14 months, running from harvest in July to planting in September of the next year. The fallow period for spring wheat is about 21 months, extending from early August harvest to planting in the second spring.

To conserve soil water during fallow, in the early days of dryland farming, weeds were controlled by multiple tillage (plow, harrow, one-way disk) operations. As the acreage of clean-fallowed land increased, the hazards of water and wind erosion multiplied, resulting in the Dust Bowl in the 1930s. Scientists and farmers in the plains then turned to stubble-mulch (a V-shaped sweep or blade pulled at shallow depth) or subsurface tillage to control erosion (Duley and Russel, 1939). Stubble-mulch tillage is currently the dominant method of summer fallow in the plains. It is well documented that fallow increases the probability of having adequate soil water at planting to maximize initial wheat stand establishment and development, and therefore we do not dwell on this. In this chapter we further investigate "the paradox of summer fallow" first noted by Haas *et al.* (1974).

A. The Paradox of Summer Fallow

Most farmers in the Great Plains agree that water is the primary limiting factor controlling dryland production. Yet only a small portion of the precipitation received is stored during fallow, and soil evaporation far exceeds other losses by weeds, volunteer plants, runoff, deep seepage, and snow blowoff. In a classic USDA Conservation Research Report, Haas *et al.* (1974) state, "It seems paradoxical that water should be proclaimed the primary factor limiting crop production in the northern Great Plains, when more than 1 year's precipitation is lost during the fallow period for spring wheat." For no-till winter wheat-fallow in the west-central Great Plains, Farahani *et al.* (1998) found that on average, only 20% of the precipitation received during the fallow was stored in the soil profile. For the region, average (1948–1995) precipitation for the 14-month fallow is 552 mm, resulting in 442 mm of lost precipitation. That is indeed more than an average year's precipitation of 410 mm.

Mathews and Army (1960) summarized soil-water and precipitation data for 25 stations representing over 450 wheat-fallow years on well-managed fallow lands in the Great Plains. The average soil-water storage during the fallow (for both winter and spring wheat-fallow systems) was 100 mm or 16% of the precipitation (617 mm), corresponding to a 84% loss of precipitation. They attributed this loss to evaporation from the soil, since runoff and deep percolation losses were known to be very low. Although significant progress in fallow tillage and management has been made since then, investigators still report unacceptably low fallow water storage efficiencies, even under modern conservation practices of reduced- and no-till (Unger, 1984; Stewart and Steiner, 1990; Norwood, 1994; Jones and Popham, 1997; McGee *et al.,* 1997).

In a recent review, Peterson *et al.* (1996) examined the effects of tillage and residue management on fallow soil-water storage from Canada to Texas. Water storage efficiencies using no-till summer fallow in the Great Plains were reported as 10% in Texas, 22% in eastern Colorado, and 25–30% in western Kansas for the 14-month winter wheat-fallow system; and from 18 to 37% in the northern plains for the 21-month fallow of spring wheat. From their summary, an average efficiency of 25% was found for water storage during fallow (both winter and spring wheat) in the Great Plains. Comparing this with the earlier findings of Mathews and Army (1960), one may conclude that from the dust mulch days in the early 1900s to the present era, fallow efficiency has only improved from 16% storage to 25% storage with no-till fallow. A huge loss, 75% of the fallow precipitation, still remains a reality, even with our best known soil and water conservation practices.

Summer rainfall prevails in the Great Plains, with nearly 75% of the annual precipitation occurring from April to September. Ironically, precipitation-storage efficiency during fallow is lowest, even negative at times, during summer periods when precipitation is greatest. Paradoxically, fallow is not only inefficient but most inefficient during the periods when precipitation is most substantial (i.e., summer). There appears to be little possibility of further reducing evaporation by use of surface residue, particularly since residue production in Great Plains dryland agriculture is limited for efficient water storage (Peterson *et al.,* 1996). Existing soil and water conservation practices, very important to erosion and soil productivity, are at or near their practical limits. A different approach to water conservation and efficient use of precipitation is obviously needed.

Enhancing the efficient use of precipitation is the primary key to a sustainable dryland agriculture (Peterson *et al.,* 1996). It appears that the most direct and practical solution to improving efficient use of precipitation is the inclusion of a summer crop (i.e., corn [*Zea mays* L.], sorghum [*Sorghum bicolor* L. Moench], millet [*Panicum miliaceum* L.], or sunflower [*Helianthus annuus* L.]) in the year following the wheat crop that would utilize the summer precipitation. Peterson and Westfall (1996) stated, "Planting a spring crop that can utilize both the stored water and the summer precipitation is the key; . . . the summer precipitation is used by the crop instead of being lost to evaporation during the second summer of fallow." The 2-year wheat-fallow system is replaced by a 3-year wheat-corn (-sorghum, -millet, or -sunflower) fallow rotation. The former produces one crop every 2 years; or a 0.5 cropping (and 0.5 summer fallow) intensity per year. In the 3-year system, cropping intensity increases to 0.67 (two crops every 3 years), and summer fallow intensity decreases to 0.33 (one summer fallow every 3 years). The term "cropping intensification" is used as an umbrella term, defining dryland systems with more crops and less summer fallow per unit time.

In the Great Plains, dryland-cropping intensification has shown pronounced increases in annualized grain yield and biomass production (Peterson *et al.*, 1993, 1996; Halvorson *et al.*, 1994; Norwood, 1994; Jones and Popham, 1997). Even soil-surface organic matter has increased in some instances (Wood *et al.*, 1991). Dhuyvetter *et al.* (1996) summarized economic studies from across the Great Plains and concluded that more intensive systems also yielded greater net returns.

What principles govern the efficient use of precipitation in intensified systems? The underlying concepts that favor cropping intensification as a solution to inefficient fallow are not entirely evident from the literature. The question is, How does intensification provide the potential for growing more crops (per unit time) in a given precipitation regime that traditionally produced only one wheat crop every 2 years?

B. Objective

Our objective in this article is two-fold: (1) to explore the concept of dryland-cropping intensification as a fundamental and practical solution to improved use of precipitation, and (2) to propose a systems approach for analyzing, evaluating, and comparing intensified dryland-cropping systems. In this quest, we first present a review (Section II) of research on precipitation storage and efficiency during different parts of the fallow period in the Great Plains. The review is not intended to be exhaustive, but it examines significant findings in winter and spring wheat-fallow systems. The emphasis in this chapter is mainly on systems involving winter wheat, but the concepts discussed are equally relevant to spring wheat. We then provide (Section III) a more in-depth examination of the various periods of fallow using data from a long-term dryland–no-till cropping systems field study.

