Crop Choices and Rotation Principles

R. LOUIS BAUMHARDT
USDA-ARS
Bushland, Texas

RANDY L. ANDERSON
USDA-ARS
Brookings, South Dakota

Dryland cropping systems must integrate planting sequences or rotations with the selection of a crop to minimize production risk, for example, crop failure, and protect the soil resource while competing within an aggressively contested world commodity market. Erratic precipitation common to semiarid climates and the volatile nature of commodity markets further exacerbate crop selection and rotation implementation that profitably meet the universal goal of protecting natural resources. In this chapter, we introduce and contrast various plant adaptations that permit a best crop choice for growth under dryland conditions based on the suitability of physiological and agronomic characteristics. Cropping systems used with dryland production in semiarid regions must optimize precipitation use and, therefore, implement the sequence of growing crops and intervening fallow (idle) periods to increase storage of precipitation as soil water. In addition, crop selections must produce rotations that optimize cropping intensity while ameliorating weed, insect, and disease pressures. We present various cropping systems to illustrate the mechanics of crop-fallow sequences to conserve soil and water resources in a semiarid climate and suitable crop rotations to enhance overall cropping system productivity, profitability, and production risk control. Although water conservation is a critical concern to crop production under semiarid dryland conditions, we describe and contrast several other rotation benefits, for example, dinitrogen (N₂) fixation.

PHYSIOLOGY OF CROPS ADAPTED TO DRYLAND PRODUCTION

Sustainability under dryland cropping conditions is often governed by how well crop water demands are matched by the water resources. That is, crops must be able to efficiently use precipitation and stored soil water, while cropping sequences or rotations must provide suitable opportunities for precipitation storage.
as soil water. In contrast to humid or subhumid regions, precipitation is often erratic in both quantity and temporal distribution throughout semiarid regions; however, definite annual patterns emerge to reveal periods of more frequent rainfall, that is, "rainy" periods. Moreover, it is during these typically rainy periods that many crops must be established to grow and ultimately produce a mature commodity. Successful dryland cropping systems have resulted from the selection of crops to efficiently use water for grain and forage production within those crop sequences that effectively use fallow periods to conserve precipitation as soil water while minimizing any cumulative weed, insect, and disease pressures.

Dryland cropping systems in semiarid regions must rely on erratic rainfall to provide necessary planting moisture. Insufficient and poorly timed rain often delays planting and, consequently, shortens the growing season; therefore, the required time for a crop to grow and mature is an underemphasized crop adaptation. For example, cotton (*Gossypium hirsutum* L.) is well adapted to dryland growing conditions, but requires a relatively long and warm growing season. Although cotton production is generally confined to the warmer climates, it often fails to achieve economic yields in areas where the growing season duration is made marginally adequate because of planting delays due to limited precipitation or cool early season soil temperatures. Alternatively, some crops can be cultured so that the time of peak water demand occurs when typical seasonal precipitation would provide sufficient water to meet the mid-summer crop water use. Determinant crops such as corn (*Zea mays* L.), which have an established critical water requirement period, for example, tassel; can be managed to limit production risk by varying planting date to synchronize crop water demand with expected precipitation.

**Crop Physiological Adaptation**

Dryland cropping systems rely entirely on precipitation to supply water for crop growth; however, limited water availability presents a common dryland production problem that is often challenged through selection of crops having a reduced water requirement. Blum (1985) noted that crops adapted for lower water requirements often possessed physiological traits designed to minimize water vapor transport, that is, transpiration. The plant canopy accounts for virtually all transpiration from the leaf surface boundary to the atmosphere, which is largely driven by the interception of radiant energy. As the amount of intercepted radiant energy increases, either the leaf temperature or the amount of evaporation (latent heat transport) must increase. To reduce energy interception and, consequently, transpiration; some crops have evolved away from planar (horizontal) canopies toward erect (vertical) leaves, while other crops have evolved leaf-rolling mechanisms to reduce the exposed leaf surface area.

Additionally, the difference in vapor pressure between the leaf surface and the atmosphere, that is, the vapor pressure deficit, produces a gradient that draws water from plants as transpiration. In van den Honert's (1948) description of water transport in plants as a catenary process, he concluded that the "master-process" of gaseous transport largely dictates the potential plant water use. Models of plant water status illustrate that increasing the leaf surface resistance to vapor transport,
consequently, lowered crop water use (Fernandez and McKree, 1991). Therefore, crops have evolved various strategies to increase resistance to vapor transport including: rolling the leaf edges inward, sunken stomata, and pubescent (hairy) leaves (Blum, 1985). Other practical plant adaptations to offset drought stress under dryland conditions rely on the development of extensive root systems, that explore a larger volume of soil for water, as observed for sunflowers (*Helianthus annuus* L.) (Unger, 1990; Anderson et al., 2003), or an early maturing characteristic to avoid late summer water stress such as with winter or cool-season annuals, that is, wheat (*Triticum aestivum* L.).

Although many factors govern the crop adaptability to manage water stress, one crucial factor for increasing dry matter produced from transpired water or the water-use efficiency (WUE) is the metabolic pathway for fixing carbon (C). Plants, for example, grain sorghum [*Sorghum bicolor* (L.) Moench], commonly found in tropical and arid regions achieve optimum growth with day time temperatures of 25 to 40 °C by using the C₄ metabolic pathway (Jones, 1992) to more efficiently produce dry matter during hot dry summers with limited water resources. In contrast, plants like wheat use the C₃ metabolic pathway to achieve optimum growth in temperate regions with day time temperatures of 15 to 30 °C. Crop WUE determined from the transpiration ratio (TR) calculated as the mass of water transpired divided by the total dry matter produced (TDM) is listed by increasing TR (decreasing efficiency) for various crops in Table 5–1. The TRₒDₘ (column 1) indicates that, crops with C₄ metabolic pathways transpire less water for TDM production, followed by cereals, oil and root crops, and legumes. The crop transpiration ratio for dry matter production by corn, grain sorghum, millet (*Chaetochloa italica* L.) and proso millet (*Panicum miliaceum* L.) requires about half as much water as wheat, that is, TRₒDₘ of various crops divided by the TRₒDₘ for wheat, TRₒₘ (column 2), varied from 0.48 to 0.63. Based solely on the TRₒDₘ, the C₄ crops would be better adapted to dryland production than practically all other crops because of more efficient water use. Improved WUE with C₄ is further demonstrated by the lower crop yield based transpiration ratio, TRₒₚ (column 3), calculated as the ratio of water use to commodity yield. Compared to TRₒDₘ, the TRₒₚ did increase more for corn than for the other C₃ crops. Consequently, the corresponding ratio of TRₒₚ taken with respect to TRₒₙ for wheat, TRₒₚ (column 4), indicated that some other crops (cereals and legumes) are very well adapted to dryland production, for example, barley (*Hordeum vulgare* L.) or cowpea (*Vigna sinesis* L.). Both wheat and cotton, C₃ crops, are considered to be well adapted to semiarid crop production in contrast to corn, a C₄ crop; therefore, the degree of crop sensitivity to water deficits ultimately determines its overall suitability for use in dryland cropping systems.

