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ALLELOPATHY

Allelopathy of Sorghum on Wheat under Several Tillage Systems

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ABSTRACT

Allelopathy by grain sorghum [*Sorghum bicolor* (L.) Moench] frequently harms wheat (*Triticum aestivum* L.) when the crops are grown in rotation. Responses of seven wheat cultivars to different methods of tilling sorghum stover were investigated to determine if the problem might be remedied by genetic resistance or improved management of the stover. Field trials on Kahola silt loam soil (fine-silty, mixed mesic Cumulic Hapludolls) compared effects of fallow, tilled sorghum stover, and no-till sorghum stover during the first season and the same treatments plus no-till millet [*Pennisetum glaucum* (L.) R. Br.] stover the second season. The seven wheat cultivars were planted after the sorghum and millet were harvested and tilled, and their emergence, stand density, and yield components were measured. Tilled sorghum residue often delayed development of the following wheat crop but did not affect grain yields, probably because allelopathic compounds degraded in the soil. No-till sorghum stover had little effect on stand establishment but frequently reduced grain yields of wheat, possibly because allelopathic compounds leached slowly. Wheat grain yields (means of all seven cultivars) were 3.3, 2.8, and 2.3 Mg/ha in fallow, tilled sorghum residue, and no-till sorghum residue, respectively, during 2 yr and 3.1 Mg/ha in no-till millet residue in the second year. Selection of resistant wheat cultivars is probably impractical, because differences were small and inconsistent. However, if erosion of soil is not a concern, allelopathy might be reduced by prompt tillage and other practices that promote rapid decomposition of sorghum stover.

ALLELOPATHY, the interference of one plant species by another, occurs in several crops that are grown in rotation (Guenzi and McCalla, 1966; Hedge and Miller, 1990). Growth of winter wheat, which is double cropped frequently after grain sorghum in the Great Plains, was inhibited strongly by the sorghum (Guenzi and McCalla, 1966; Guenzi et al., 1967). Changes in production practices, as from conventional tillage to minimum tillage, might affect allelopathic interactions between sorghum and wheat, and wheat cultivars that resist the inhibitory effects of sorghum might be selected for planting. However, allelopathy in crops has been investigated little, particularly under field conditions, and factors that are involved in the interactions are not well understood.

Grain sorghum was allelopathic to many crops and weeds (Alsaadawi et al., 1986; Einhellig and Rasmussen, 1989). Water extracts from sorghum residues inhibited germination and decreased root and shoot growth of corn (*Zea mays* L.) and wheat (Guenzi et al., 1967). Weed growth was suppressed up to 1 yr following grain sorghum compared with corn or soybean [*Glycine max* (L.) Merr.] (Einhellig and Rasmussen, 1989). Radicle growth of green foxtail [*Setaria viridis* (L.) P. Beauv], velvetleaf (*Abutilon theophrasti* Medikus), and smooth pigweed (*Amaranthus hybridus* L.) was reduced by grain sorghum seedlings (Hoffman et al., 1996). Residues of sorghum–sudangrass [*Sorghum bicolor* (L.) Moench var. *sudanense*] cover crops preceding no-till establishment of alfalfa (*Medicago sativa* L.) significantly reduced weed populations compared with no residue or foxtail millet [*Setaria italica* (L.) P. Beauv] residue (Fortney and Foy, 1985).

Phenolic acids from decomposing residue and roots were probably responsible for growth and yield reductions associated with allelopathy of sorghum (Einhellig and Rasmussen, 1978). They were identified as the allelopathic agents more often than all other classes of compounds combined (Mandava, 1984). Guenzi and McCalla (1966) quantified five phenolic acids in sorghum residue—ferulic, *p*-coumaric, syringic, vanillic, and *p*-hydroxybenzoic. The concentration of coumaric acid was greatest and sufficient to reduce growth of other species. Cherney et al. (1991) also found vanillic acid, p-hydroxy-benzaldehyde, *p*-coumaric acid, and ferulic acid in four sorghum hybrids; again the concentration of *p*-coumaric was highest followed by ferulic acid.