The number of crop and noncrop periods in an intensified cropping system depends on the degree of intensification. Evaluation and comparison of intensified systems are made difficult because the duration and frequency of crop and noncrop periods vary, and their time-of-year precipitation characteristics vary among systems with differing crop choice and sequence. Quantitative measures and indices are needed to evaluate intensified rotations on a system basis. In Section IV, we propose a systems approach to intensification and present a collection of single-value system indicators that allow comparison of cropping systems on an equal basis, i.e., irrespective of the cropping intensity. Our goal is to simplify cropping systems analysis for the purposes of research and application.

II. SUMMER FALLOW: A SECOND LOOK

The focal point of previous fallow research has been enhanced soil-water storage through improved tillage equipment, reduced number of tillage operations, and increased surface residue cover. Less tillage coupled with more surface residue coverage has provided the most practical means of minimizing erosion, enhancing infiltration, and retarding runoff and evaporation. Most previous research, however, concentrated on evaluating fallow as a whole. Literature on precipitation storage and efficiency during different parts of the fallow period is limited. A summary of significant research is presented in Tables I (spring wheat) and II (winter wheat).

A. Spring Wheat-Fallow System

Haas and Willis (1962) summarized data collected over 40 years for the alternate spring wheat-fallow system and reported that 54% of the total 21-month fallow storage of 111 mm was stored from August harvest to spring (Table I), and 84% was stored by July 1 (not shown in Table I). Of the 300-mm precipitation received from spring to fall, only 17% (51 mm) was stored in the soil profile. On the average, no precipitation was stored during the second winter of fallow. These inefficient periods of fallow reduced the 40-year mean efficiency for the entire 21-month fallow to only 19%. These results were reconfirmed in a study conducted at Sidney, Montana, by Black and Power (1965). As summarized in Table I, fallow storage efficiency was the highest from harvest to spring (60%) and lowest for the summer of fallow from spring to fall (5%). On average, of the 109-mm total fallow storage, 76% was stored the first winter, 9% during the summer of fallow, and 15% the second winter. Both sets of investigators regarded runoff as insignificant on their sites, suggesting that the evaporation was the major cause of low efficiency. For stubble-mulch and no-till fallow in spring wheat, Tanaka and Aase (1987) reported that over 60% of water storage occurred from harvest to spring when the land was in stubble, a lesser amount from the following spring until fall, and still less during the second winter.

For the northern plains data (Table I), mean precipitation was greatest during the summer of fallow (214 mm), of which 84% (180 mm) was lost. Note that the mean precipitation storage of 74 mm from harvest to spring plus the average 214

Table I

Soil-Water Storage (*SWS*) and Precipitation Storage Efficiency (*PSE*) during Specific Periods of the 21-Month Fallow in a Spring Wheat-Fallow System

Reference	Years of data	Harvest to spring *SWS* (mm)	Harvest to spring *PSE* (%)	Harvest to spring % of total *SWS*	Spring to fall *SWS* (mm)	Spring to fall *PSE* (%)	Spring to fall % of total *SWS*	Fall to seeding *SWS* (mm)	Fall to seeding *PSE* (%)	Fall to seeding % of total *SWS*	Entire 21-month fallow *SWS* (mm)	Entire 21-month fallow *PSE* (%)
		Specific periods of the 21-month fallow[a]										
Haas and Willis, 1962	1915–1954											
Plow (Mandan, ND)		60	33	54	51	17	46	0	0	0	111	19
Black and Power, 1965	1956–1964											
Minimum- and no-till (Sidney, MT)		83	60	76	10	5	9	16	19	15	109	27
Tanaka and Aase, 1987	1981–1985											
Stubble-mulch (Sidney, MT)		72	51	65	34	19	31	4	9	4	110	29
No-till		80	56	62	41	23	31	9	19	7	130	35
Mean precipitation (mm)			151			214			64			429
Soil water storage (mm)			74			34			7			115
Precipitation lost (mm)			77			180			56			314

[a]*SWS* (for a given fallow period) = profile soil water at the end minus the profile soil water at the beginning of the fallow period. *PSE* (for a given fallow period) = (*SWS* divided by precipitation during that fallow period) × 100. Percentage of total *SWS* = *SWS* during a given period of fallow divided by total stored water during the entire fallow) × 100.

mm of summer precipitation provides the potential for 288 mm of available water for possible inclusion of a summer crop in the rotation.

B. Winter Wheat-Fallow System

Black *et al.* (1974) summarized 14 years of winter wheat-fallow data from Sidney, Montana, and divided the fallow into two periods: (1) harvest to spring, and (2) summer of fallow. For stubble-mulch fallow, an astonishing 84% of the total fallow storage was saved from harvest to spring, a period in which only 36% of total fallow precipitation was received. The remaining 64% of precipitation (216 mm) during the summer of fallow only contributed 16% (15 mm) to storage and the rest (201 mm) to evaporation. Greb *et al.* (1967) studied the effects of mulch loading rates on fallow storage in a winter wheat-fallow system and reported that water storage from harvest to late spring represented over 90% of the total fallow storage (determined from Table II by summing storage from harvest to fall and from fall to late spring). As shown in Table II, a large portion of precipitation storage occurred during winter of fallow. During the summer of fallow (from late spring to seeding), 7 out of 10 experiments yielded a negative water storage, even under residue amounts as high as 10 t ha^{-1}. Over the entire fallow period, fallow storage increased with increasing residue loading rate. Examining a range of tillage and residue management methods, the work of Smika and Wicks (1968) and Tanaka and Aase (1987) confirmed previous findings (Table II).

The most intriguing observation from Table II is that across the Great Plains, from 68 to 148 percent of total precipitation storage in the entire 14-month fallow period was achieved from harvest to spring. The overwinter period was by far the most efficient, and the summer of fallow the least efficient period of fallow. Precipitation during the latter period was almost entirely lost to evaporation. The problem of low precipitation-storage efficiency has been only partially improved by modern tillage and residue management practices. Fallow storage efficiency has increased from the 10% range under intense tillage operation at the turn of this century to the 20–30% range under the modern no-till and residue management techniques. It is evident that even under modern conservation practices, the original criticism of fallow still remains, and fallow precipitation-storage efficiency remains low.