Crop sensitivity to water deficits, often encountered in dryland production systems, will act to reduce yield independently of transpiration efficiencies. Doorenbos and Kassam (1979) used crop yield response factors, *Kₚ*, to quantify the sensitivity of various crops to available water by growth stage and averaged during the season. They related the ratio of actual to maximum evapotranspiration, *ETₚ/ETₘ*, with the yield achieved under water deficits *Yₚ* relative to the maximum yield *Yₚ* when the corresponding water available was adequate for the prevailing growing conditions as a ratio, *Yₚ/Yₚ*, using the equation:
Table 5-I. Crop transpiration ratio (TR) calculated as the water transpired divided by the aboveground total dry matter (TDM) or harvest product, YIELD, (Schantz and Piemeisel, 1927), its comparison with wheat TDM, TR_{wet} or wheat YIELD, TR_{wet}, and the seasonal yield response factor, K_y, (Doorenbos and Kassam, 1979) of selected agronomic crops (listed by decreasing TR_{TDM}). Crops with C_4 metabolic pathways have higher TR_{TDM} and TR_{YIELD}. The K_y increased with increasing crop sensitivity to drought (water deficits) resulting in yield reductions.

<table>
<thead>
<tr>
<th>Crop</th>
<th>TR_{TDM} kg kg^{-1}</th>
<th>TR_{wet} kg kg^{-1}</th>
<th>TR_{YIELD} kg kg^{-1}</th>
<th>TR_{YIELD} kg kg^{-1}</th>
<th>Seasonal K_y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proso millet (Panicum miliaceum L.)</td>
<td>267</td>
<td>0.48</td>
<td>567</td>
<td>0.30</td>
<td>–</td>
</tr>
<tr>
<td>Millet (Chaetochloa italica L.)</td>
<td>285</td>
<td>0.51</td>
<td>959</td>
<td>0.51</td>
<td>–</td>
</tr>
<tr>
<td>Grain sorghum (Sorghum bicolor (L.) Moench)</td>
<td>304</td>
<td>0.55</td>
<td>868</td>
<td>0.46</td>
<td>0.9</td>
</tr>
<tr>
<td>Corn (Zea mays L.)</td>
<td>350</td>
<td>0.63</td>
<td>1405</td>
<td>0.75</td>
<td>1.25</td>
</tr>
<tr>
<td>Barley (Hordeum vulgare L.)</td>
<td>518</td>
<td>0.93</td>
<td>1241</td>
<td>0.66</td>
<td>–</td>
</tr>
<tr>
<td>Wheat (Triticum aestivum L.)</td>
<td>557</td>
<td>1.00</td>
<td>1872</td>
<td>1.00</td>
<td>1.0–1.15</td>
</tr>
<tr>
<td>Cotton (Gossypium hirsutum L.)</td>
<td>568</td>
<td>1.02</td>
<td>–</td>
<td>–</td>
<td>0.85</td>
</tr>
<tr>
<td>Cowpea (Vigna sinesis L.)</td>
<td>569</td>
<td>1.02</td>
<td>1632</td>
<td>0.87</td>
<td>–</td>
</tr>
<tr>
<td>Potato (Solanum tuberosum L.)</td>
<td>575</td>
<td>1.03</td>
<td>2101</td>
<td>1.12</td>
<td>1.1</td>
</tr>
<tr>
<td>Sunflower (Helianthus annuus L.)</td>
<td>577</td>
<td>1.03</td>
<td>–</td>
<td>–</td>
<td>0.95</td>
</tr>
<tr>
<td>Soybean (Glycine max (L.) Merr.)</td>
<td>715</td>
<td>1.28</td>
<td>1974</td>
<td>1.05</td>
<td>0.85</td>
</tr>
<tr>
<td>Alfalfa (Medicago sativa L.)</td>
<td>844</td>
<td>1.52</td>
<td>–</td>
<td>–</td>
<td>0.7–1.1</td>
</tr>
</tbody>
</table>

† Indicates C_4 metabolic type plants.
‡ Seasonal yield reduction sensitivity: low K_y <0.85, medium low K_y 0.85–1.0, medium high K_y 1.0–1.15, high K_y >1.15.

\[
\frac{Y_a}{Y_m} = 1 - \left[ \left( 1 - \frac{ET_a}{ET_m} \right) \times K_y \right]
\]  

[1]

For example, if \( ET_a \) equals \( ET_m \), then the ratio of \( Y_a/Y_m \) is one or \( Y_a \) equals \( Y_m \) regardless of mean crop sensitivity to available water, \( K_y \). When \( ET_a \) is half of \( ET_m \) and crop sensitivity to available water is at unity, \( K_y = 1.0 \), then \( Y_a \) is similarly reduced to half of potential yield. When the crop is water deficit sensitive, \( K_y = 1.5 \), or insensitive, \( K_y = 0.7 \), then yield for \( ET_a \) equal to half of \( ET_m \) would be reduced to:

\[
1 - \left[ \left( 1 - \frac{1}{2} \right) \times 1.5 \right] = 0.25 = \frac{Y_a}{Y_m} \text{ and } 1 - \left[ \left( 1 - \frac{1}{2} \right) \times 0.7 \right] = 0.65 = \frac{Y_a}{Y_m}
\]

or 0.25 of the potential yield for the water deficit sensitive crop and 0.65 for the water deficit insensitive crop, respectively.
Mean seasonal yield response factors, $K_y$, (Table 5–1) illustrate the relative crop sensitivity to water deficits and, often, supersede transpiration ratio as the principal discriminator for dryland crop selection. The indeterminate crop, cotton, has a midrange transpiration ratio (568 kg kg$^{-1}$), but is comparatively insensitive ($K_y = 0.85$) to water deficits, thus, sustaining smaller yield reductions than other more water-use efficient crops that are also more sensitive to water deficits (Doorenbos and Kassam, 1979). In contrast to cotton, corn efficiently transpires water to produce dry matter (350 kg kg$^{-1}$), but corn, unlike cotton, is highly sensitive to water deficits (seasonal average $K_y = 1.25$) and must have water during critical growth stages to yield grain. Crop conversion of water to agronomic yield, that is, transpiration ratio serves as a guide in selecting suitable crops for semiarid production; however, crop sensitivity to water stress is equally important for sustained dryland crop production.