Two other compounds, dhurrin and sorgoleone, were associated with allelopathy by sorghum. Dhurrin, a cyanogenic glycoside that degraded to p-hydroxybenzaldehyde, HCN, and glucose, reduced germination of radish (*Raphanus sativus* L.), okra [*Abelmoschus esculentus* (L.) Moench], and tomato (*Lycopersicon esculentum* L.) and inhibited the growth of various bacteria (Nicollier et al., 1983). Sorgoleone, a long-chain hydroquionone exuded from growing sorghum roots (Netzly and Butler, 1986), reduced growth of various weed species at concentrations as low as 10 μM (Einhellig and Souza, 1992).

The concentration and effect of allelochemicals in grain sorghum differed among environmental conditions, cultivars, and plant parts. Water extracts of field-grown sorghum affected growth of wheat seedlings differently over 2 yr (Ben-Hammouda et al., 1995a). The allelopathic potential of decomposing sorghum residue decreased with time and had no effect on wheat seedlings after 28 wk (Guenzi et al., 1967). Concentrations of phenolic compounds in sorghum differed considerably among cultivars and always decreased as the plants matured (Woodhead, 1981). Environmental factors also affected the level of phenolics in residue. High irradiance and attacks by insects and pathogenic fungi in-

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creased the phenolic content of the residue, depending on the cultivar and its development stage. Water extracts from six sorghum hybrids differed in inhibition of wheat seedling growth. Stems, leaves, and roots were most inhibitory, reducing radicle elongation of wheat by up to 75% compared with water controls (Ben-Hammouda et al., 1995a).

Allelopathic effects of sorghum on wheat might be alleviated in several ways. Genetic differences in the allelopathic potential of sorghum suggest that hybrids might be selected for low inhibition of wheat (Woodhead, 1981; Ben-Hammouda et al., 1995a). Winter wheat cultivars that resist the major inhibitory compounds in sorghum also might be planted, but genetic variation for the trait has not been reported. Because the allelopathic potential dissipated by decomposition over time (Guenzi et al., 1967), the sorghum residue might be managed to reduce inhibition of the following wheat crop. Objectives of these experiments were to (i) ascertain the variability in responses of popular winter wheat cultivars to allelopathic compounds in sorghum and (ii) determine the effect of conventional and reduced tillage management of sorghum residues on wheat growth and productivity.

MATERIALS AND METHODS

Crop Culture

Field experiments were conducted on a Kahola silt loam soil at the Agronomy Research Center, Manhattan, KS, during the 1996 to 1997 and 1997 to 1998 seasons. Treatments were arranged in a split-plot design with fallow and sorghum tillage methods as main plots and seven winter wheat cultivars as subplots in three replications. During the first season, grain sorghum hybrid Taylor Evans Y-101G (San Diego, CA) was planted on 10 June 1996 and the grain was harvested on 15 Oct. 1996 in two main plots, and a third plot was fallowed in each replication. Taylor Evans Y-101G sorghum was selected because of its high allelopathy to wheat in previous experiments (Ben-Hammouda et al., 1995a). Recommended production practices were followed for sorghum (Kansas Coop. Ext. Serv., 1998). Only the panicles were removed during harvest, and all other plant parts were left standing on the soil. Bioassays of water extracts of the mature leaf blades and stalks of the sorghum on 'Cardinal' wheat found approximately the same allelopathic potential as Ben-Hammouda et al. (1995b).

After harvest, one of the sorghum main plots and the fallowed main plot were tilled twice by discing; the other sorghum plot was not tilled. Nitrogen fertility was equalized according to soil tests by applying 112 kg N/ha as NH_4NO_3 to the sorghum main plots. No N was needed on fallowed plots. Other nutrients were adequate for wheat (Kansas Coop. Ext. Serv., 1997). The seven wheat cultivars were planted on 17 Oct. 1996 at the rate of 101 kg/ha in 1.5 by 12 m plots and a row spacing of 25 cm. Weeds were controlled manually as needed; no pesticides were applied during the season.

