Crop Sequencing to Improve Use of Precipitation and Synergize Crop Growth

D. L. Tanaka,* R. L. Anderson, and S. C. Rao

ABSTRACT

Cropping systems will not be sustainable without change. Broad-scope problems associated with developing sustainable cropping systems are how to choose and sequence crops in cropping systems. Our objectives were twofold: (i) evaluate impacts of crop sequencing on precipitation use and (ii) show how crop sequencing can accentuate synergistic interactions among crops. Crop–fallow systems that developed in the Great Plains resulted in precipitation storage efficiencies of about 20% in the early 1930s to about 40% in the late 1980s. Integrated crop–livestock systems have been developed in the southern Great Plains to take advantage of bimodal annual precipitation pattern to produce high quality pigeonpea [*Cajanus cajan* (L.) Millsp.] forage during the noncrop period between winter wheat (*Triticum aestivum* L.) harvest and seeding. Pigeonpea can be grown after a mid-June winter wheat harvest since pigeonpea uses precipitation received from wheat harvest to late September and pigeonpea has a root system that allows it to use soil water below the effective rooting depth of wheat. In the central Great Plains, water-use efficiency of winter wheat was improved 18 to 56% by including broadleaf crop in a grass-based rotation. Cropping systems in the northern Great Plains tend to be more diverse, and research at Mandan, ND, suggests that seed yield of flax (*Linum usitatissium* L.) can be tripled with a safflower (*Carthamus tinctorius* L.)–flax crop sequence vs. a flax–flax crop sequence. Great Plains cropping systems of the future will not only need to take advantage of crop sequences through synergism, but also take advantage of the interactions associated with diversity in space (polyculture).

Crop production systems over the years have become more specialized, standardized, and simplified to meet the increasing needs of the industrialized food system (Kirschenmann, 2002). These systems have approached or are currently approaching monoculture systems and need to incorporate technological advances that include new knowledge on management, genetics, and engineering to be sustainable in the long term. Current crops have evolved and been adapted from wild plants to meet man's needs. These crops are characterized by synchronous tillering, flowering, and maturity and in most instances by determinate plant growth (Oka, 1982). Many of these crops have been adapted to monoculture systems and produce optimum crop yields with high inputs from fertilizer, pesticides, and fossil fuels. How we use these crops in a diverse cropping system and their sequence and management determine what resources may become inherent to a cropping system, if the system is to be sustainable.

One problem associated with cropping systems is how to choose and sequence crops to develop the inherent internal resources of the system while taking advantage of external resources such as weather, markets, government programs, and new technology (Tanaka et al., 2002). To better understand and appreciate cropping systems and the crops used in them, we must consider the evolution that crops and cropping systems have gone through. Our goal is to stimulate researchers to think at the systems level when conceptualizing and developing intensive-diverse cropping systems. Our objectives were twofold: (i) evaluate the impact of crop sequencing on use of precipitation and (ii) show how crop sequencing can accentuate synergistic interactions among crops in the Great Plains.

IMPROVEMENTS IN FALLOW

Fallow was one of the first strategies producers used to help stabilize crop yields during drought periods in the Great Plains (Black et al., 1974). During fallow, neither crops nor weeds are allowed to grow since the goal of fallow is storing precipitation in the soil. Early fallow techniques used inversion implements to create a condition know as "dust mulch" fallow. As fallow techniques improved from dust mulch to no-till, where all crop residues remain on the soil surface, precipitation storage efficiency increased from 20 to 40% (Greb, 1983). While significant progress has been made toward increased soil water storage during fallow, fallow efficiencies seldom exceed 40% (Greb, 1983; Unger, 1984; Tanaka and Aase, 1987; Dao, 1993). This means at least 60% of the precipitation received during fallow is lost to evaporation. Increased residue levels on the soil surface during no-till or minimum-till fallow have helped reduce evaporation and control soil erosion, but residue levels in the Great Plains seldom exceed 6000 kg ha^{-1} (Greb, 1983; Jones and Popham, 1997; Tanaka and Anderson, 1997). At the present, soil and water conservation practices for soil water storage during fallow are at their practical limits. Therefore, it is obvious that a new approach is needed to more efficiently use precipitation.