Suitability of a crop for use in various dryland rotations must integrate its WUE or transpiration ratio, crop sensitivity to water deficit or yield response factors ($K_y$), and the prevailing or expected climatic conditions. Dryland production risk in climatic regions where expected precipitation consistently meets crop demand is frequently managed using more drought sensitive crops with higher efficiency transpiration ratios. Corn is successfully used in rotations implemented throughout the northern Great Plains because limited water stress occurs during sensitive growth stages. In contrast, corn is not generally grown under dryland conditions on the southern Great Plains because the expected precipitation is inadequate to meet the crop water of demand during the entire growing season, but, especially, during the flowering period when $K_{y-f} = 1.5$ (Doorenbos and Kassam, 1979). Alternatively, when the growing season is sufficiently long, cotton and grain sorghum are often selected for dryland rotations because of similarly low mean water deficit sensitivities ($K_y = 0.85–0.90$); however, grain sorghum has a significantly better transpiration ratio. Indeterminate crops can distribute drought stress during a longer growing season and extended reproductive period, which increases the opportunity to use seasonal precipitation. Cotton and soybean ($Glycine max$ (L.) Merr.) have similar mean crop sensitivity to seasonal water deficit ($K_y = 0.85$), but the greater sensitivity of soybean to water deficits incurred during flowering and pod formation and fill often eliminates it from dryland cropping sequences.

**Crop Adaptation and Rotation Requirements**

Dryland crop rotation sequences are often selected to meet specific production goals or conservation purposes, which, in turn, define optimum crop adaptation characteristics to meet the rotation requirements. Cropping sequence goals often include: (i) increasing the total mature commodity yield, (ii) producing a forage product for animal harvest, or (iii) providing green fallow residues that benefit the soil physical and chemical properties or reduce soil erosion. For example, wheat cropping systems are often adapted to meet forage production goals to avoid yield reduction caused by shortages in expected precipitation or available soil water by shortening the growing season. Crop susceptibility to water deficits, $K_y$, varies with growth stage and is, generally, smallest during the vegetative
Table 5-2. Amount of residue produced by fall planted spring cereals, chemically terminated winter wheat, and bare soil at Lubbock, TX. Infiltration amount and rate into bare soil, determined using the methods of Baumhardt and Wendt (1988), were significantly \( P = 0.05 \) less than for any residue crop.

<table>
<thead>
<tr>
<th>Fall planted crop</th>
<th>Residue amount</th>
<th>Infiltration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mg ha(^{-1})</td>
<td>Amount</td>
</tr>
<tr>
<td>Bare</td>
<td>0</td>
<td>51.4</td>
</tr>
<tr>
<td>Spring-barley</td>
<td>1.1</td>
<td>58.3</td>
</tr>
<tr>
<td>Spring-oat</td>
<td>1.2</td>
<td>62.9</td>
</tr>
<tr>
<td>Spring-wheat</td>
<td>1.1</td>
<td>62.5</td>
</tr>
<tr>
<td>Terminated winter wheat</td>
<td>1.3</td>
<td>61.8</td>
</tr>
<tr>
<td>LSD</td>
<td>0.6</td>
<td>6.4</td>
</tr>
</tbody>
</table>

growth period, for example, winter wheat \( K_{yv} \) vegetative growth was 0.2 compared to a 1.0 average during the entire growing period (Doorenbos and Kassam, 1979). Therefore, increased crop productivity goals may be met by using rotation sequences that exploit only the vegetative growth of crops that are cultured to produce forages harvested as hay, or by grazing livestock.

Crop residues are generally accepted as the best resource for protecting soil from water or wind erosion. Both soybean and cotton produce a limited amount of residue cover; therefore, residue-producing crops are typically included in an alternating annual crop rotation sequence to meet soil conservation goals, for example, grain sorghum with cotton and corn with soybean. Keeling et al. (1989) describe an alternative cropping sequence with a primary rotation goal of producing a soil-conserving wheat residue intercrop that is chemically terminated (Plate 5-1). The wheat residues protect against wind erosion, but not at the expense of eliminating cotton as the principal summer cash crop. Also, cereal grain crops normally adapted for spring culture were seeded in the fall for vegetative growth, only, and produced needed residues to protect the soil (Bilbro and Fryrear, 1985). Utilizing spring cereals in this way generated as much residue as chemically terminated winter cereals (Table 5-2). The resulting residue cover was adequate to protect the soil from raindrop impact and significantly increase infiltration amount and rate after 1 h of rainfall compared to bare soil.

**CROP ROTATION, SEQUENCING MECHANICS**

Dryland cropping sequences in semiarid regions have been developed primarily to maximize crop system productivity and stability by minimizing crop water deficits within the available growing season. Rotations that do not provide adequate water for crop establishment or reproductive growth are quickly abandoned or modified to stabilize productivity. Example cropping sequences will illustrate the mechanics of crop rotations in order of decreasing intensity including: Double (two crops per year), Annual (crop every year), and Fallow (crop and idle period producing less than one crop per year).
Double Crop Rotations

When the growing season duration is sufficiently long, cropping sequences can accommodate two crops per year; however, precipitation must be sufficient and timely to meet crucial crop establishment and reproduction needs. These requirements are more consistently met by the rain-fed crop production in humid and subhumid regions compared with dryland production in semiarid regions. However, the dryland multiple crop sequences not receiving adequate, timely, precipitation to meet crop water demand may produce no more than a limited or partial harvest such as forage or soil-conserving residue.

Although cropping intensity is typically elevated to increase productivity and profitability, double crop rotations may also use green fallow, that is, legume or forage crop planted immediately after the principal cash crop, to improve soil organic matter and nutrient status or increase residue cover. Increasing the amount of protective residue produced in a cropping sequence can be critical for controlling soil erosion, as first mandated by the 1985 Food Security Act (Federal Register, 1987). For example, crops such as cotton produce too little protective residue to control wind erosion in the Texas South Plains (Bilbro and Fryrear, 1985). Keeling et al. (1989) describe a cereal crop green fallow system where wheat is seeded after cotton harvest during the fall and chemically terminated in the spring before replanting otherwise continuous cotton (Fig. 5–1). This practice is possible because, fall and spring rain is generally adequate to establish and grow wheat, and to recharge the soil water profile before cotton is planted. Residues produced with the terminated wheat–cotton rotation protect the soil from wind, increase rain infiltration, and limit seedling establishment risk from damaging rain (Baumhardt and Lascano, 1999). Alternatively, precipitation normally

Cotton-Terminated Wheat

![Cotton-Terminated Wheat Diagram](image)

Fig. 5–1. The terminated wheat–cotton rotation (diagramed with October at the top) begins with fall seeding of winter wheat following cotton harvest. Wheat is established and grown using fall and winter precipitation and chemically terminated in March at a height of about 150 mm 4 mo later to prevent competition with the annual cotton crop for soil water. The residue in place from mid-February to mid-May protects the soil from wind erosion. After a short, 2.5 mo, fallow period ending in mid-May, the principal cash crop, cotton, is established and grown during those months with the greatest probability for rain.
stored in the soil for establishment of the principal cash crop is redirected for the production of residue (Fig. 5–2). Baumhardt and Lascano (1999) reported crop establishment failures during years with below average spring or fall precipitation because of competition for water.