The study was conducted similarly on an adjacent, separate area during the second season. A main plot of millet was added to each replication to simulate soil moisture conditions in the sorghum plots. Bioassays by the procedure of Ben-Hammouda et al. (1995a, 1995b) did not detect any allelopathicity of water extracts of mature millet tissues on Cardinal wheat. Millet main plots were randomized with the sorghum and fallowed main plots, and the seven wheat cultivars were subplots in a split-plot design with three replications. All plot dimensions were the same as during the first year.

Sorghum hybrid Taylor Evans Y-101G and millet hybrid 79-2068 × 89-0083 (Courtesy of W.D. Stegmeier, Kansas State Univ.) were planted on 6 June 1997 and harvested on 7 Oct. 1997. After harvest, one of the sorghum main plots and the fallowed main plot in each replication were tilled; the other sorghum main plot and the millet main plot were not tilled. The seven wheat cultivars were planted on 21 Oct. 1997 and fertilized, with the grain sorghum and millet main plots received 101 kg N/ha and the fallowed main plots received 56 kg N/ha as NH_4NO_3.

Wheat Performance

Wheat seedling emergence was counted in two 1 m long rows that were selected randomly within each subplot both years. Seedlings were counted once each week until emergence ceased, and results were expressed as an emergence promptness index (EPI) that incorporated their number and rate of emergence:

$$\mathrm{EPI} = \sum_{i=1}^{5} (n/i)$$

where n = number of emerged seedings and i = days after planting. Stands of mature plants were counted in two 1 m long rows in the same sections immediately before harvest each spring.

Chlorophyll concentration in the flag leaves of five randomly selected wheat plants within each subplot was measured at the boot stage (Feekes 10) using a Minolta Spad-502 meter (Tokyo, Japan). Shoot N concentration of five randomly selected plants within each subplot was measured at the same growth stage. Samples were dried at 60°C to constant weight, ground to 1.7-mm mesh, and analyzed for total N using a CN-2000 Carbon/Protein/Nitrogen Elemental Analyzer (Leco Corp., St. Joseph, MI).

Two 0.3 m long rows were sampled randomly from all subplots at ripeness (Feekes 11.4) to determine the harvest index both years. All aboveground material was harvested and dried at 60°C to constant weight and weighed, and the grain was threshed and weighed separately. In 1998, the number of spikes and the mass of 1000 kernels in the samples were measured, and the mean kernel number per spike and kernel weight were calculated.

The inner three rows of each subplot were harvested with a grain bundler (Model B300D, Suzue Agricultural Equipment Co., Nankoku, Japan) and then threshed (Almaco, Ames, IA) on 11 July 1997. All rows of each subplot were harvested with a Hege 125 plot combine (Waldenberg, Germany) on 1 July 1998. In both years, moisture content of the grain was determined with a Dickey-John GAC 2000 grain sampler (Auburn, IL). Grain yields were adjusted to 13.5% moisture.

Weather Conditions

Precipitation, temperature, and soil moisture were recorded at a nearby weather station. During the 1996 sorghum growing season, precipitation totaled 390 mm and the average daily mean temperature was 23°C. Rainfall during the first 2 mo after planting the wheat totaled 130 mm, and the daily mean temperature was 9°C. From March to June 1997, precipitation totaled 290 mm, and the average daily mean temperature was 15°C. During the 1997 sorghum and millet growing season, total rainfall was 290 mm, and the mean daily temperature was 24°C. For wheat during the second year, rainfall was 100 mm and mean daily temperature was 11°C during the first