By diversifying the wheat–fallow rotation in the central Great Plains, Farahani et al. (1998b) hypothesized and found that fallow efficiency increased to 47% by including summer annual crops into a wheat–fallow rotation to create a wheat–summer annual crop–fallow rotation. They also noted that precipitation use efficiency, the percentage of annual precipitation accessible for crop growth through evapotranspiration, approached 75% for continuous annual cropping systems compared with less than 45% for winter wheat–fallow system (Farahani et al., 1998a).

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Diverse cropping systems also provide an opportunity for green fallow, which is growing a crop for soil improvement rather than for grain harvest. Previously, the purpose of green fallow was to produce crop residues for erosion control and biological N for future crop use in wheat–fallow rotations (Brown, 1964). The focus on residue and N production led to excessive water use and lower wheat yield. However, we suggest that green fallow may be beneficial to the soil resource by influencing nutrient cycling and microbial activity, especially in diverse cropping systems. With this goal, green fallow may need to be grown for only 6 to 8 wk before terminating growth. Cropping system research at Akron, CO, showed that a 12- to 14-mo fallow was detrimental to both nutrient cycling (Bowman et al., 1999) and microbial community functioning (Wright and Anderson, 2000), even in rotations where three crops were grown before fallow. Thus, short-term green fallow may improve crop growth by its impact on soil functioning.

Taking into account precipitation frequency and distribution, green fallow legumes can be managed so that soil water content does not differ between fallow and 6 to 8 wk of legume growth (Biederbeck and Bouman, 1994; Tanaka et al., 1997). While the 6 to 8 wk of legume growth may not produce large quantities of biological N, N use efficiency by a succeeding wheat crop can be increased because of disease suppression and growth-promoting substances released from decaying legume residues that promote healthier wheat roots (Stevenson and Van Kessel, 1996).

INTENSIVE CROPPING SYSTEMS

Dryland cropping systems with more diverse crops and less fallow per unit of time (diversity in time) may be one strategy to make more efficient use of precipitation lost to evaporation during fallow (Peterson et al., 1996). Diversifying crops in cropping systems favors synergism or the "rotation effect," where rotating crops generally increases yield compared with monoculture (Porter et al., 1997). We define synergism as the greater effect of two components than would be expected from summing the effect of each component alone. Cropping systems that efficiently exploit the internal resources of a system take advantage of crop sequences through synergism. To develop these intensive-diverse cropping systems may be difficult since farm specialization by regions has been highly influenced by climate, soil properties, economic conditions, and crops (Kirchmann and Thorvaldsson, 2000).

We have chosen three research sites as examples to illustrate the potential for improved precipitation use and the role synergism may play in crop production. In general, the sites vary drastically and, according to Stewart and Robinson (1997), have an aridity index in the semiarid zone, $0.20 < P/\mathrm{ETP} < 0.50$, where P is precipitation and ETP is the calculated potential evapotranspiration. The aridity index for the three locations were Mandan, ND, about 0.32; Akron, CO, about 0.24; and El Reno, OK, about 0.43 using criteria by Stewart and Robinson (1997).

In the southern Great Plains, crop–livestock systems have been able to use precipitation more efficiently through the development of a relay forage system that includes pigeonpea for forage during the summer months of the traditional winter wheat system (Rao et al., 2002a, 2002b). They examined precipitation (Fig. 1) and temperature (Fig. 2) patterns and took advantage of the potential production niche in temperature and precipi-