Competition between principal grain crops and green-fallowed legumes for soil water similarly reduced the net grain yield of the subsequently planted crops in studies at Akron, CO (Vigil and Nielsen, 1998) and Tribune, KS (Schlegel and Havlin, 1997). That is, when vetch was green-fallowed for progressively longer periods, Schlegel and Havlin (1997) noted that the corresponding increased soil water depletion decreased yields by an average of 19 kg mm$^{-1}$ for wheat and 12 kg mm$^{-1}$ for grain sorghum. Similarly, Vigil and Nielsen (1998) concluded that the negative effect of legume water use in competition with grain crops was not offset by N$_2$ fixation. Early terminated legume forage yields, however, appeared adequate to support livestock production without severely reducing wheat grain yield compared to an unfertilized control (Schlegel and Havlin, 1997).

**Livestock as Double Crop Rotations**

Cropping intensity is most easily increased by using livestock to harvest forage crops inter-seeded after conventional harvest of the principal cash crop.
Crop residue yield can be harvested as forage by livestock and marketed; thus, imparting management flexibility to the producer. Two examples are grazing legume forage double cropped after wheat as suggested by Schlegel and Havlin (1997) for the North American Great Plains and, in West Africa, cowpea that is seeded following grain sorghum harvest to produce protein-rich forage harvested as a composite hay. In temperate climates, the cowpea forage and sorghum residues (fodder) can be directly grazed after frost or chemical termination of the cowpea.

Livestock can also intensify annual crop production by permitting use of intervening cover crops as forage. That is, winter wheat can be seeded following harvest of a summer crop such as grain sorghum or cotton and harvested as winter forage. Cattle production systems in the Great Plains use wheat crop pastures and adjoining fields of sorghum residues as forage for grazing livestock. Wheat provides high quality palatable forage capable of meeting cattle protein, energy, and fiber demand when supplemented with dry hay or sorghum stubble (Shroyer et al., 1993). A stocking rate of 0.25 to 0.50 Mg live animal weight per hectare, can achieve daily gains of as much as 0.75 kg. In a review article on livestock grazing of wheat, Redmon et al. (1995) related the impact of grazing on grain production to crop recovery; however, any negative impact on grain yield may be ignored where grazing is the primary production goal.

**Annual Crop Rotations**

Annual cropping sequences typically consist of monocultures or alternate year rotations of suitable summer or winter crops grown with no intervening fallow period to interrupt production. Annual cropping sequences are found in regions with adequate precipitation and sufficient growing season duration to produce one dryland crop per year. Annual crop rotations occasionally include planting fallowed land out of sequence to take advantage of favorable growing conditions, that is, beneficial rain may be used by “opportunity cropping” to produce annual crops (Unger, 2001a). Opportunity cropping systems appear in regions where the growing season duration is sufficient, but precipitation is typically inadequate for stable annual cropping. These transformed crop rotations often include summer forage/grain crops like sorghum, cowpea, millet, or winter cereals because the produced biomass may be harvested early as forage or hay before the crop achieves physiological maturity and produces grain.

Annual winter wheat monoculture crop sequences have been grown regularly on the North American Great Plains. Wheat monocultures minimize the fallow period when water may be lost to evaporation; thereby, increasing the annual precipitation-use efficiency during a 10-mo growing season before repeating (Fig. 5–3). The use of livestock to graze the vegetative wheat during the winter months, although limited under dryland conditions, contributes to the desirability of this system. Grazing of wheat forage in this or related systems is critically dependent on timely grazing termination to preserve both wheat grain yield and residue production (Winter and Unger, 2001). Often, precipitation distribution favors summer crop production (e.g., much of the Great Plains receives approximately 60% of the annual rainfall total during the summer growing sea-
son) allowing continuous grain sorghum or cotton to be grown. In the case of continuous grain sorghum, planting takes place in soil idled since the previous harvest or during the time when rain is most probable and grows/matures during a short 5-mo season (Fig. 5–4). Similarly, cotton is produced during a summer growing season that is only slightly longer than for sorghum. The benefits of these annual monocultures are largely economic, in that land productivity is optimized and specialized production resource requirements are limited to the single

Fig. 5–3. Annually cropped wheat is planted during October and harvested about 9 mo later. A short 3-mo fallow period beginning in July provides a limited opportunity to replenish the soil water profile before the rotation is repeated.

Fig. 5–4. Annually cropped sorghum (diagramed with October at the top) is divided into a 7-mo fallow period ending in mid-June when the probability of summer precipitation is greatest. Grain sorghum is established and grown during the 5-mo summer season. Annually grown summer crops achieve the greatest fallow water-use efficiency and cropping intensity by relying on normal precipitation patterns.
crop. Potential hazards beyond loss of rotation benefits are loss of production diversity and recurrent or escalating production hazards, such as, surviving weed, insect, or pathogen populations that require additional management input for control.

True annual crop rotations are often implemented by alternating production of different summer crops, such as corn, cotton, millet, grain sorghum, soybean, and sunflower. Numerous factors govern crop selection in annual rotations including crop suitability for the available water and minimization of weed, disease, and insect pressures by culturing nonhost plants. Because of the greater productivity during the summer growing season and generally favorable precipitation, the alternating annual summer crop rotations are economically desirable. As an example, Fig. 5–5 shows sorghum grown in an alternating summer rotation with cotton, which is a particularly useful rotation for establishing residues for soil conservation. This type of rotation also provides management options for reducing recurrent weed populations by varying weed control herbicides with different modes of action such as the dinitroanilines commonly used with cotton (soybean or sunflower) and s-triazines used with grain sorghum (or corn). Although these crops are produced annually, the soil remains idle about 6 to 7 mo each year and has the opportunity to store some precipitation. Like double crop rotations, annual summer crop rotations are practical when seasonal precipitation is timely and sufficient for crop establishment, but the growing season is not sufficiently long to produce more than one crop per year.

Fallow Crop Rotations

Fallow crop rotations use an idle period between crops for an opportunity to increase precipitation storage as soil water and, therefore, average less than one crop per year. Introducing fallow periods into a cropping sequence also provides an opportunity to manage weed, insect, and disease infestations by removing potential host plants. However, under dryland conditions, cropping sequences that
include fallow periods benefit greatly from the stored soil water for augmenting growing season precipitation, which would otherwise be insufficient to support a single annual crop without significant risk of failure.

Numerous cropping sequences introduce fallow periods for water storage; however, the success of a fallow cropping sequence depends on several factors governing fallow efficiency, that is, the fraction of fallow precipitation stored as soil water. For example, progressively higher fallow efficiencies were achieved as weed control during fallow shifted from maximum tillage "dust mulch" used 1916 to 1930 to minimum and no-tillage management after 1975 (Stewart, 1994). The resulting fallow efficiency increased from approximately 19% of the precipitation where tillage repeatedly exposed moist soil to drying conditions to 40% of the precipitation when residue cover was present. Unger (1978) illustrated the importance of residue cover on water conservation, which increased from 23 to 37% of the rain during fallow when wheat residue increased from 0 Mg ha\(^{-1}\) to 3.2 Mg ha\(^{-1}\) and, consequently increased dryland sorghum grain yield from 1.4 to 2.4 Mg ha\(^{-1}\). Fallow periods must appear during a crop sequence when the typical precipitation amount is adequate for water storage in the soil. Because of the finite water storage capacity of soil, fallow periods can be excessively long and reduce precipitation storage efficiency by idling soil with a fully replenished available water reservoir. Also, prolonged fallow periods increase the opportunities for water loss to evaporation or runoff (Jones and Popham, 1997). The principal objection to including fallow periods in cropping sequences, however, is an overall decrease in land productivity. This objection fuels research efforts to intensify crop rotations and, generally, encourages minimization of fallow period duration.