III. DRYLAND CROPPING INTENSIFICATION

Enhanced soil and water conservation is essential to the sustainability of dryland agriculture in the Great Plains. Fallowing is highly inefficient, as shown in

Table II

Soil Water Storage (*SWS*) and Precipitation Storage Efficiency (*PSE*) during Specific Periods of the 14-Month Fallow in a Winter Wheat-Fallow System

			Specific periods of the 14-month fallow[a]										
			Harvest to late fall			Late fall to late spring			Late spring to seeding		Entire 14-month fallow		
Reference	Residue level (t ha^{-1})	Years of data	*SWS* (mm)	*PSE* (%)	% of total *SWS*	*SWS* (mm)	*PSE* (%)	% of total *SWS*	*SWS* (mm)	*PSE* (%)	Precip. (mm)	*SWS* (mm)	*PSE* (%)
Greb *et al.*, 1967		1962–1965											
Sidney, MT	0		5	—	9	78	—	139	−22	—	355	56	16
	1.7		3	—	5	87	—	132	−21	—	355	66	19
	3.4		4	—	5	86	—	109	−7	—	355	79	22
Akron, CO	1.7		40	—	28	87	—	61	15	—	549	142	26
	3.4		31	—	19	114	—	70	18	—	549	163	30
	6.7		44	—	24	119	—	65	20	—	549	183	33
North Platte, NE	3.4		92	—	48	105	—	55	−7	—	648	190	29
	6.7		92	—	45	114	—	56	−3	—	648	203	31
	10.1		90	—	40	150	—	67	−17	—	648	223	34
Smika and Wicks, 1968		1963–1966											
Plow (North Platte, NE)			−44	−23	−30	178	64	122	12	7	640	146	23
Stubble-mulch			4	2	2	184	66	91	14	9	640	203	32
Reduced-till			11	6	5	220	78	97	−6	−4	640	226	35
No-till			34	18	12	258	92	94	−18	−11	640	274	43
Tanaka and Aase, 1987		1981–1984											
Stubble-mulch (Sidney, MT)			37	43	37	41	52	41	21	16	299	99	33
No-till			40	46	35	38	48	33	36	27	299	114	38

[a] *SWS* (for a given fallow period) = profile soil water at the end minus the profile soil water at the beginning of the fallow period. *PSE* (for a given fallow period) = (*SWS* divided by precipitation during that fallow period) × 100. Percentage of total *SWS* = (*SWS* during a given period of fallow divided by total stored water during the entire fallow) × 100.

the previous section. The soil-water storage data suggest that enhanced efficient use of precipitation may be possible if summer crops are inserted in periods that have low water-storage efficiency.

In the remainder of this chapter, we use data from the Sustainable Dryland Agroecosystem Management Project (Peterson *et al.*, 1993) as a case study to develop a better understanding of the concept of intensification and its influence on precipitation storage and use. That project was established in 1985 to address precipitation use efficiency under dryland–no-till cropping systems at three locations in the west-central Great Plains region. The experimental locations, with long-term precipitation ranging from 400 to 450 mm year^{-1}, represent nearly a two-fold increase in pan evaporation from north (Sterling, Colorado) to south (Walsh, Colorado). The crop-management systems imposed in each location are a continuum with increasing cropping intensity and fewer summer fallow periods per unit time (Table III). All systems are managed with no-till techniques. The benchmark cropping system is the winter wheat-fallow (WF). Cropping intensity increases for the 3-year rotations of winter wheat-corn-fallow (WCF) and winter wheat-sorghum-fallow (WSF), and the 4-year rotations of winter wheat-corn-millet-fallow (WCMF) and winter wheat-sorghum-sorghum-fallow (WSSF). Herafter we refer to sorghum in WSF and the first-year sorghum in WSSF as sorghum-1 and the second-year sorghum in WSSF as sorghum-2.

In part A of this section, we provide a summary of results from the preceding case study along with other modern no-till cropping studies from the central and southern Great Plains region. Our intention is to reiterate the state-of-the-art research findings regarding the potential of intensifying cropping systems in the Great Plains.

A. Modern Dryland–No-Till Cropping Systems

Table IV provides a summary comparison of modern no-till winter WF and more intense 3- and 4-year cropping systems from the Great Plains. The longest fallow period in a dryland cropping system always precedes the winter wheat crop and varies in duration from approximately 14 months in WF to 10–13 months in the 3- and 4-year systems. Length and time of fallow influence the amount of precipitation received during fallow, with the 14-month fallow in WF having the largest mean precipitation of 657 mm for all locations.

Two of the most significant observations from Table IV are as follows. First, available soil water at wheat planting in all systems at a given location was similar, in spite of the fact that precipitation received during the 14-month fallow in WF was 140–250 mm greater than precipitation during the fallow preceding wheat in the 3- and 4-year systems. We can conclude that available soil water at wheat planting is not a function of the intensity of the cropping system as long as the

Table IV

Summary of Plant-Available Soil Water (*PASW*) at Crop Planting and Precipitation (*P*), Soil-Water Storage (*SWS*), and Precipitation Storage Efficiency (*PSE*) during the Noncrop (Fallow) Period Just Preceding That Crop[a]

			Wheat				Corn (sorghum-1)[b]				Millet (sorghum-2)[c]			
Reference	Years of data	Cropping systems	*PASW* (mm)	*P* (mm)	*SWS* (mm)	*PSE* (%)	*PASW* (mm)	*P* (mm)	*SWS* (mm)	*PSE* (%)	*PASW* (mm)	*P* (mm)	*SWS* (mm)	*PSE* (%)
Unger, 1994	1984–1991													
Bushland, TX														
(no-till)		WSF	226	463	74	16	228	517	145	28	—	—	—	—
Norwood, 1994	1987–1992													
Garden City, KS														
(no-till)		WF	212	598	137	23	—	—	—	—	—	—	—	—
		WSF	181	455	146	32	215	381	175	46	—	—	—	—
Jones and Popham, 1997	1984–1993													
Bushland, TX														
(no-till)		WF	212	730	80	11	—	—	—	—	—	—	—	—
		WSF	205	477	81	17	214	480	101	21	—	—	—	—
Farahani *et al.*, 1998	1988–1995													
Sterling, CO (no-till)		WF	187	610	99	16	—	—	—	—	—	—	—	—
		WCF	176	420	82	19	197	362	131	37	—	—	—	—
		WCMF	200	449	51	11	200	361	127	36	167	196	80	40
Stratton, CO (no-till)		WF	286	646	175	27	—	—	—	—	—	—	—	—
		WCF	271	456	112	25	286	338	161	54	—	—	—	—
		WCMF	279	485	63	12	278	338	161	48	234	194	95	52
Walsh, CO (no-till)		WF	203	703	103	15	—	—	—	—	—	—	—	—
		WSF	216	471	117	26	215	474	108	21	—	—	—	—
		WSSF	205	454	77	17	202	474	98	19	177	239	82	37
Mean		2-year	220	657	119	18	—	—	—	—	—	—	—	—
		3-year	213	457	102	23	226	425	137	35	—	—	—	—
		4-year	228	463	63	13	227	391	129	34	193	210	85	43

[a]Values are means across years. *PASW* = total soil-water profile (average depth of 1.5 m) minus soil-water profile at 15-bar water content. *SWS* (for a given fallow) = soil-water profile (average depth of 1.5 m) at the end of fallow minus soil water at the beginning of fallow. *PSE* (for a given fallow) = (soil-water storage divided by precipitation during that fallow period) × 100.