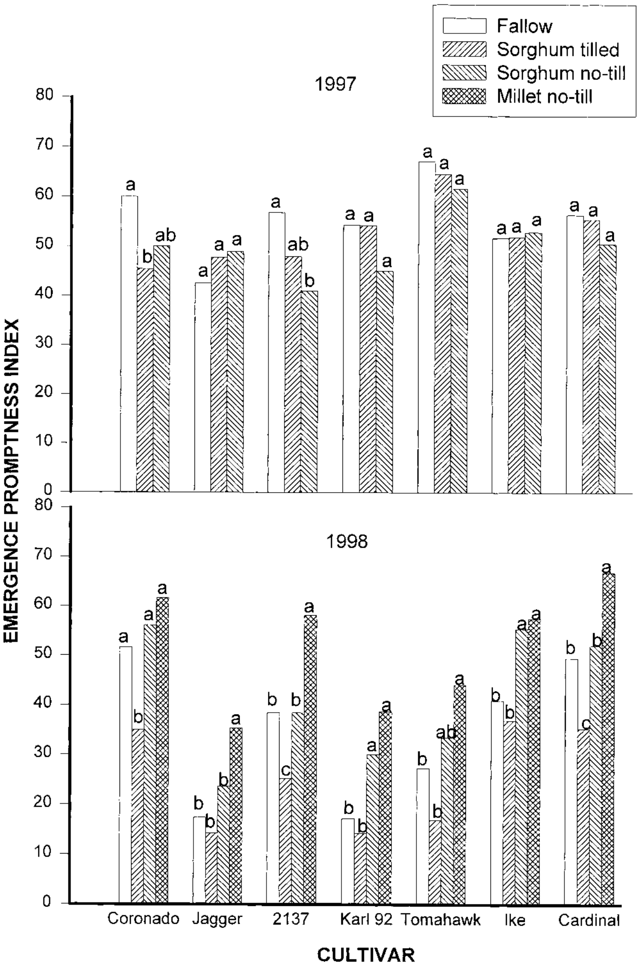

Fig. 1. Emergence promptness index of seven wheat cultivars after different sorghum and millet residue treatments. LSD (0.05) = 11 among cultivars and 9 among residue treatments during 1997 and 12 among cultivars and 14 among residue treatments during 1998. Within each cultivar, bars with different letters differ significantly among residue treatments at *P* = 0.05.

2 mo after planting, and rainfall was 360 mm and mean daily temperature was 15°C from March though June 1998. Soil moisture was not measured. Weather station data and moisture probes indicated that precipitation during September and/or October brought the topsoil and subsoil to field capacity to a 122-cm depth both years.

Statistical Analyses

Data were analyzed by conventional analysis of variance procedures for split-plot designs. Treatment means were compared by least significant differences (*P* = 0.05).

RESULTS

Sorghum and Millet Performance

Sorghum yielded 6 to 7 Mg/ha of grain in both years. Assuming a harvest index of 0.5 (Hammer and Muchow, 1994), approximately 6 to 7 Mg/ha of sorghum stover also was produced. Two passes with a disc in the tilled sorghum plots incorporated approximately 80% of the residue (estimated visually) and left about 1.3 Mg/ha of the stover on the soil surface when wheat was planted.