Winter wheat is commonly grown in semiarid regions of the world and was the principal cash crop grown during the Euro-American settlement of the Great Plains (Hurt, 1981). Other feed and cash crops such as oats and corn were grown, but annual cropping of winter wheat (Fig. 5–6a) generated the income required to fuel this farm migration into the Great Plains beginning in the 1890s, which corresponds to a period of above average precipitation. The annual wheat cropping system expanded with increased mechanization and European demand for wheat during World War I but at the expense of good soil husbandry. The good fortunes of above average precipitation ended during the 1930s when the "Dust Bowl" era punctuated the consequences of excessive tillage and need for improved cropping systems. Under drought, previously successful annually cropped dryland wheat rapidly evolved into wheat cropped with an intervening 12-mo fallow period (Fig. 5–6b) resulting in one crop every 2 yr. The wheat–fallow sequence stabilized wheat production by storing precipitation as soil water that subsequently provided adequate moisture for grain production (Greb, 1983).

One negative consequence of the winter wheat–fallow cropping rotation is the prolonged 14-mo idle period that accounts for about 60% of the crop sequence and noticeably reduces potential land productivity. Fallow and the associated tillage degrades soil quality over time by the loss of organic matter that contributes to aggregate stability and increasing erosion potential of more smaller aggregates (Peterson et al., 1993; Unger, 2001b). A second negative consequence of winter wheat–fallow occurs as considerable water is wasted; a wheat–fallow rotation
Annual Wheat

**Fig. 5-6.** The annual wheat (A) and wheat fallow (B) cropping sequences diagramed as a 1- or 2-yr cycle beginning with wheat establishment in October (top). In both sequences, wheat is harvested about 10 mo after planting in July and fallowed during typically low precipitation months of July to September. Annual wheat crops rely on fall precipitation for establishment and growth; however, insufficient moisture often results in an additional 12-mo fallow period or wheat fallow sequence. The similarly planted wheat fallow sequence uses the additional 12-mo fallow period to store precipitation as soil water, but produces only one crop in 2 yr.

uses only approximately 40% of precipitation received during one rotation cycle (Peterson et al., 1996). The remainder of precipitation occurs during fallow and is subject to losses by evaporation and, in some years, by percolation beyond the rooting depth of winter wheat. The resulting fallow efficiency varies from about 11% at Bushland, TX (Jones and Popham, 1997) to 16% at Sterling, CO (Farahani et al., 1998). Nevertheless, the wheat–fallow rotation increased wheat grain yield throughout much of the central and southern Great Plains (Table 5–3) by augmenting precipitation with stored soil water.

Efforts to reduce fallow period duration resulted in the use of summer crops in sequence with wheat. One frequently used rotation is the wheat–sorghum–
Table 5-3. Mean wheat, wheat–fallow, and wheat–sorghum–fallow crop yields of common cropping sequences used on the Great Plains (listed from north to south) after 60 yr at Akron CO, Colby, KS (Greb et al., 1974), and after 10 yr at Tribune, KS (Norwood et al., 1990) and Bushland, TX (Jones and Popham, 1997).

<table>
<thead>
<tr>
<th>Crop sequence</th>
<th>Sorghum</th>
<th>Wheat</th>
<th>Combined rotation</th>
<th>Annualized yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Akron, CO</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Continuous wheat (1 yr)</td>
<td>–</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>Wheat fallow (2 yr)</td>
<td>–</td>
<td>1.42</td>
<td>1.42</td>
<td>0.71</td>
</tr>
<tr>
<td>Colby, KS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Continuous wheat (1 yr)</td>
<td>–</td>
<td>0.62</td>
<td>0.62</td>
<td>0.62</td>
</tr>
<tr>
<td>Wheat fallow (2 yr)</td>
<td>–</td>
<td>1.32</td>
<td>1.32</td>
<td>0.66</td>
</tr>
<tr>
<td>Tribune, KS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Continuous wheat (1 yr)</td>
<td>–</td>
<td>1.14</td>
<td>1.14</td>
<td>1.14</td>
</tr>
<tr>
<td>Wheat fallow (2 yr)</td>
<td>–</td>
<td>2.38</td>
<td>2.38</td>
<td>1.19</td>
</tr>
<tr>
<td>Wheat–sorghum–fallow (3 yr)</td>
<td>2.41</td>
<td>2.28</td>
<td>4.69</td>
<td>1.56</td>
</tr>
<tr>
<td>Continuous sorghum (1 yr)</td>
<td>2.18</td>
<td>–</td>
<td>2.18</td>
<td>2.18</td>
</tr>
<tr>
<td>Bushland, TX</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Continuous wheat (1 yr)</td>
<td>–</td>
<td>1.33</td>
<td>1.33</td>
<td>1.33</td>
</tr>
<tr>
<td>Wheat–fallow (2 yr)</td>
<td>–</td>
<td>1.95</td>
<td>1.95</td>
<td>0.98</td>
</tr>
<tr>
<td>Wheat–sorghum–fallow (3 yr)</td>
<td>4.21</td>
<td>1.99</td>
<td>6.20</td>
<td>2.06</td>
</tr>
<tr>
<td>Continuous sorghum (1 yr)</td>
<td>3.66</td>
<td>–</td>
<td>3.66</td>
<td>3.66</td>
</tr>
</tbody>
</table>

Fallow cropping sequence (Fig. 5-7) that produces two crops in 3 yr. The rotation begins with October planted winter wheat that is harvested 10-mo later, followed by an 11-mo fallow that ends during the summer of the second year when grain sorghum is planted. Grain sorghum is harvested in the fall of the third year and the sequence is repeated after another 11-mo fallow when wheat is again planted. Other summer crops such as proso millet or corn have been substituted in place of grain sorghum for this cropping sequence (Anderson et al., 1999). Rotations of winter and summer crops reduce the intervening fallow periods to about 11 mo, but the soil still remains idle for 21 of the 36 mo or about 60% of the sequence. This is practically the same proportion of fallow as observed in the wheat–fallow rotation. However, fallow efficiency with the wheat–summer crop–fallow cropping sequence was significantly better than wheat–fallow, ranging from about 17% at Bushland, TX (Jones and Popham, 1997) to 27% at Sterling, CO (Farahani et al., 1998). Wheat and grain sorghum yields after fallow at Tribune, KS and Bushland, TX were usually greater than the corresponding continuously (annual) cropped sorghum and wheat (Table 5-3) because of improved soil water conditions.