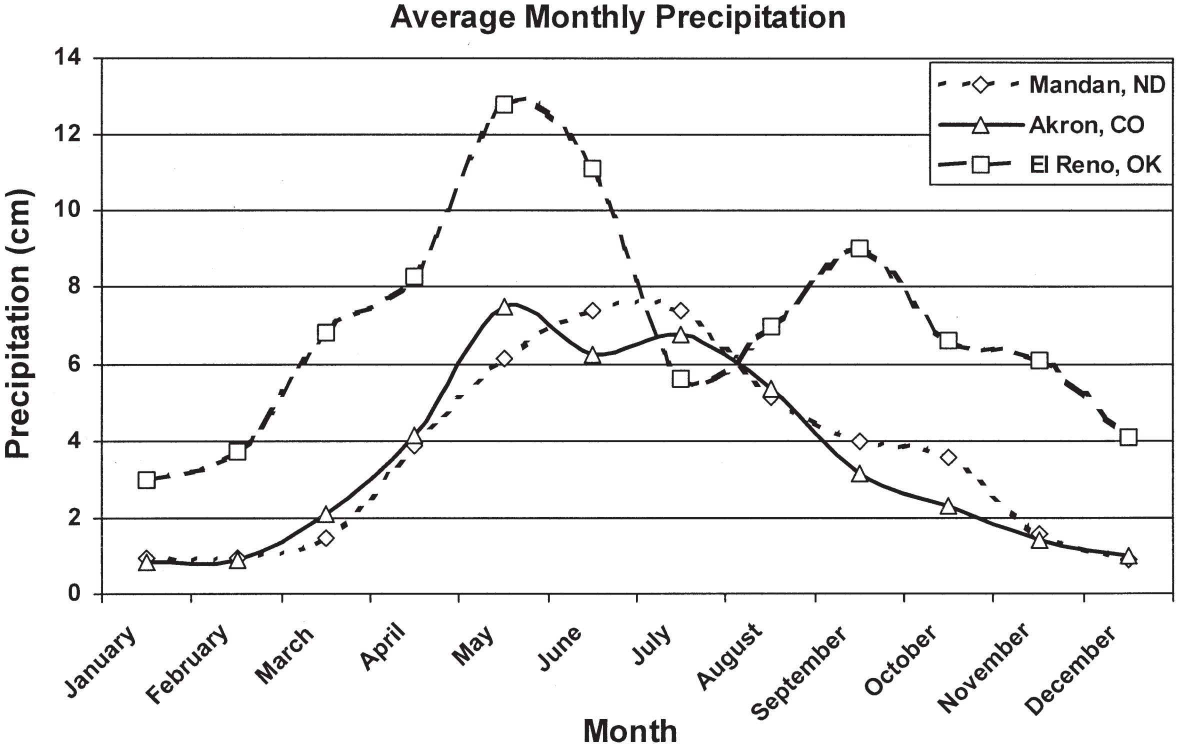

Fig. 1. Long-term monthly precipitation for Mandan, ND; Akron, CO; and El Reno, OK.