[b]Sorghum-1 denotes sorghum in WSF and the first sorghum following wheat in WSSF.

[c]Sorghum-2 denotes the second sorghum following wheat in WSSF.

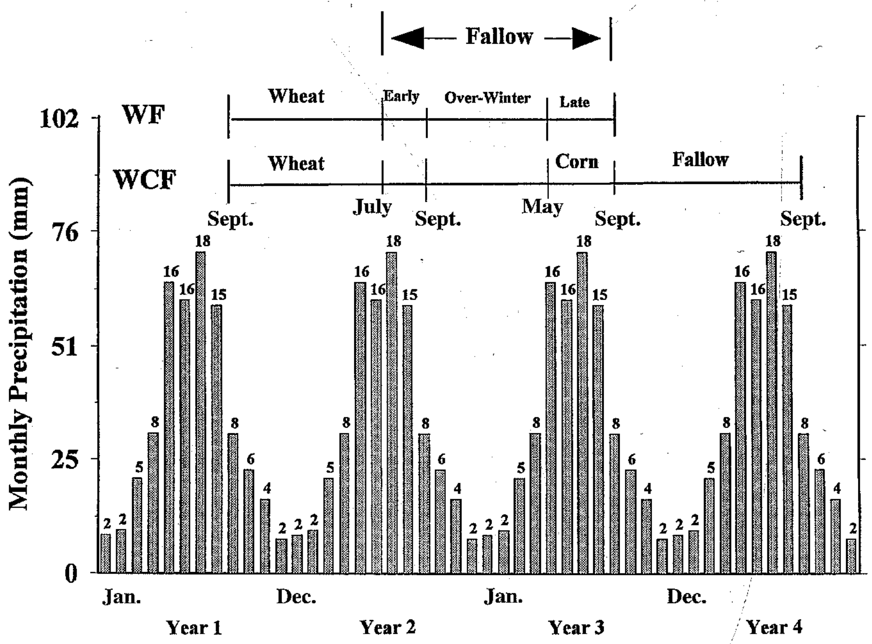

Figure 1 A time-scaled representation of the winter wheat-fallow (WF) and winter wheat-corn-fallow (WCF) systems marking the beginning and ending of all crop and noncrop periods. Average (1948–1995) monthly precipitation amounts are also shown for the Stratton experimental location. (Numbers above bars represent percentage of yearly precipitation occurring in that month.)

wheat maturity in July to mid-September), (2) overwinter period (from fall to early May), and (3) late period (from spring to wheat planting in mid-September). Note that the various crop and noncrop phases in the WCF system fit nicely within these periods. The noncrop period preceding corn is represented by the sum of the early and overwinter periods, and the fallow after corn harvest corresponds to the sum of the overwinter and late periods in WF.

The partitioning of fallow into these three periods was not arbitrary. Each phase bears a distinct identity in regard to soil-water status, climate, precipitation, and duration conditions (Black and Bauer, 1988), except that the climate is similar during the early and late fallow periods. The early period represents the highest residue level in the WF cycle (and even higher in the WCF system due to remaining corn residue), the driest soil profile in the cycle, a short duration of about 3 months, and an average (1988–1995) precipitation of about 200 mm. In this period, the high residue levels coupled with dry soil profiles are ideal for enhanced infiltration, even though evaporation potential is high. The overwinter period has the lowest potential evaporation rates, low to medium soil-water profiles, and a long duration of about 6 months with a mean precipitation of 186 mm—conditions favorable for potentially high storage of precipitation. The late fallow period, on the other hand, represents the lowest residue levels in the cycle, the highest potential evaporation rates, medium to wet soil-water profiles, and a duration of about 4 months with a mean precipitation of 261 mm. These conditions favor evaporation and runoff.

These qualitative descriptions of the three periods of fallow in WF are represented quantitatively in Table V. This table was constructed by using the 1988–1995 data from WF and WCF (WSF at Walsh) systems in our case study. Soil-water storage values were first calculated for the early, overwinter, and late periods. For each fallow period in our systems, mean rates of evaporation (mm day^{-1}) were determine as the ratio of fallow precipitation minus the storage to fallow duration in days.

The three periods of fallow are distinctly different (Table V). Ranked in order of fallow efficiency, overwinter period was the most efficient (61%), having the lowest mean rate of evaporation per day (0.56 mm day^{-1}) and the greatest amount of storage (111 mm) even though precipitation was at its lowest (at Sterling and Stratton) during this period. The early period ranked second in terms of storage (22 mm), efficiency (12%), and evaporation rate (1.86 mm day^{-1}). The late (or the summer of fallow) period was by far the most inefficient (−4% storage), even though the greatest amount of precipitation (261 mm) is received during this time. It had evaporation rates of about 2.2 mm day^{-1}.

To simplify discussion of results, we assigned colors (zones) to each fallow period based on the intensity-of-evaporation rates during the period—the orange zone refers to the early period, the blue zone to the overwinter period, and the red zone to the late period. On average (see Table V), 111 mm (or 89%) of the total 125-mm fallow storage occurred during the blue zone. During the red zone, no water was conserved in this no-till fallow. As shown in Fig. 1, the red zone fallow (i.e., the primary zone of inefficiency in the WF system) is precisely the period that is replaced by corn or sorghum in the more intensified 3-year systems. It appears that if no plants are present to use the soil-water reservoir during the red zone fallow, the atmosphere will consume it through evaporation. The red zone or the summer of fallow can be eliminated only by abandoning winter wheat. That solution is unrealistic, since winter wheat is the corner stone of dryland agriculture in the Great Plains. Thus, the only plausible and practical solution to the unavoidable red zone fallow is to reduce its frequency of occurrence by intensification or summer cropping. Inclusion of one summer crop in the WF system reduces the frequency of occurrence of the red zone fallow by 33%—from one in every 2 years to one in every 3 years.

