LONG TERM MONO- AND DOUBLE-CROPPING WHEAT, SOYBEAN, AND GRAIN SORGHUM UNDER RAINFED AND IRRIGATED CONDITIONS

AND

EVALUATION OF POTASSIUM QUANTITY-INTENSITY RELATIONSHIPS OF TWO OKLAHOMA SOILS

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This manuscript is dedicated to my late Mother-In-Law, Madam Janet Aduke Oyinlola, and my late son, Oluwaseyi Adedayo Adesina, who went to be with the Lord while I was studying in the United States of America. We shall soon meet to part no more at the feet of our Lord Jesus Christ where all tears shall be wiped away.

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"Because Thy Loving Kindness Is Better Than Life, My Lips Shall Praise Thee.

Thus Will I Bless Thee While I Live; I Will Lift Up My Hands In Thy Name.

My Soul Shall Be Satisfied As With Marrow and Fatness; And My Mouth Shall Praise Thee With Joyful Lips:

When I Remember Thee Upon My Bed, And Meditate On Thee In The Night Watches.

Because Thou Hast Been My Help, Therefore In The Shadow Of Thy Wings Will I Rejoice.

My Soul Followeth Hard After Thee: Thy Right Hand Upholdeth Me."

Psalm 63:3-8

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INTRODUCTION

Each part of this dissertation is a separate manuscript to be submitted for journal publication. Both parts will be submitted to Agronomy Journal, an American Society of Agronomy Publication. Articles in this journal are peer reviewed and must report experiments repeated over time and/or space.

PART I

LONG TERM MONO- AND DOUBLE-CROPPING WHEAT, SOYBEAN, AND GRAIN SORGHUM UNDER RAINFED AND IRRIGATED CONDITIONS

ABSTRACT

Many growers continue to have interest in double-cropping hard red winter wheat (Triticum aestivum (L.) em Thell), soybean (Glycine max L. Merr.), and grain sorghum (Sorghum bicolor (L.) Moench) in the eastern part of Oklahoma. Fall, winter, and spring precipitation is usually sufficient in this part of the state to produce wheat. Removal of water from the soil profile by the wheat crop and erratic distribution of rainfall during the summer months, however, often results in soil moisture deficits during the reproductive growth stages of both double-cropped soybean and grain sorghum. An eight-year (1981-1988) field study was conducted at the Oklahoma Vegetable Research Station, Bixby, Oklahoma, on a Wynona silt loam soil (Cumulic Haplaquoll) with 0-1% slope. The objective of the field investigation was to evaluate the long-term yields of mono- and double-cropped wheat, soybean, and grain sorghum. All wheat was produced under rainfed conditions while soybean and grain sorghum were produced under both conventional and no-till systems and under irrigated and rainfed conditions in eastern Oklahoma. Over the 8-yr study period, monocropped wheat yielded an average of 2970 compared with an average of 2405 kg ha^{-1} for all double-cropped wheat. When the data for wheat yields were pooled and analyzed over years, there was a significant ($P < 0.01$) cropping system (C) x year (Y) interaction. The higher yields under monocropping were expected as monocropped wheat is planted around the first to third week of October

and benefits from more fall growth and tillering compared with early November to early December planting and less tillering of the double-cropped wheat. Irrigated monocropped soybean yielded an average of 3110 compared with 2720 kg ha^{-1} for rainfed, monocropped soybean, and irrigated double-cropped yielded an average of 2250 compared with 1940 kg ha^{-1} for rainfed, double-cropped soybean. When the data for soybean yields were pooled and analyzed over years there were significant water (W) x Y, C x Y, and W x C x Y interactions. When compared with rainfed conditions the application of supplemental irrigation consistently increased soybean yields under monocropping. Under double-cropping, irrigation increased yields in five out of eight years. These results are most likely responsible for the significant interaction effects of C x W x Y interaction. Irrigated conventionally tilled monocropped grain sorghum averaged 6220 compared with 6010 kg ha^{-1} for rainfed conventionally tilled monocropped grain sorghum. Irrigated no-till double-cropped sorghum yielded an average of 5300 compared with 4360 kg ha^{-1} for rainfed no-till double-cropped sorghum. When the data for grain sorghum were pooled and analyzed over years, there were significant ($P < 0.01$) C x W, W x Y, C x Y, and W x C x Y interactions. The C x W, W x Y, and C x Y interactions can be attributed to the contrasting yield differences between rainfed and irrigated treatments over years for different cropping systems. These interaction effects were due to wide variation in amounts and distributions of rainfall during the 8-yr period. The significance of the three-factor interaction (C x W x Y) for both soybean and grain sorghum implies that the two-factor interaction effect of C x W was not the same for yields in all the eight years.

INTRODUCTION

With some 215 frost free days and the desire to more fully utilize climatic resources, land, equipment, labor, and management skills, many growers continue to have interest in double-cropping hard red winter wheat [Triticum aestivum (L.) em Thell], soybean (Glycine max L. Merr.), and grain sorghum [Sorghum bicolor (L.) Moench] in the eastern part of Oklahoma. Fall, winter, and spring precipitation is usually sufficient to produce wheat. Removal of water from the soil profile by the wheat crop and erratic distribution of rainfall during the summer months, however, often results in soil moisture deficits during the reproductive growth stages of both double-cropped soybean and grain sorghum.