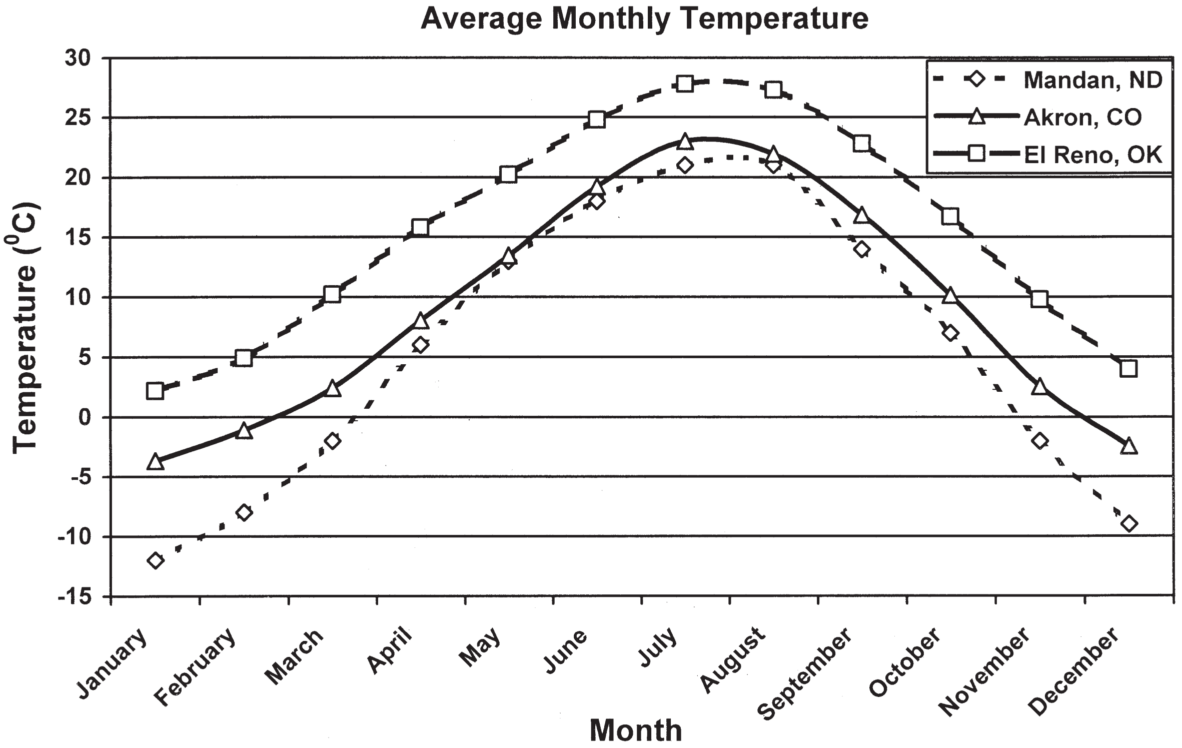

Fig. 2. Long-term average monthly temperature for Mandan, ND; Akron, CO; and El Reno, OK.

tation at El Reno, OK, to produce a winter wheat crop and a pigeonpea forage crop after winter wheat harvest in mid-June. The deep-rooting pigeonpea crop uses the soil water below the effective rooting depth of wheat as well as precipitation from mid-June to late September. Winter wheat can be seeded after pigeonpea since the increased precipitation (Fig. 1) in September provides sufficient moisture to replenish the soil water at the 0- to 15-cm soil depth (data not shown) as well as at the 15- to 30-cm depth (Fig. 3). Soil water content (Fig. 3) was measured using time domain reflectometer (TDR). Precipitation for October and November in 1998 was 17.1 cm greater than the 25-yr average. Total precipitation for 1998 was 12.6 cm below the 25-yr average. Because of the increased precipitation in September, winter wheat can be established in early October. In the past, precipitation received from mid-June to late September was subject to high evaporative losses associated with high temperatures during this time period (Fig. 2). Pigeonpea enhances the succeeding winter wheat crop, which may not be due to precipitation or improved water-use efficiency, but due to pigeonpea and pigeonpea residue; and Rao et al. (2002b) are investigating other winter wheat–summer legume rotations that may have potential for the southern Great Plains.

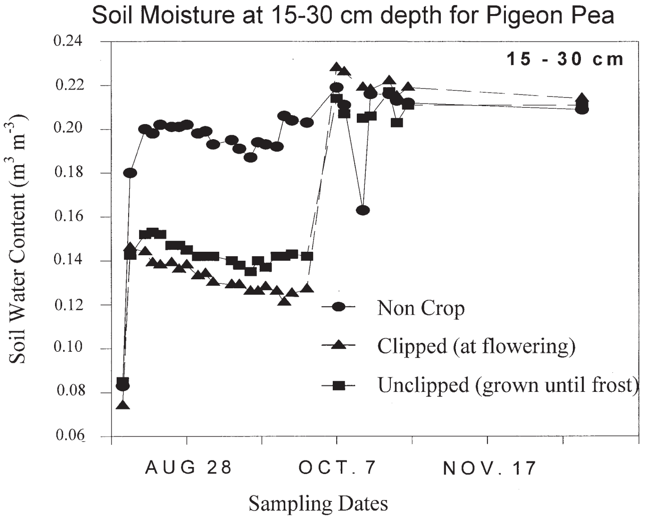

Fig. 3. Soil water content at the 15- to 30-cm depth for clipped and unclipped pigeonpea forage treatments when compared with a noncrop treatment at El Reno, OK, in 1998.