Table V

Mean Precipitation (P), Soil-Water Storage (SWS), Precipitation Storage Efficiency (PSE), Duration (D), and Daily Evaporation Rate (E_r) for Three Specific Periods of the 14-Month Fallow in the Wheat-Fallow System as Affected by Location (Climate) Treatments[a]

	Entire 14-month fallow in wheat-fallow system														
	Early period (orange zone)					Overwinter period (blue zone)					Late period (red zone)				
Location	D (days)	P (mm)	SWS (mm)	PSE (%)	E_r (mm day^{-1})	D (days)	P (mm)	SWS (mm)	PSE (%)	E_r (mm day^{-1})	D (days)	P (mm)	SWS (mm)	PSE (%)	E_r (mm day^{-1})
Sterling	90	197	17	9	1.92	180	169	114	66	0.63	129	251	− 32	− 13	2.17
Stratton	87	189	64	34	1.44	178	146	97	66	0.55	136	310	14	5	2.16
Walsh	111	232	− 14	− 6	2.22	252	243	123	51	0.49	102	229	− 6	− 2	2.30
Mean	96	204	22	12	1.86	203	188	111	61	0.56	122	261	− 8	− 4	2.21

[a]Values are means for 1988–1995.

IV. A SYSTEMS APPROACH TO INTENSIFICATION

A. Systems Analysis

The importance of evaluating field agronomic problems from a systems perspective was emphasized by Peterson *et al.* (1993). The complexity and the highly interrelated processes in the natural environment require a systems approach. The element of interest herein is the influence of varying crop and noncrop periods on systems behavior. We suggest an analytical approach that simplifies the complexity of the interactions among the many possible crop and noncrop phases and provides a tool for preliminary testing of newly proposed systems.

In our study, the system is defined as a complete cycle of a dryland rotational cropping sequence. A dryland system includes all crop and noncrop periods. For convenience, the system is assumed to have a similar day-of-year beginning and ending. For instance, in 2-, 3-, and 4-year systems of WF, WCF, and WCMF, respectively, wheat planting to wheat planting defines system duration. The benchmark cropping system is the winter WF with one crop every 2 years; or a 0.5 cropping (and 0.5 summer fallow) intensity per year. Cropping intensity increases to 0.67 (0.33 summer fallow intensity) for 3-year rotations that include a fallow preceding wheat (i.e., WCF and WSF), and to 0.75 (0.25 summer fallow intensity) for 4-year rotations that include a fallow preceding wheat (i.e., WCMF and WSSF). A cropping intensity of unity is attained for continuous (not necessarily monoculture) cropping, i.e., winter wheat-corn-millet (WCM).

We used the long-term (1948–1995) precipitation data in Table V to conduct an analysis of cropping systems. The systems evaluated were WF, WCF (WSF), and WCMF (WSSF), as in the case study presented earlier. Hypothetical systems of even greater intensity, such as WCM, winter wheat-millet (WM), and winter wheat-corn (WC), also were evaluated. Figure 2 is a time-scaled representation of the systems we analyzed. A 12-year period was selected for the analysis because it marks the first simultaneous closure of all systems. This choice, however, has no bearing on the interpretations. For the analysis, planting and harvest dates of each crop were set as constants for every year in the 12-year period and corresponded to average dates obtained from our previous field experiments. From the 47-year (1948–1995) precipitation record for the three experimental locations, average precipitation was determined for the orange, blue, and red zones, along with annual and growing-season precipitation for all crops. For convenience, the length of the orange, blue, and red zones was set at 2.5 months (July 1 to mid-September), 7.5 months (mid-September to the end of April), and 4.5 months (May 1 to mid-September), respectively. We then used the efficiencies computed previously for each of the three periods of fallow (Table V) to construct Table VI.

From Table VI, we can see that as cropping intensity increased from 0.5 for WF

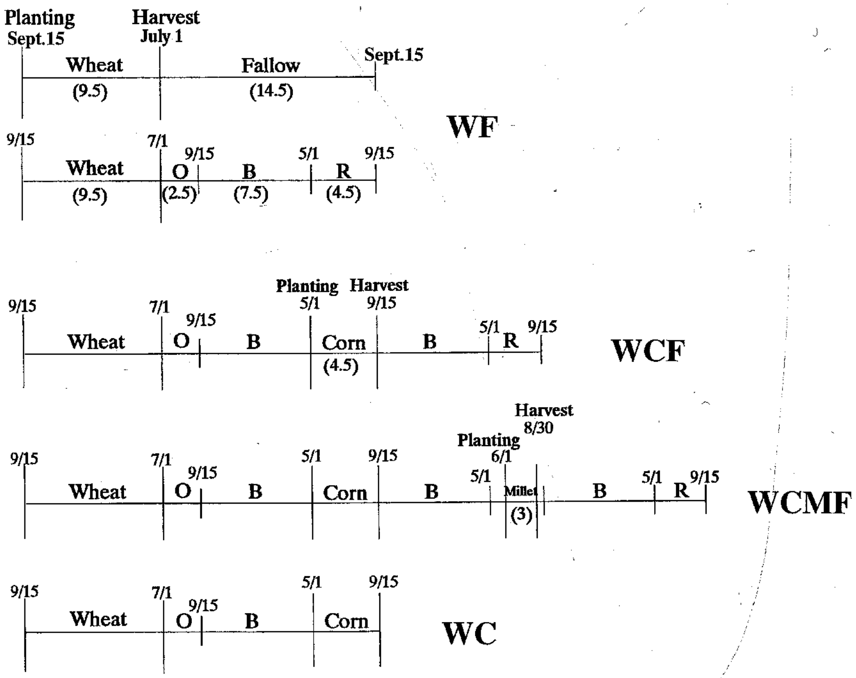

Figure 2 A time-scaled representation of the wheat-fallow (WF), wheat-corn-fallow (WCF), and wheat-corn-millet-fallow (WCMF) systems of the case study plus the hypothetical cropping system of wheat-corn (WC). O, orange zone; B, blue zone; R, red zone; (#), period in months.

to 0.75 for the 4-year systems, the total months in noncrop (fallow) for the 12-year (144 months) period actually increased. Cropping intensification did not reduce months of noncrop (fallow), but the duration of the fallow period preceding wheat planting was reduced. The greatest reduction in noncrop (fallow) months occurred for the hypothetical continuous cropping systems of WCM, WM, and WC. It is important to note that intensification, moving from WF to 3- and 4-year systems, increased the amount of noncrop time in the blue zone and reduced the time in the red zone. By reducing the noncrop time spent in the red zone, the amount of precipitation lost to evaporation was decreased. In comparing WF with the 3- and 4-year systems, total noncrop (fallow) time was reallocated to the more efficient blue zone from the efficient orange and red zones. This decreased the *E*/*ET* ratio (the ratio of total system fallow evaporation, *E*, to total system evapotranspiration, *ET*) from 1.13 (1.71 at Walsh) for WF to 0.65 for WCF (1.09 at Walsh for WSF) and 0.6 for WCMF (1.00 at Walsh for WSSF).