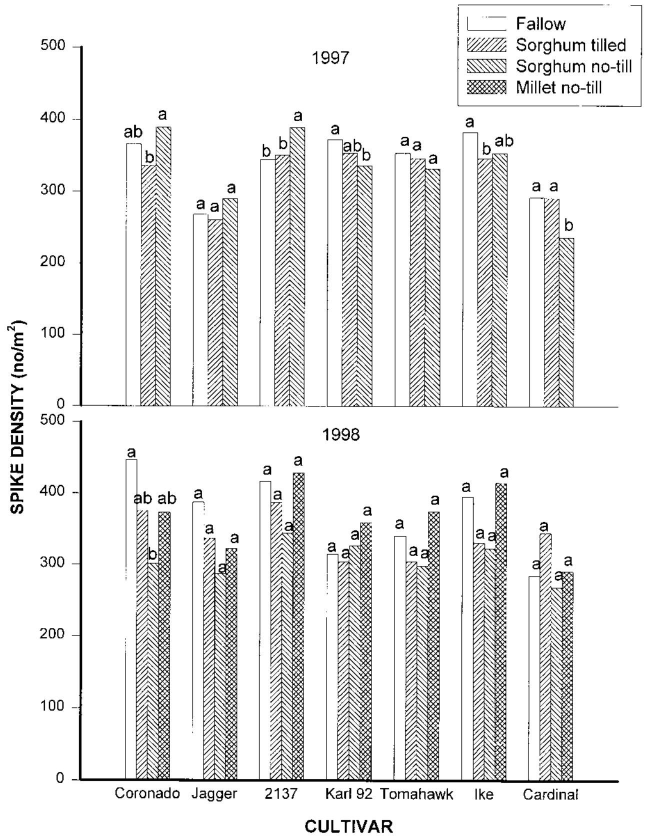

Fig. 2. Spike densities at maturity of seven wheat cultivars after different sorghum and millet residue treatments. LSD (0.05) = 38 among cultivars and 34 among residue treatments during 1997 and NS among cultivars and 127 among residue treatments during 1998. Within each cultivar, bars with different letters differ significantly among residue treatments at *P* = 0.05.

Millet yielded 4 to 5 Mg/ha of grain in the second year but had a lower harvest index and left about the same amount of stover as the sorghum.

Wheat Emergence and Growth

Emergence rate of wheat was affected significantly by cultivars and residue treatments during the 2 yr of the study (Fig. 1). Tomahawk emerged faster than the other cultivars during the first season, and Coronado, 2137, Ike, and Cardinal emerged fastest during the second season. Fallow and no-till millet favored rapid emergence of wheat during the first and second seasons, respectively.

Final stands varied little in autumn 1997 (data not shown). Stands of Tomahawk were lower after tilled sorghum than after fallow. In 1998, more differences occurred in the final autumn stands. Karl 92 had higher stands after no-till sorghum than after fallow and tilled sorghum. Five cultivars had higher emergence counts after millet than after one or more of the other residue management treatments.

Spike density at maturity was affected by cultivar and residue treatments and by their interaction (Fig. 2). Jagger and Cardinal generally had low stand densities during the first season, and the same cultivars plus Karl 92 and Tomahawk had low stand densities during the

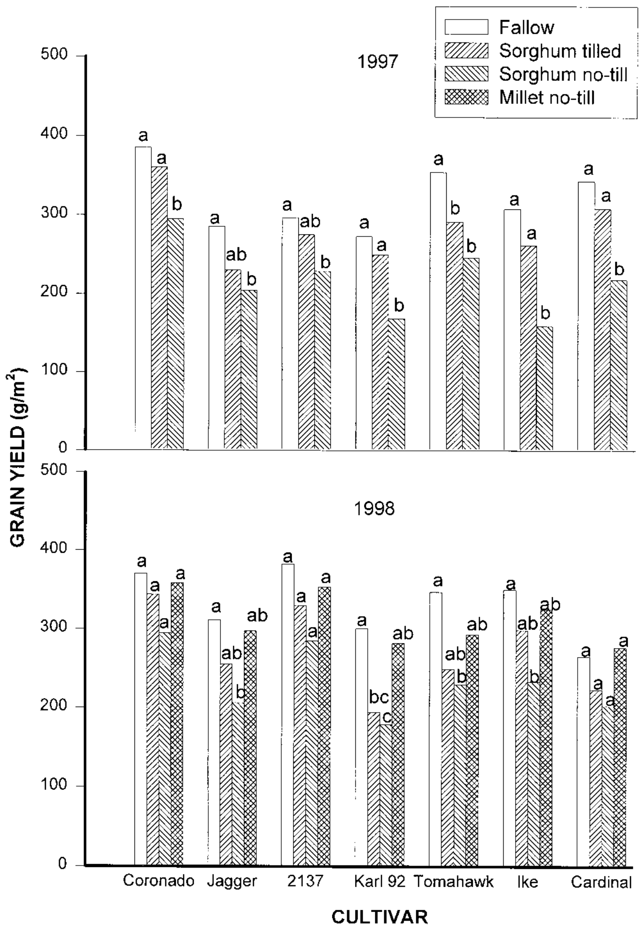

Fig. 3. Grain yields of seven wheat cultivars after different sorghum and millet residue treatments. LSD = 68 among cultivars and 62 among residue treatments during 1997 and 79 among cultivars and 97 among residue treatments during 1998. Within each cultivar, bars with different letters differ significantly among residue treatments at $P = 0.05$.