The sequence of crops in cropping systems results in interactions among crops that are synergistic, such as those demonstrated by Rao et al. (2002b) with pigeonpea in the southern Great Plains. Therefore, greater attention must be paid to synergistic and symbiotic relationships associated with crop sequencing to better understand the relationships and determine how to employ them in sustainable cropping systems in the Great Plains. Cropping systems that specialize in one or two crops provide minimal or no plant diversity to a system and ultimately lead to biological and physical soil property degradation and in many instances to soil chemical property degradation (Kirschenmann, 2002). For sustainable cropping systems to promote greater soil biological, physical, and chemical property enhancement, more diverse and adapted crops are needed. Examples of the benefits of crop diversity and synergism have been shown in the central Great Plains (Anderson et al., 1999). For example, water-use efficiency of winter wheat increased 56% when following dry pea (*Pisum sativum* L) compared with

Table 1. Pea synergism to winter wheat yields at Akron, CO (adapted from Anderson, 2002).

	Cropping system†	
	W–C–M	W–CP
Yield, kg ha^{-1}	1020	1800
Water use, cm	25	28
WUE, kg ha^{-1} cm^{-1}‡	41	64

† W = winter wheat, C = corn, M = proso millet, and P = dry pea.
‡ WUE = water use efficiency.

Table 2. Sunflower impact on water use efficiency (WUE) of winter wheat in a 4-yr cropping system at Akron, CO (adapted from Anderson, 2002).

	Cropping system†	
	W–C–M–F	W–C–S–F
Yield, kg ha^{-1}	3000	2820
Water use, cm	41	33
WUE, kg ha^{-1} cm^{-1}	73	86

† W = winter wheat, C = corn, M = proso millet, S = sunflower, and F = fallow.

proso millet (*Panicum miliaceum* L.) (Table 1). Similarly, when sunflower (*Helianthus annuus* L.) replaced proso millet in a winter wheat–corn (*Zea mays* L.)–proso millet–fallow system (Anderson, 2002), water-use efficiency of winter wheat increased 18% (Table 2). Anderson (1998) has also found that increased crop diversity and synergism have improved precipitation use for cropping systems from 42% for a wheat–fallow system to 65% for a wheat–corn–sunflower–fallow or a wheat–corn–millet–fallow system.

Adding dry pea and sunflower to the cropping system changed the system from one that had only grass plants to one that included broadleaf plants. Composition of the plant community in cropping systems influences the diversity of soil organisms and soil environment. Soil organisms and soil environmental changes that result from diverse plant communities can alter the internal resources of cropping systems: soil biological, physical, and chemical properties (Kennedy, 1995). Limited attention has been given to the efficient exploitation of synergism in cropping systems built on crop sequences or cropping patterns that are beneficial to succeeding crops (Francis, 1986).

In the northern Great Plains, researchers are starting to evaluate the influence of synergism on succeeding crops (Tanaka et al., 2002) through development of a dynamic cropping system concept that attempts to effectively exploit synergism by sequencing crops in cropping systems. A crop-by-crop residue matrix method (Tanaka et al., 2002) was used to evaluate the synergism among 10 crops that included canola (*Brassica napus* L.), crambe (*Crambe abyssinica* H.), flax, dry pea, dry bean (*Phaseolus vulgaris* L.), safflower, soybean [*Glycine max* (L.) Merr.], sunflower, spring wheat, and barley (*Hordeum vulgare* L.). A multidisciplinary team approach was used to determine as many of the causative factors of crop sequencing as possible for no-till cropping systems, and the practical implications of the research were made available to producers on a CD-ROM (Krupinsky et al., 2002b).