Note that the sum of *E* and *ET* is equal to total system precipitation (assuming no precipitation losses other than evaporation). Thus, the ratio *E*/*ET* quantifies the

Table VI

Twelve-Year (144 months) Analysis of Dryland Cropping Systems in the West-Central Great Plains[a]

		Total 12-year duration (D), precipitation (P), and soil-water storage (SWS)												Total 12-year period					
		Total 12-years		Orange zone (early)[b]			Blue zone (overwinter)[b]			Red zone (late)[b]			Noncrop			Crop			
Cropping system	Cropping intensity	Noncrop (months)	Crop[c] (months)	*D* (months)	*P* (mm)	*SWS* (mm)	*D* (months)	*P* (mm)	*SWS* (mm)	*D* (months)	*P* (mm)	*SWS* (mm)	*P* (mm)	*E*[d] (mm)	*SWS* (mm)	*P* (mm)	*ET*[e] (mm)	*E*/*ET* (mm/mm)
Systems at Walsh, Colorado																		
WF	0.5	87	57	15	869	− 52	45	747	381	27	1649	− 33	3264	2968	296	1440	1736	1.71
WSF	0.67	90	54	10	579	− 35	58	962	491	22	1344	− 27	2885	2456	429	1819	2248	1.09
WSSF	0.75	92	52	10	579	− 35	65	1070	546	20	1191	−2 24	2840	2353	487	1864	2351	1.00
Systems at Sterling and Stratton, Colorado																		
WF	0.5	87	57	15	854	184	45	873	576	27	1698	− 68	3425	2733	692	1723	2415	1.13
WCF	0.67	88	56	10	569	122	60	1164	768	18	1132	− 45	2865	2020	845	2283	3128	0.65
WCMF	0.75	93	51	9	512	110	68	1310	864	17	1038	− 42	2859	1927	933	2289	3222	0.60
WCM	1	76	68	12	683	147	60	1164	768	4	252	− 10	2098	1193	905	3050	3955	0.30
WM	1	63	81	15	854	184	45	873	576	9	566	− 23	2293	1556	737	2855	3592	0.43
WC	1	60	84	15	854	184	45	873	576	0	0	0	1727	967	760	3422	4182	0.23

[a]Mean long-term (1948–1995) annual (Jan.–Dec.) precipitation for the three locations analyzed are 429 mm at Sterling and Stratton and 392 mm at Walsh.

[b]Mean long-term (1948–1995) precipitation for the non-crop (fallow) periods are 571 mm (Sterling and Stratton) and 534 mm (Walsh) for the 14.5-month fallow (July 1–Sept. 15), 142 mm (Sterling and Stratton) and 145 mm (Walsh) for the 2.5-month orange zone (July 1–Sept. 15), 146 mm (Sterling and Stratton) and 124 mm (Walsh) for the 7.5-month blue zone (Sept. 16–April 30), and 283 mm (Sterling and Stratton) and 275 mm (Walsh) for the 4.5-month red zone (May 1–Sept. 15).

[c]Beginning and ending crop growing seasons used to construct the table are wheat (Sept. 16–June 30), corn (May 1–Sept. 15), millet (June 1–Aug. 30), sorghum (June 1–Sept 30).

[d]*E* = total 12-year evaporation from the soil during all noncrop (fallow) periods.

[e]*ET* = total 12-year evapotranspiration during all crop periods.

relative allocation of system precipitation to noncrop (fallow) evaporation and crop *ET*, defined herein as "system precipitation allocation index (SPAI)." As shown in Table VI, the *E*/*ET* ratio for the WF system was about double that for the 3- and 4-year systems. In a relative sense, the lower the ratio, the more precipitation efficient the system. Note that for WF, the ratio *E*/*ET* was above unity (particularly at Walsh), implying that the loss of system precipitation to fallow evaporation exceeded the water allocated for crop production (or *ET*) by 13% (Sterling and Stratton) and 71% (Walsh). It is interesting that the inclusion of a summer crop in the WF system (i.e., the 3-year WCF system) caused a significant reduction in the *E*/*ET* ratio as a result of reducing *E* by 26% and increasing *ET* by 30%.

Continuous cropping systems like our hypothetical WCM, WM, and WC substantially decreased the *E*/*ET* ratio. In the WC system, the *E*/*ET* ratio was decreased five-fold compared with WF, as a result of a 65% reduction in *E* and a 73% increase in *ET*. The red zone fallow period was reduced to nil. Note that the total 12-year soil-water storage during all noncrop (fallow) periods in WC was about 70 mm (or 10%) more than the soil-water storage during fallow in WF, while precipitation received in the latter fallow was about 1700 mm greater than in the former fallow. In other words, it was not the amount of precipitation storage between crops that made the difference, but the strategically placed summer corn crop in the red zone that utilized the 1700 mm of precipitation to produce biomass in the WC system as opposed to being lost to evaporation in the WF system. Some have credited the increased surface residue mass (cover) as being the major factor contributing to the improved efficient use of precipitation in intensified cropping systems. In contrast, our data indicate that residue is not the key concept but only a single component of the system. The gains in efficiency with cropping intensification are due not to an enhanced water conservation but to a reallocation of water from evaporation from the soil during the summer of fallow into the transpiration stream of a plant. Thus, the underlying basis for intensification is a partial replacement of soil evaporation with crop transpiration.

Figure 3 shows the systems ranked according to their *E*/*ET* ratio. The systems with an intensity of unity (i.e., WCM, WM, or WC) are predicted to be much superior to WF. In these hypothetical systems, it is quite obvious that the wheat crop may have a yield reduction due to less stored water at planting. The possible superiority of the continuous systems in efficient utilization of precipitation still may not be profitable. The research question at hand is, is a cropping intensity of unity economically sustainable? That, of course, remains to be determined.