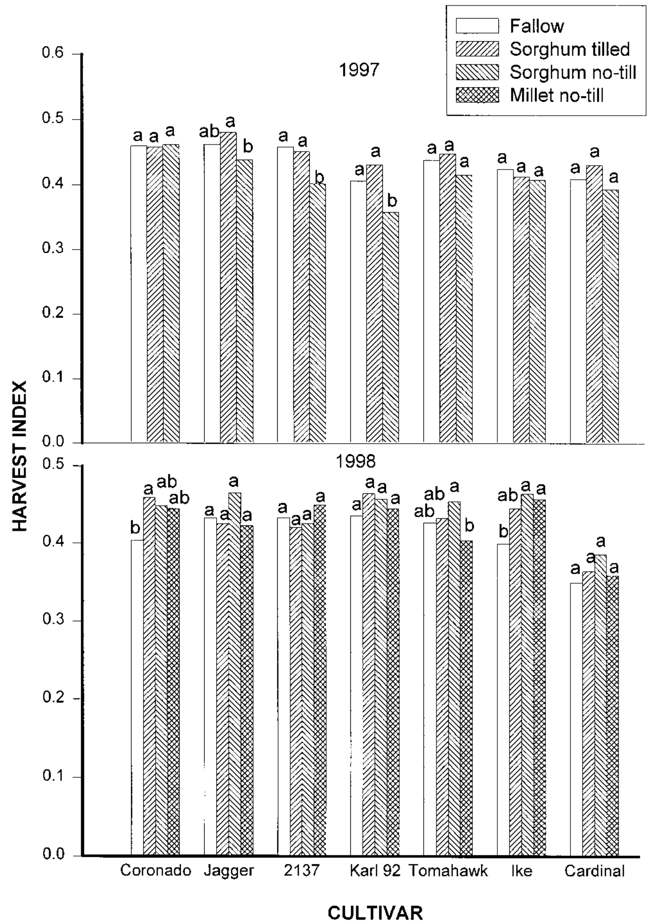

Fig. 4. Harvest index of seven wheat cultivars after different sorghum and millet residue treatments. LSD = 0.03 among cultivars and residue treatments during 1997 and 0.04 among cultivars and residue treatments during 1998. Within each cultivar, bars with different letters differ significantly among residue treatments at $P = 0.05$.

second season. Differences among residue treatments were inconsistent, however, because of the interaction. Spike densities of two cultivars were higher after no-till sorghum than after tilled sorghum, but densities of two other cultivars were higher after fallow than after no-till sorghum in 1997. The stands were more uniform among tillage treatments in 1998, and the only effect noted was a slightly lower density for Coronado after no-till sorghum than after fallow.

Chlorophyll concentration in the flag leaves and total plant N concentration at the boot stage of wheat were similar for all treatments and cultivars. Mean values of 45.2 Spad chlorophyll units and 21 g/kg total N were adequate for excellent yields both years (Kansas Coop. Ext. Serv., 1997).

Wheat Yield and Yield Components

Grain yields differed significantly among cultivar and residue treatments both years (Fig. 3). Coronada, Tomahawk, and Cardinal were higher yielding the first season, and Coronada, 2137, Tomahawk, and Ike yielded more the second season. Yields were often lower after no-till sorghum than after fallow during both seasons. Grain yields of all wheat cultivars after fallow exceeded yields after no-till sorghum in 1997, and yields following tilled sorghum were usually intermediate. Four of the cultivars—Jagger, Karl 92, Tomahawk, and Ike—responded similarly in 1998, with higher grain yields after fallow than after no-till sorghum. Yields of the other cultivars did not differ among the residue treatments.