In 1999, seed yield for canola, sunflower, and barley was not significantly influenced by any of the 10 previous crops (Table 3). On the other hand, seed yields of 7 out of 10 crops (crambe, dry bean, dry pea, flax, safflower, soybean, and spring wheat) were significantly influenced by the previous crop. For safflower and flax, seed yields were suppressed when these crops were seeded on their own respective residues. The seed yields for 1999 suggest that synergism among crops in sequence, and in some instances antagonism, occurs even in years when growing season precipitation (May through August) is above average (181% of the long-term average of 26.0 cm).

In 2000, May through August precipitation was about average (104% of the long-term average of 26.0 cm). Previous crop influenced seed yield for more crops in 2000 than in 1999 (Tables 3 and 4). Nine of the 10 crops (canola, crambe, dry bean, flax, safflower, soybean, sunflower, spring wheat, and barley) were influenced by the previous crop (Table 4). Dry pea was the only crop in 2000 not influenced by the previous crop. For 6 of the 10 crops, the lowest seed yield resulted when the previous crop was either canola or crambe. Seed yields for canola, flax, sunflower, spring wheat, and barley were significantly suppressed when these crops were seeded on their own respective crop residues. The best seed yield for 7 of the 10 crops occurred when the previous crops were sunflower, safflower, or flax. In a year with about average growing season precipitation, it became apparent that sunflower, safflower, or flax as the previous crop synergizes the seed yield of canola, crambe, dry bean, flax, safflower, spring wheat, and barley.

Table 3. Seed yield of canola, crambe, dry bean, dry pea, flax, safflower, soybean, sunflower, spring wheat, and barley as influenced by crop sequences in 1999 at Mandan, ND.

	1999 Seed yield									
Previous crop	Canola	Crambe	Dry bean	Dry pea	Flax	Safflower	Soybean	Sunflower	Spring wheat	Barley
	kg ha^{-1}									
Canola	1413a	1688bc	1241ab	2335b	1639ab	1012a	2032bc	1597a	3591ab	4680a
Crambe	1290a	1769bc	968abc	2148b	1605ab	869a	2039bc	1738a	3217ab	4981a
Dry bean	1400a	1559c	1175abc	2550ab	1521ab	888a	2237ab	1609a	3308ab	4189a
Dry pea	1530a	2362a	1216ab	2581ab	1430ab	1042a	2112abc	1768a	3114ab	4674a
Flax	1543a	1791bc	1131abc	2660ab	690c	867a	1995bc	1769a	3651a	4617a
Safflower	1220a	1518c	816bc	2532ab	1387b	458b	1735c	1196a	3031b	4579a
Soybean	1239a	1649bc	1098abc	2300b	1752a	886a	2501a	1498a	3466ab	4363a
Sunflower	1363a	1763bc	989abc	2610ab	1625ab	760ab	1951bc	1306a	3388ab	4852a
Spring wheat	1312a	1879bc	758c	3045a	1571ab	1026a	1844bc	1499a	3428ab	4728a
Barley	1480a	2025ab	1332a	2549ab	1641ab	1106a	2090bc	1758a	3385ab	4482a
Crop grand mean	1379	1800	1072	2531	1486	891	2054	1574	3358	4614
LSD 0.05	378	425	450	596	339	368	404	726	579	832

Table 4. Seed yield of canola, crambe, dry bean, dry pea, flax, safflower, soybean, sunflower, spring wheat, and barley as influenced by crop sequences in 2000 at Mandan, ND.