Crop yield benefits resulting from cropping sequences that include a fallow period may be contrasted using an annualized grain yield (AGY) that is calculated from the sum of all crop yields divided by the number of sequence or rotation years. The AGY for continuous wheat equals the mean wheat yield; whereas, the AGY for the wheat–fallow sequence equals the mean wheat yield divided by the 2-yr cropping sequence period. Although the AGY of wheat–fallow and annual wheat cropping rotations listed in Table 5-3 varied by location, the annualized wheat–fallow grain yield was greater than for continuous wheat in Akron, CO,
lower in Bushland, TX, and similar for both Kansas locations. The greater AGY at Akron, in the north, compared with Bushland, to the south, may be attributed to differences in temporal precipitation distribution and the decreasing ratio of precipitation to evaporation. Cropping systems at Bushland and Tribune, KS that included the wheat–fallow–sorghum cropping sequence achieved consistently greater AGY compared with either continuous wheat or wheat–fallow rotation sequences. Introduction of a C₄ crop, grain sorghum, during the summer increased AGY approximately 50% over corresponding wheat, C₃ crop, only sequences. Furthermore, the annualized continuous sorghum yields were greater than annualized sorghum plus wheat yields after fallow at these locations and suggest that where summer precipitation is usually adequate for summer crop production, fallow periods may not be required for crop establishment and yield. Alternatively, the problem that previous crops in a rotation may deplete the soil water reservoir and depress subsequent dryland crop yields was illustrated by reduced dryland winter wheat yields after sunflower (Norwood, 2000). The desire to increase cropping system intensity often counters the practical concern for soil water storage to stabilize dryland crop yields.

To further increase cropping intensity, modifications to successful wheat–summer crop–fallow sequences to include an additional crop before planting wheat was proposed by researchers in Colorado. Using minimum-till production systems and residue management to improve water conservation and water-use efficiency, the wheat–corn–fallow cropping sequence was intensified to include millet resulting in the winter wheat–corn–millet–fallow crop sequence (Peterson et al., 1993) that produces three crops in 3 yr (Fig. 5–8). Other 3-yr sequences
rotate three crops, such as winter wheat, corn, and sunflower successfully (Anderson et al., 1999), but yields have suffered. With appropriate crop choice in no-till systems, continuous cropping may be successful, as winter wheat–corn–proso millet yields were twofold greater than winter wheat–fallow (Anderson et al., 1999). However, semiarid regions may lack the water and nutrient resources to meet the potential biological requirements in support of continuous cropping. Schlegel et al. (2002) modified the wheat–sorghum–fallow rotation by immediate recropping of wheat or sorghum to obtain a 4-yr rotation that produced four crops and determined that although overall production increased profitability was practically unaffected. More intensive cropping systems may fail to provide an incentive of greater profitability (Schlegel et al., 2002) or production stability under semiarid dryland conditions.

Some alternative crop rotations increase land productivity and net return while reducing financial risk compared to winter wheat–fallow (Dhuyvetter et al., 1996). A concern with more intensive cropping is that yield variability will increase; fallow was adopted by producers to manage yield variability in semiarid climates. A long-term rotation study in the semiarid Great Plains of the USA showed that although yield variability was high with individual crops, diversifying crops in rotations minimized yield variability at the rotation level (Anderson et al., 1999). For example, annualized yield variability in a winter wheat–corn–proso millet rotation was similar to winter wheat–fallow. Thus, rotations comprised of several crops did not increase overall yield variability.

**BENEFITS AND INTERACTIONS OF CROP SEQUENCING AND ROTATION INTERVALS**

Crop yield can be affected by the sequence or arrangement of crops, a response termed the “rotation effect” (Higgs et al., 1990). For example, rotating
pearl millet \([\text{Pennisetum glaucum} \, (\text{L.}) \, \text{R. Br.}]\) with cluster bean \([\text{Cynopsis tetragonoloba} \, (\text{L.}) \, \text{Tauber}]\) increased pearl millet grain yield twofold compared to a monoculture of pearl millet in India (Praveen-Kumar et al., 1997). Rotating corn with soybean improved yield of both crops at least 15\% compared to a monoculture system of either crop (Crookston et al., 1991). As conservation-oriented systems increase worldwide, crop sequencing will become more valuable as a management strategy because the rotation effect on yield is greater in minimum- and no-till systems (Pierce and Rice, 1988).

The rotation effect has been attributed to a multitude of factors, such as changes in soil moisture levels, nutrient cycling and availability, soil structure, soil microbial community, and pest infestations (Kurtz et al., 1984; Higgs et al., 1990). Understanding causes and trends of yield responses to crop sequences will help scientists and producers develop productive rotations that are more diverse. Therefore, interactions among crops for impact on grain yield will be examined to identify principles that can guide crop sequencing.

**Broadleaf Benefits for Grass Crops**

Broadleaf crops usually increase yield of subsequent grass crops, but identifying the specific cause of this yield response has been difficult. Wright (1990) compared three legume crops, peas \((\text{Pisum sativum} \, \text{L.})\), lentils \((\text{Lens culinaris} \, \text{Medik.})\), and fababean \((\text{Vicia faba} \, \text{L.})\) for impact on barley yield in Saskatchewan, Canada. Barley responded equally to the each of the preceding crops, yielding 21\% more than if barley was grown as a monoculture. Searching for possible causes of the legume effect, Wright found that barley’s yield response was unrelated to differences in N cycling, soil moisture, or disease. He suggested that only an explanation based on the complex interaction of multiple soil factors could elucidate the yield response.

Bourgeois and Entz (1996), comparing rotations in the continuous spring wheat region of Manitoba, Canada, found that the impact of flax \((\text{Linum usitatissimum} \, \text{L.})\) on wheat yield was twofold greater than peas or canola \((\text{Brassica napus} \, \text{L.})\), when compared to continuous wheat. They also determined that flax provided the most consistent wheat yield benefits. Flax is not a legume, thus its yield stimulus with wheat must be related to factors other than N\(_2\) fixation. Bourgeois and Entz (1996) also felt that multiple factors contribute to the broadleaf effect on grass crops as proposed by Wright (1990).

In a semiarid site in southern Spain, Lopez-Bellido et al. (1996) examined the impacts of sunflower, chickpea \((\text{Cicer arietinum} \, \text{L.})\), and fababean on winter wheat yield compared with continuous winter wheat. Wheat responded the most to fababean, with yield 46\% greater than if wheat followed wheat (Fig. 5–9). Similarly, wheat yields increased 18\%, when grown after sunflower and 28\% following chickpea. The increased yield of wheat planted after sunflower compared with chickpea probably reflected differences in soil water levels when planting the wheat crop, because this yield benefit did not occur in growing seasons with above normal precipitation (Lopez-Bellido et al., 2000). However, fababean was always more favorable than either chickpea or sunflower, regardless of growing conditions. Applying N fertilizer did not eliminate the yield response of wheat
Fig. 5-9. Yield of annual winter wheat compared with wheat after broadleaf crops (W: winter wheat; Sun: sunflower; CP: chickpea; FB; faba bean; and F: fallow). Data are averaged across 7 yr from a study conducted at Cordoba, Spain; columns with the same letter are not significantly different (adapted from Lopez-Bellido et al., 1996).

to these two species, nor were differences in pests or diseases observed. These data suggest that other factors influenced the yield difference.