Straw weights of the seven wheat cultivars differed less than the grain yields (data not shown). Tomahawk had more straw after fallow than after both sorghum residue treatments in 1997, and Karl 92 and Ike had more straw after fallow than after tilled sorghum and no-till sorghum, respectively, in 1998.

Cultivar and residue treatments significantly affected harvest index but responses varied because of their interaction (Fig. 4). Jagger had a lower harvest index after no-till sorghum than after tilled sorghum, and 2137 and Karl 92 had lower harvest indices after no-till sorghum than after both fallow and tilled sorghum in 1997. In 1998, Coronado and Ike had lower harvest indices after tilled sorghum and no-till sorghum and millet, respectively, and Tomahawk had a lower harvest index after millet than after no-till sorghum.

Mean values of the two yield components measured were similar for all cultivars, 36 kernels per spike and 32 mg/ kernel. Residue treatment affected kernel number of only two cultivars. Values were lower in Tomahawk after millet (29) than after fallow (38) and in Cardinal after tilled sorghum (30) than after no-till sorghum (37). Kernel weight differed more frequently, being lower in Coronado, Jagger, Karl 92, and Tomahawk after fallow than after one or more of the other residue treatments.

DISCUSSION

Responses of wheat to the treatments suggested that tillage affected solubilization of allelopathic compounds from sorghum stover. Allelopathic compounds in sorghum that was tilled into the soil probably were solubilized rapidly by soil moisture from ample rainfall (Purvis, 1990). As was particularly evident during the second season, emergence of wheat cultivars was delayed following tilled sorghum compared with other residue treatments. However, allelopathic compounds released from sorghum that was worked into the soil were presumably degraded over time (Guenzi et al., 1967). Early degradation of the allelopathic compounds apparently allowed the seven wheat cultivars to produce grain yields following tilled sorghum that were indistinguishable from yields following fallow. Although emergence was delayed by tilled sorghum in many cases, the marked ability of wheat to compensate for differences in seedling development probably also contributed to the absence of any effect on grain yield (Paulsen, 1987).

Responses of the wheat cultivars to no-till sorghum differed substantially from the responses to tilled sorghum. The small effects of no-till sorghum on emergence and stand establishment of wheat during both autumns suggested that the allelopathic compounds were not released immediately into the soil. However, depressed wheat grain yields in the following summers indicated that the allelopathic compounds were solubilized and leached from the sorghum stover during the winter and spring. Yields of all seven wheat cultivars were reduced in the first year, and yields of four cultivars were reduced in the second year after no-till sorghum compared with fallow.

Solubilization and leaching of allelopathic compounds from the stubble of no-till sorghum undoubtedly depended on precipitation, as was the case with sorghum incorporated into soil (Purvis, 1990). The amount, intensity, and duration of precipitation and the air temperature probably influenced the leaching pattern of allelopathic compounds, just as they affected loss of other soluble constituents from senescing tissue (Noodén, 1980). The delayed effect of no-till sorghum also suggested that allelopathic compounds degraded slowly, if at all, in nonincorporated stover compared with their rapid degradation in soil (Guenzi et al., 1967).

Genetic differences in the allelopathic potential among sorghum hybrids were evident in previous reports (Ben-Hammouda et al., 1995a, 1995b). Sorghum hybrids differed in the phenolic contents of the residues (Ben-Hammouda et al., 1995b) and in their effects on radicle elongation of one wheat cultivar (Ben-Hammouda et al., 1995a). Our results, in contrast, found no consistent differences in tolerance to sorghum residue among the wheat cultivars. Some differences in responses of the wheat cultivars to allelopathy were evident during different growth stages, but none of the cultivars was resistant at both the seedling and grain filling stages. If they were available, cultivars that resist allelopathy during the latter stage might be combined with suitable tillage of sorghum residue for highest yields of wheat.