	2000 Seed yield									
Previous crop	**Canola**	**Crambe**	**Dry bean**	**Dry pea**	**Flax**	**Safflower**	**Soybean**	**Sunflower**	**Spring wheat**	**Barley**
	kg ha^{-1}									
Canola	1125c	242c	1522bc	2935a	868b	588c	2226abc	1120ab	3319abc	3282abc
Crambe	1418ab	1072ab	1038c	3442a	959ab	882bc	1540c	870b	3592a	3850a
Dry bean	1660a	929b	1883ab	3386a	1160ab	847bc	1770bc	1545a	3505ab	3663ab
Dry pea	1480ab	979b	2111ab	2835a	1033ab	1172ab	2058abc	1537a	3367ab	3628ab
Flax	1430ab	1303ab	1978ab	3239a	415c	1367a	2296abc	1336ab	3349abc	3879a
Safflower	1576a	922b	1914ab	3466a	1317a	754bc	1774bc	1004ab	3673a	3568ab
Soybean	1306bc	1129ab	2018ab	3744a	1284a	913abc	2529ab	1181ab	3000bc	3416abc
Sunflower	1422ab	1540a	2137a	2888a	1246ab	1145ab	2779a	883b	3212abc	3192bc
Spring wheat	1476ab	1150ab	2010ab	3308a	1146ab	1174ab	2122abc	1306ab	2847c	3748ab
Barley	1585a	1297ab	1826ab	3277a	1218ab	1183ab	2394abc	1201ab	3267abc	2905c
Crop grand mean	1448	1056	1844	3252	1064	1002	2149	1198	3313	3513
LSD 0.05	269	530	600	1002	398	481	886	559	513	614

FUTURE CROPPING SYSTEMS

Present cropping systems rely on extensive use of fertilizer and pesticides and the low cost of fossil fuel energy. Future challenges for cropping systems will exploit synergism through crop sequencing to improve crop yields without additional inputs and to reduce deterioration of the environment (Kirschenmann, 2002). Alternating crops or crop varieties annually (diversity in time) has been a way of adapting synergism to cropping systems. These cropping systems have reduced deterioration of soil quality factors and buildup of pests and diseases by creating a diverse soil organism population that benefits succeeding crops (Oka, 1982). Cropping systems of the future not only need to take into consideration crop sequences that promote synergism among crops, but also that adapt diversity in space (polyculture and/or relay cropping) to the systems (Fig. 4). It is imperative we learn how to manage these interspecies and relay cropping systems to learn about the principles and processes involved in interactions in these complex systems since most of our current knowledge is from monoculture systems where high inputs such as pesticides and fertilizers have been used (Francis, 1986). Based on the research at Mandan, one can speculate that diverse-intensive cropping systems have the potential to improve crop production without increased inputs and need to include cool-season grasses and broadleaf crops and also warm-season broadleaf crops to take advantage of synergism among crops. Inclusion of warm-season grasses at Mandan may synergize cool-season crops, but research is needed. Each crop or a closely related crop species should not be grown more than every 4 yr because of increased pest problems (Bailey et al., 2001; Krupinsky et al., 2002a). We will need to know how to adapt these systems at the producer level to take advantage of potential internal mechanisms for soil renewal as we enter an era of greater environmental awareness.

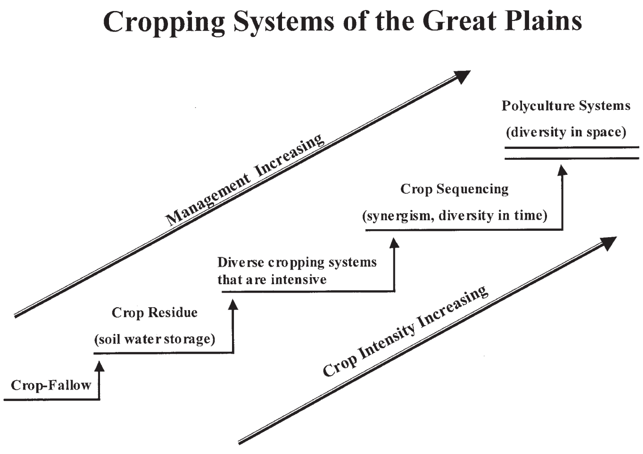

Fig. 4. Great Plains cropping systems evolution as influenced by management and crop intensity.

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