Investigation of these factors by Beckie and Brandt (1997) differentiated the broadleaf effects on wheat into “N benefit” supplied by a legume as a result of N\textsubscript{2} fixation and “non-N benefits,” such as disease suppression or reduction of allelopathy associated with cereal residue. They found that the N benefit by a legume varied among years. Pursuing this concept, Stevenson and van Kessel (1996) quantified the N and non-N benefit of pea on wheat yields at several sites. They found that the ratio of N:non-N benefits not only varied among sites but also was affected by crop management histories and growing season conditions. Both research teams suggested devising cereal rotations that included both legumes and non-legume broadleaf crops to maximize the rotation effect.

Crookston et al. (1991), evaluating soybean impact on corn, suggested that the broadleaf effect on corn was related to “corn being bad for corn” rather than a beneficial effect of soybean. Further research by this team supported this hypothesis as the broadleaf effect on corn did not differ among alfalfa (Medicago sativa L.), soybean, or sunflower (Porter et al., 1997a); they theorized that auto-toxins from decomposing roots of the previous corn crop reduced yield in continuous corn (Nickel et al., 1995).

Even though broadleaf crops are usually favorable for grass crops, in some situations, they can be detrimental to subsequent crops. For example, in the semi-arid plains of the USA, sunflower was found to decrease yield of winter wheat (Anderson et al., 1999). Comparing two rotations, wheat–sunflower–fallow with wheat–corn–fallow, wheat yielded 32% less with sunflower in the rotation. Yield loss was partially attributed to less soil water at planting time of winter wheat.
The authors speculated that sunflower stalks were less effective in capturing snow than corn stalks, thus reducing recharge of the soil profile during fallow.

**Grass Benefits for Broadleaf Crops**

Most of the research examining rotation effects has focused on improving yield of grass crops, such as corn or wheat. However, the rotation effect also occurs when grasses precede broadleaf crops. For example, soybean yield increased 17% when rotated following corn, compared to continuous soybean (Crookston et al., 1991). They were unable to identify the cause of this yield response, but found that corn and soybean achieve the rotation benefit by different means. Beckie and Brandt (1997) reported that flax yields were greater when grown after wheat compared to canola, an oilseed crop similar to flax. Yield response to wheat was attributed to reduced diseases compared to canola.

**Interactions Between Similar Crop Types**

Rotations using similar crop types like cereals, such as flax and canola, or wheat and barley, are not as beneficial as between crop types, that is, cereals with broadleaf crops. The difficulty with sequencing similar crop types together is that plant diseases and problem weeds usually proliferate. Bailey (1996), summarizing crop diseases for selected conservation tillage systems, cautioned producers from growing broadleaf crops, especially oilseeds, too frequently because of disease problems. Furthermore, oilseed and legume crops can serve as common host plants for pathogens that infest both crops, such as *Sclerotinia*. If such plant pathogens are present, broadleaf crop frequency may have to be reduced to avoid extensive disease infestation. She suggested mixing a diversity of grass crops with oilseed and legume crops in long-term rotations.

Alternating grass species usually does not impact yield as much as rotating broadleaf crops with grasses. For example, a rotation study in Turkey showed that winter wheat yield did not differ between a wheat–barley rotation and continuous wheat (Durutan et al., 1988). In contrast, rotating wheat with safflower (*Carthamus tinctorius* L.) increased wheat yield 32%. Soil water and N levels at wheat planting were similar in both rotations, suggesting that other factors improved wheat growth after safflower.

Grass sequences can also be detrimental to yield. In the central Great Plains of the USA, planting winter wheat into sorghum residue reduced grain yield 15 to 30%, compared to wheat planted into pearl millet stubble or fallow (Roth et al., 2000). Yield loss was attributed to allelopathic compounds released by decomposing sorghum residue. Sorghum also was detrimental to corn in Ghana (Schmidt and Frey, 1988). Comparing sorghum and corn as preceding crops for corn, yield was reduced 20 to 25% if sorghum was the preceding crop. Yield loss was attributed to allelopathy and N immobilization by sorghum residue.

However, anomalies among grass crop sequences can occur where crop yield is increased. A long-term rotation study at a semiarid site in the USA demonstrated that growing corn in place of proso millet in rotation with winter wheat increased the efficiency of wheat to convert water into grain (Anderson et al.,
That is, in a wheat–corn–fallow rotation, wheat produced 3010 kg ha\(^{-1}\) with 250 mm of water use; in contrast, wheat in a wheat–proso–fallow rotation produced only 2060 kg ha\(^{-1}\) with the same water use (Fig. 5–10). With corn in the rotation, wheat produced 46% more grain with the same water use than if proso was in the rotation. In this same study, corn also improved water-use efficiency of proso millet, but only after the rotations had been in place for 6 yr. Averaged during Years 7 through 10 of the study (4 yr), mean proso yield was 2320 kg ha\(^{-1}\) in a winter wheat–corn–proso rotation compared with only 2020 kg ha\(^{-1}\) for proso grown in rotation with wheat or a decrease of 15\% (Anderson, 2002). The corresponding water use with these rotations was similar; therefore, water-use efficiency of proso grown after corn was 23\% greater than proso after wheat.

Surprisingly, including fallow in the rotation eliminated corn's effect on proso yield and water-use efficiency. Proso yield did not differ in wheat–corn–proso–fallow and wheat–proso–fallow, rotations with the same crop sequence as above, but including fallow. Furthermore, proso yield in these rotations were similar to wheat–proso, 15\% less than in wheat–corn–proso rotation. This trend demonstrates a fallow by crop interaction, as fallow did not eliminate corn's effect on wheat, as occurred with proso.
Crop Specific Interactions

The rotation effect appears to be a universal phenomenon with appropriate crop sequencing. A guiding principle in designing rotations is to diversify crops as much as possible, especially rotating grass and broadleaf crops. However, it is difficult to extrapolate across all crop combinations, soil types, and environments. For example, soybean’s effect on corn was more pronounced in low yielding environments (Porter et al., 1997b), contrasting with cereal grain response to broadleaf crops, which was more pronounced in high yielding environments (Bourgeois and Entz, 1996; Lopez-Bellido et al., 1996). Another contrast occurred with the interaction between corn and winter wheat or proso millet; fallow eliminated corn’s impact on proso, but not corn’s effect on wheat (Anderson et al., 1999). These contrasts suggest that the complexity of crop–soil–environment interactions may lead to anomalies among crop combinations, with results contrary to expectations; the rotation effect may be crop specific.

Effects of Rotation Interval

Crop yield is affected by how frequently the crop is grown. This concept, known as the “crop interval,” relates grain yield to number of years before the same crop is grown again; longer intervals favor the natural decline of pathogen populations in soil (Cook and Veseth, 1991). The optimum interval varies among crops and climatic conditions. Corn’s optimum interval was 2 yr in Wisconsin (Lund et al., 1993), 3 yr in Minnesota (Porter et al., 1997a) and 4 yr in Nebraska (Peterson and Varvel, 1989), whereas soybean’s highest yield occurred with a crop interval of either 2 or 3 yr (Meese et al., 1991; Porter et al., 1997b). Winter wheat yielded the most in the Pacific Northwest when grown once every 3 yr (Cook and Veseth, 1991).