Our results suggest that the effect of sorghum residue on the following wheat crop depends in large part on the degree of decomposition of the stover before the wheat is planted. Prompt tillage of the stover after harvest of the sorghum could alleviate allelopathy by extending the duration for decomposition and, in many cases, enabling it to occur at a more favorable soil temperature before wheat is planted. Although it was not investigated here, chopping the sorghum stover finely also might accelerate decomposition. The beneficial effects of adequate soil moisture (Purvis, 1990) also suggest that irrigation of dry soil could promote decomposition and lessen allelopathy from sorghum on wheat.

The merits of practices that reduce allelopathy from sorghum must be weighed against the soil-conserving benefits of not tilling the stover. Tillage should only be considered when the soil is not subject to erosion from water and wind. Sorghum residue on highly erodible soil should not be tilled.

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TROPICAL SOIL MANAGEMENT

Sequential Cropping as a Function of Water in a Seasonal Tropical Region

Ricardo Radulovich*

ABSTRACT

In the seasonal (wet–dry) tropics, yields of rainfed staple crops are usually low and variable. However, our simulations have indicated that rainfall could be used more efficiently, increasing the length of the rainfed cropping season, the number of crops grown, and their yields, while decreasing yield variability and risk. To evaluate these predictions, cropping schemes with two or three annual rainfed crops grown in sequence were field-tested. Irrigated plantings were subsequently added to evaluate year-round cropping. Work was conducted in Costa Rica during 4 yr at one site and 1 yr at a second site. Both sites have a half-year-long, bimodal rainy season, and have deep soils with high water-holding capacity. The first crop of each year was planted early using preseason rains, and the last was planted to mature after the rainy season to maximize depletion of available soil water. Rainfed cropping sequences averaged 255 d long, which is from 50 to 100 d longer than local practices. Adding an irrigated planting during the dry season brought the mean length of the cropping season up to 346 d. Of 115 plantings, only 7 had low yields; all others had medium or high yields. Adding an irrigated crop increased yield potential of a year-round cropping season composed of two or more plantings. All low yields were attributed here to extended water excess conditions. However, water excess effects do not remain after the rainy season, nor into the next rainy season.

The major limitation to all-year cropping in the tropics is imposed by water, where rainfall distribution dictates the seasons. Water shortages and excesses contribute significantly to low and highly variable yields, and often to complete crop failure. This is particularly important for the seasonal (wet–dry) tropics, due to large and often unpredictable variations in water conditions. For example, water deficit and excess explained from 70 to 90% of regional yield variability of bean (*Phaseolus vulgaris* L.), maize (*Zea mays* L.), and rice (*Oryza sativa* L.) in a seasonal tropical area (Radulovich, 1990).

Optimizing the use of available rainfall will contribute to increased productivity and to decreased yield variability. Thus, it will be possible to improve further annual cropping in seasonal tropical regions, which occupy 1.0 to 1.5 billion ha of potentially cultivable land area in the world (Sanchez, 1976; Lal, 1987). Because both economic and water resources available to expand irrigation are limited, selecting the right crops while increasing the use of rainfall water are, in many cases, the only options to increase productivity. Moreover, this must be done while dealing with water excess during the peaks of the rainy season.

Multiple cropping has clearly been recognized as an important method to increase resource use (e.g., Papendick et al., 1976). With sequential cropping, benefits are derived from obtaining the yield of more than one crop per year, grown one after another. In general, the longer actively growing crops are in the field, the more radiation will be intercepted and used for biomass and harvestable yields. However, largely due to highly variable rainfall characteristics, traditional rainfed farmers optimize using cautious, low-input cropping schemes—mainly a single maize crop, planted late to mature soon

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Abbreviations: AQUA, Agricultural Query and Analysis, a water balance model; CATIE, Tropical Agronomy Center for Research and Teaching, Turrialba, Costa Rica; CIAT, International Center for Tropical Agriculture, Cali, Colombia; FAO, Food and Agriculture Organization of the United Nations.