B. Systems Evaluation: Quantitative Indices

Information regarding individual crop and noncrop (fallow) periods are not by themselves a sufficient measure of the effectiveness of the entire system. For the

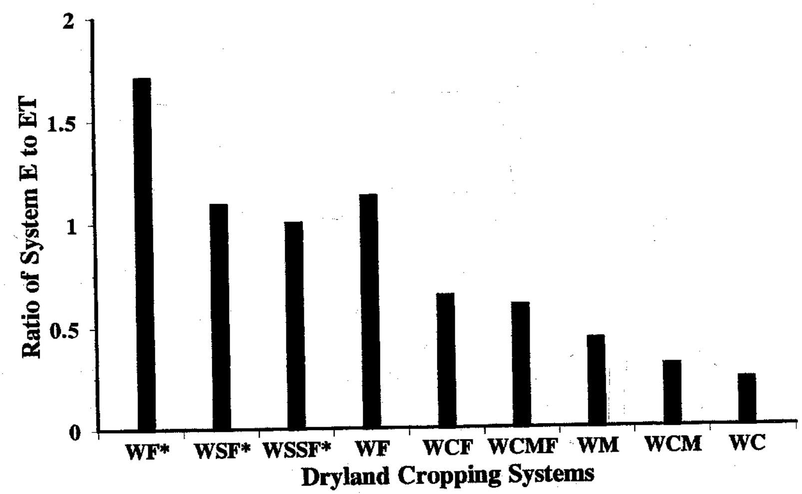

Figure 3 Ranking of dryland cropping systems in order of increasing system precipitation use, given by the ratio *E*/*ET* (*E* = total system fallow evaporation, *ET* = total system crop evapotranspiration). Systems denoted by * are based on precipitation and storage data from Walsh, Colorado; all others are based on mean precipitation and storage data from Sterling and Stratton, Colorado.

purposes of system design, evaluation, comparison, and management, quantitative indicators are needed to measure the systems individually and to weigh them against each other. In terms of system design, there are many elements associated with intensified systems. In the Great Plains, however, the most important system element is the fate of incident precipitation. Other important elements are weeds, fertility, pests, and equipment. Obviously, system adaptation by farmers would require additional information about system economics and practical feasibility, which are not discussed in this chapter.

Our discussion concerns quantifying the effectiveness of an intensified system to utilize precipitation. En route, three questions are of particular importance: (1) how efficiently precipitation received during the noncrop periods is stored in the soil, (2) how effectively system precipitation is allocated between crop and noncrop periods, and (3) how efficiently the stored water is utilized to produce biomass.

Farahani *et al.* (1998) calculated system indices to address the first two questions. These indices are the system precipitation storage index (SPSI), a measure of how efficiently the incident precipitation during all noncrop (fallow) periods is collectively stored in the soil, given by

$$\text{System precipitation storage index (SPSI)} = 1 - \frac{E_f}{P_f} \tag{1}$$

and system precipitation use index (SPUI), a measure of how the system as a whole allocates total incident precipitation to crop production, given by

$$\text{System precipitation use index (SPUI)} = 1 - \frac{E_f}{P_s} \tag{2}$$

where E_f is the sum of all noncrop (fallow) precipitation losses (assumed to be equal to evaporation from the soil), P_f is the sum of all noncrop (fallow) precipitation, and P_s is the total precipitation during a complete cycle of the system (i.e., from wheat planting to wheat planting). The difference between P_s and P_f is the total amount of incident precipitation during all crop periods (P_c). Both indices have upper limits of unity recognized as $E_f \rightarrow$ zero. The SPSI has a lower limit of zero as fallow evaporation (or losses) approaches P_f. The lower limit for SPUI varies among systems; however, it is equal to P_c/P_s as $E_f \rightarrow P_f$.

The SPSI quantifies the unit fraction of noncrop (fallow) precipitation allocated to soil-water storage (S_f), and thus may be written as S_f/P_f. This is the equivalent of the storage efficiency for a single fallow but is written for the whole system. The SPUI quantifies the unit fraction of system precipitation (P_s) allocated to crop season (i.e., evapotranspiration, ET_s), and thus may be written as ET_s/P_s. The advantages of these indices over storage efficiency for individual noncrop (fallow) periods are that they synthesize the behavior of all phases of the system into single-value indicators, allowing system comparison on an equal basis (i.e., irrespective of the intensity of the cropping system). The goal is to devise systems that increase both SPSI and SPUI toward unity within the bounds of commercial feasibility. By examining Eqs. (1) and (2), the most obvious solution to enhancing both indices is reducing noncrop (fallow) evaporation E_f.

Our third question concerns system production and productivity and its relation to the enhanced use of precipitation. Water-use efficiency (WUE), defined as the ratio of dry matter produced per unit of water used, has been used extensively in the past to quantify productivity on a seasonal basis. Peterson *et al.* (1996) considered WUE an equally important parameter for evaluating intensified systems, serving as a diagnostic tool that provides a single quantitative measure combining production and water use. Based on a literature review from the Great Plains, Peterson *et al.* (1996) concluded that with modern no-till techniques, WUE for WF has not increased significantly since the 1970s—a direct consequence of the corresponding stagnant fallow storage efficiencies. They stated, "Cropping systems intensification has allowed us to make the next step in improving WUE in the Great Plains."

Many investigators have discussed means of improving individual crop WUE (Tanner and Sinclair, 1983). Our interest is in WUE on a system basis, defined by WUE_s (Peterson *et al.*, 1996)

$$WUE_s = \frac{Y_s}{ET_s} \tag{3}$$

where Y_s is the system yield (i.e., sum of harvest grain yields from all crops) (kg ha^{-1}) and ET_s is the system growing season *ET* (i.e., sum of growing-season crop-water use from all crops) (mm). The *ET* for each crop was estimated as seasonal soil-water depletion plus seasonal precipitation. The advantage of WUE_s over WUE for single crops is that it synthesizes the productivity of all crops in the system into a single-value indicator, allowing system comparison on an equal basis.

A general rule to ensure that WUE_s is increased by moving from the 2-year WF system to a 3-year intensified system is that the added crop must have a WUE value greater than that of wheat. Two examples from the literature are sorghum at Garden City, Kansas, with a WUE value of 12.6 as compared with 7.1 kg ha^{-1} mm^{-1} of *ET* for wheat (Norwood, 1994); or corn at Sterling, Colorado, with a WUE value of 9.3 as compared with 6.0 kg ha^{-1} mm^{-1} of *ET* for wheat (Peterson *et al.*, 1996). Fortunately, most adapted summer crops in the Great Plains have WUE values greater than that of winter wheat. This is why nearly all WUE_s values in every climate regime from Texas, Kansas, and Colorado were found to be greater than the corresponding values for the 2-year wheat-fallow system (Peterson *et al.*, 1996), averaging 8.5 kg ha^{-1} mm^{-1} in the 3-year system as compared with 6.1 kg ha^{-1} mm^{-1} for WF. By the same argument, improving on the WUE_s of a 3-year system by moving to a 4-year system will be ensured by adding a crop with a WUE greater than the WUE_s of the 3-year system. For instance, to improve on the 8.5 kg ha^{-1} mm^{-1} in the 3-year systems reported by Peterson *et al.* (1996), we need to include a crop with a WUE value greater than 8.5 kg ha^{-1} mm^{-1} (e.g., proso millet). The preceding procedure may be used to devise intensified systems that tend to increase WUE_s.