During a rotation study comprised of wheat, corn, proso millet, and sunflower crops grown under semiarid conditions (Anderson et al., 1999), sunflower was the most responsive to crop interval, yielding the most if grown once every 4 yr (Fig. 5–11). When grown more frequently, soil-borne diseases such as phoma (Phoma macdonalldii Boerma) severely reduced sunflower yield. Grass crops were less affected by crop interval; yields of corn and winter wheat were reduced when grown every 2 yr compared to a 4-yr crop interval, but proso millet was not affected by crop interval. These data affirm Bailey’s (1996) concern about plant diseases proliferating if oilseed crops such as sunflower are grown too frequently.

Designing rotations to favor the crop interval effect can also influence crop interactions; an example of this effect was demonstrated with sunflower in a semiarid rotation study (Anderson et al., 1999). Compared to wheat yields measured in a wheat–corn–proso millet–fallow rotation, winter wheat yield was reduced 36% following sunflower in a wheat–sunflower–fallow rotation; in contrast, wheat yield was reduced only 8% with a wheat–corn–sunflower–fallow rotation. Furthermore, a disturbing trend occurred with the wheat–sunflower–fallow rotation, that is, wheat yield decreased with time compared to wheat yields measured in a wheat–corn–proso millet–fallow rotation, declining from 81% in
Sunflower Corn Wheat Proso

Crop Interval

- 2-Year
- 3-Year
- 4-Year

Fig. 5-11. Sunflower (S), corn (C), proso millet (M), and winter wheat (W) response to crop interval at Akron, CO; data are averaged across 4 yr. An asterisk signifies that 2- or 3-yr crop interval mean differed from 4-yr mean within each crop. Data derived from crop sequences for sunflower: S-M, W-S-fallow (F), and W-C-S-F; for corn: M-C, W-C-F, and W-C-M-F; for proso millet: W-M, W-M-F, and W-C-M-F; and for winter wheat: W-F, W-C-F, and W-C-M-F (adapted from Anderson et al., 1999).

1994 to 48% in 1999 (Fig. 5-12a). Wheat yield in a wheat—corn—sunflower—fallow rotation remained above 90% the wheat yields measured in a wheat—corn—proso millet—fallow rotation 5 yr out of 6 (Fig. 5-12b). Wheat yields in 1995 and 1998 with a wheat—corn—sunflower—fallow rotation reflect precipitation extremes; with above normal precipitation in 1995 and below normal in 1998. However, yield in a wheat—sunflower—fallow rotation declined 7% per year ($r^2 = 0.86$), regardless of precipitation. The explanation for this trend has not been determined, but lengthening the rotation by adding corn ameliorated sunflower’s negative impact on wheat yield.

As shown with sunflower, length of rotation can also alter the rotation effect. Crop growth can be further improved by arranging different crops in a sequence of four. Debaeke and Hilaire (1997), evaluating rotation length in a rain-fed region of southwestern France, found that a four-crop rotation was more productive compared to rotations with fewer crops. Bailey (1996) suggested balancing two cereal crops and two broadleaf crops in a cycle of four to minimize the detrimental effect of plant diseases. Weed management was improved by a cycle of four crops with two winter annual crops followed by two summer annual crops; this design favored the natural decline of weed seeds in the soil, thus reducing weed densities.
Fig. 5-12. Impact of sunflower on winter wheat grain yield in two rotations, (A) wheat-sunflower-fallow (W-S-F) and (B) wheat-corn-sunflower-fallow (W-C-S-F). Wheat yields in these rotations were compared to wheat yield in wheat-corn-proso millet-fallow. Data collected from a rotation study at Akron, CO (adapted from Anderson et al., 1999).
in future crops (Anderson, 1998). Matus et al. (1997) found that N₂ fixation by lentils increased in rotations with four different crops compared to rotations with fewer crops.

These studies suggest that rotation design can supplement the rotation effect; greater diversity in crop interactions with longer rotations may increase yield more through ancillary benefits. Wright (1990) found that the broadleaf effect on cereal grains persisted for two cereal crops. Thus, if crop sequencing could be devised where positive interactions occur among several crops in sequence, rotational benefits would be even more enhanced.

**Crop Diversity Benefits**

In rain-fed agriculture, especially in semiarid regions, a continuing problem for producers is erratic precipitation and subsequent yield variability. Diversifying crops in rotations can moderate the effect of drought on crop yield by improving water-use efficiency. For example, Drury and Tan (1995) monitored corn yields over 35 yr as affected by crop rotation. Compared to continuous corn, not only was grain yield increased, but yield variability of corn was reduced twofold in diverse rotations. They attributed this response to improved root growth of corn. Sahs and Lesoing (1985) also reported that diverse rotations improved water-use efficiency of corn in dry years. Similarly, Praveen-Kumar et al. (1997) found that pearl millet was more productive during dry years because the crop used the limited water supply more efficiently in a diverse rotation.

Crop diversity also stabilizes yields at the rotation level. Smolik et al. (1995) found that year-to-year variability in production of all crops was lowest in rotations with the most diversity. In a winter wheat–fallow region, yield variability was reduced 15% with diverse rotations compared to wheat–fallow (Anderson et al., 1999). Producers in a winter cereal production area of Australia found that adding broadleaf crops to their rotations not only improved farm productivity and profits, but also increased management flexibility and income stability because of diversified income sources (Locke et al., 1995). Diverse crop rotations can aid producers in minimizing the "boom or bust" cycles that are common in drier climates.

**UNIVERSAL PRINCIPLES FOR CROP SELECTION AND ROTATION SEQUENCES**

In a report on similarities and differences in worldwide dryland farming, De Brichambaut (1970) designated the optimum use of rainfall as a common management objective, but he concluded that no one standard system of dryland farming can be generally applied to all dryland areas. Common plant characteristics to regulate water use or energy interception, however, do bind logical crop selections for plants that efficiently convert water transpired to commodity harvested while minimizing the impact of extended water deficits. Grain sorghum, for example, is similarly efficient in converting water to grain as corn, but sorghum is not as sensitive to drought conditions as corn, which makes sorghum a
generally popular dryland crop. The common need for increased water conservation defines universal dryland crop rotation mechanics, such as, producing residues for covering the soil during fallow to optimize the amount of water available for plant use. Dryland crop rotations likewise vary the types of crops planted in annual rotation or with intervening fallow (idle) periods to maintain or intensify crop productivity and obtain other rotation benefits such as \( \text{N}_2 \) fixation or improved weed control. Varying cropping sequences to include fallow periods and different crop combinations comprise the rotation mechanics needed to attain the universally desirable increased crop production intensity and risk control on drylands.

REFERENCES


CROP CHOICES AND ROTATION PRINCIPLES