For our dryland–no-till case study, mean values for system indices and indicators of SPAI, SPSI, SPUI, and WUE_s and annualized grain yields are reported in Table VII. The annualized grain yield values are single-value measures of system production. According to Table VII, WUE_s averaged 5.4, 6.9, and 7.4 kg ha^{-1} mm^{-1} for the 2-, 3-, and 4-year systems, corresponding to annualized grain yields of 1030, 1770, and 1950 kg ha^{-1}, respectively. Although differences between the 3- and 4-year systems are small, intensifying beyond the 2-year wheat-fallow system increased productivity (i.e., WUE_s) by 29 and 39% and production (annualized yield) by an astonishing 72 and 90% per year in the 3- and 4-year systems, respectively. According to SPSI results (Table VII), for every unit of incident precipitation during the noncrop (fallow) periods, 0.19, 0.28, and 0.26 units were stored in the 2-, 3-, and 4-year rotations, respectively. This means that the noncrop (fallow) periods in the 3- and 4-year rotations were collectively 47 and 37%, respectively, more efficient in storing precipitation than fallow in WF. According to SPUI results, for every unit of precipitation in the WF system, only 0.36 (Walsh), 0.44 (Sterling), and 0.49 (Stratton) units are made available for crop production, with the remainder being lost. As the intensity of the cropping system increased, so did SPUI. However, the 3- and 4-year systems were not significantly different.

Table VII

Summary of System Precipitation Storage Index (SPSI), System Precipitation Use Index (SPUI), System Precipitation Allocation Index (SPAI), System WUE (WUE_s), and Annualized Grain Yield Values for the 2-, 3-, and 4-Year Cropping Systems at Three Experimental Locations in the West-Central Great Plains[a]

		Single-value system indices and indicators[b]				
		SPSI	SPUI	SPAI	WUE_s	
Location	Cropping system	(S_f/P_f) (mm mm^{-1})	(ET_s/P_s) (mm mm^{-1})	(E_f/ET_s) (mm mm^{-1})	(Y_s/ET_s) (kg ha^{-1} mm^{-1})	Annualized grain yield (kg ha^{-1})
Sterling	WF	0.16	0.44	1.30	4.8	930
	WCF	0.27	0.57	0.69	6.4	1770
	WCMF	0.26	0.58	0.68	7.2	1960
Stratton	WF	0.27	0.49	1.16	5.9	1250
	WCF	0.34	0.62	0.61	7.3	1960
	WCMF	0.31	0.61	0.63	7.7	2110
Walsh	WF	0.15	0.36	1.72	5.3	910
	WSF	0.24	0.47	1.03	7.0	1590
	WSSF	0.22	0.51	0.93	7.5	1790
Mean	2-year	0.19	0.43	1.40	5.4	1030
	3-year	0.28	0.56	0.78	6.9	1770
	4-year	0.26	0.57	0.75	7.4	1950

[a]Values are means for 1988–1995.

[b]The following variables are defined for a complete cycle of the cropping system (i.e., from wheat planting to wheat planting): S_f = sum of precipitation storage during all noncrop (fallow) periods in the system; E_f = sum of precipitation losses (assumed to be equal to evaporation from the soil) during all noncrop (fallow) periods in the system; P_f = sum of incident precipitation during all noncrop (fallow) periods in the system; P_s = total incident precipitation during a complete cycle of the system (i.e., from wheat planting to wheat planting); ET_s = sum of growing-season crop *ET* for all crops in the system; Y_s = sum of all harvest grain yields from all crops in the system.

Comparing the locations, Walsh, the site with the highest potential *ET,* was the least-efficient utilizer of precipitation, with a SPUI ranging from 0.36 to 0.51. A timely placed summer crop, such as corn or sorghum, increased the unit fraction of precipitation allocated to crop production (i.e., SPUI) from 0.43 in WF to 0.56 (i.e., an increase of 30%) in 3-year systems.

System indices and indicators of SPAI, SPSI, SPUI, WUE_s and annualized yield (Table VII) collectively suggest that intensification can substantially improve on the WF system by enhancing precipitation use, production, and productivity. The gains by intensification result from using water that would be lost by evaporation from the soil during fallow in the transpiration stream of a plant and the associated increase in biomass production. Note that for the experimental period in our case study, annual precipitation was at or greater than normal. The potential of intensification to enhance efficient use of precipitation during dry years, with precipitation amounts of less than 300 mm, is not known.

V. CONCLUSION

Research before the 1980s focused on improving the fallow practice, although Haas *et al.* (1974) and others questioned the wisdom of fallowing. Perspectives on fallowing began to change in the 1980s, and the underlying objective has been broadened to enhancing the efficient use of precipitation rather than just improving summer fallow efficiency. Particularly since research on the winter wheat-fallow system shows that in the Great Plains the amount of soil water accumulated by the late spring of the lengthy fallow preceding wheat is not significantly different from soil water accumulated 5 month later at wheat planting. This is in spite of the fact that nearly 65% of annual precipitation occurs during this latter 5-month period; meaning that on average most precipitation received during the last summer of fallow is lost unless a summer crop is planted.

Cropping diversification is an integral part of intensification. For instance, annual cropping of winter wheat is cropping intensification as compared with alternating wheat with fallow, but the former may or may not be a feasible alternative. Furthermore, in moving from the 2-year WF to 3- and 4-year rotations, cropping intensity per year increases from 0.5 to 0.67 and 0.75, respectively. However, neither the annualized noncrop (fallow) duration (0.6 for WF, 0.61 for WCF, and 0.65 for WCMF) changes (actually, it increases slightly) nor the time-in-crop per unit time increases with cropping intensification. Intensification does decrease the summer fallow intensity per year, from 0.5 in WF to 0.33 in WCF (WSF) and 0.25 in WCMF (WSSF).

A new era of dryland farming, characterized by cropping intensification and diversification, is emerging on the Great Plains and may someday dominate as summer fallow has in the past. Perhaps an even more stimulating thought is the hypothesis by Peterson and Westfall (1997) that "zero tilling, coupled with intensified crop rotations, is a movement toward an agroecosystem that mimics the Great Plains prairie ecosystem before cultivation began."

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