The objective of this field investigation was to evaluate the long-term yields of mono- and double-cropped wheat, soybean, and grain sorghum. All wheat was produced under rainfed conditions. Soybean and grain sorghum were produced under conventionally tilled mono- and no-till double-cropped systems and under rainfed and irrigated conditions.

LITERATURE REVIEW

Conventional Tillage

Conventional tillage is often considered the standard of comparison for other tillage systems (Sanford, 1982). Larson (1962) defines conventional tillage as a system of soil preparation for planting which includes plowing, disking, harrowing, and in many cases, subsequent cultivation. Baeumer and Bakermans, (1973) defined conventional tillage in much the same way as Larson, in that it usually begins with a primary deep tillage operation such as a mold-board plow followed by secondary tillage using a disk, harrow, hoe, or cultivator for seedbed preparation. Primary tillage often increases porosity and surface roughness thereby increasing water infiltration and the soil's resistance to water and wind erosion (Larson, 1962).

Secondary tillage operations usually degrade soil structure units and decrease protective cover, thereby reducing water infiltration and increasing the soil's water and wind erodibility potential (Baeumer and Bakermans, 1973). Soane and Pidgeon (1975) reported that secondary tillage is required to prepare the top 10 cm of soil so that crop seeds can be placed uniformly at the correct depth, insuring adequate soil-seed contact to provide water for germination and early growth, as well as eliminating large clods which can obstruct shoot and seedling root growth.

Kuipers (1963) reported that the principal advantage of tillage is to get a good soil environment for plant growth. According to him the relationship between the tillage operation and yield is affected by such factors as soil condition (soil type and pore space), the implements used in the operation (soil engaging heads), and the way in which the implements are used (working depth and speed).

According to Graffis et al. (1973) and Hoeft et al. (1975), some of the advantages of conventional tillage are: (1) uniform seedbed for easy planting; (2) insecticides and herbicides can be incorporated as needed; (3) flexible and adaptable to a wide range of soil, crop, and weather conditions; (4) results in yields as high or higher than other systems over a wide range of soil and climatic conditions; and (5) necessary equipment is readily available on most farms.

Unger and Phillips (1973) reported that conventional tillage practices, which expose the bare soil during periods of potentially high runoff and evaporation, can serve to deplete the soil moisture supply or reduce the possibilities for moisture recharge when it is most needed. Graffis et al. (1973) and Hoeft et al. (1975) also reported other disadvantages of conventional tillage which include: (1) high cost because of the large number of operations; (2) often results in excessive tillage so that soil crusting and compaction may be a problem; (3) results in small aggregates so that water intake is reduced; (4) takes valuable time and decreases soil moisture in the plow layer, making it less suitable for double-cropping; (5) subjects fine and compact soil particles to wind and water erosion.

Graffis et al. (1973), Hoeft et al. (1975), Buntley (1977), Soane and Pidgeon (1975), and Kamprath et al.(1979) reported that in many cases the recompaction of the layer below the cultivated soil is due to the heavy traffic of implements used to conduct secondary tillage operations. However, this was largely offset by the loosening effect of primary tillage. Hard pans, caused by cementation processes, can also reduce root proliferation and penetration into horizons below the pan so that water uptake efficiency is decreased (Kamprath et al., 1979). Unger and Stewart (1976) proposed that reducing field operations or restricting field traffic to specific zones should maintain better soil conditions for planting and seedling establishment.

Another disadvantage of conventional tillage is the formation of a soil crust. Allen et al. (1975) and Sanford (1982) found 8 cm of intense rainfall, four days after planting and accompanied by a hot dry wind, caused a dense crust formation which prevented the emergence of soybean seedlings. In contrast, soybean in no-tilled plots emerged to a near perfect stand. Sanford (1982) reported that during land preparation by disking and harrowing, the loss of soil moisture through evaporation significantly reduced emergence and survival of soybean seedlings.

No-Tillage

Young (1982) defined no-tillage as planting crops in unprepared soil by opening a narrow slot, trench or band only of sufficient width and depth to obtain proper seed coverage. He also reported that the terms no-tillage, zero tillage, chemical tillage, direct seeding, direct planting, direct drilling, no-plow tillage, eco-fallow, no-till and sod planting are all known as "no-tillage." Young (1982), also reported that a further refinement of no-tillage is aerial seeding of small grains in standing corn, grain sorghum, soybean or other crops making possible production of both row crops and small grains in a sequence without tillage.

Crosson (1981) and Young (1973) defined no-tillage as placing the crop seed into the soil by a device that opens a trench or slot through the sod, or previous crop residue, only sufficiently wide and deep enough to receive the seed and to provide satisfactory seed coverage. Sanford et al. (1973) defined no-tillage as a term which refers to tillage only by the rolling coulter at planting in the seed zone, usually 5 cm wide and 10 cm deep.

The concern for pollution of lakes, streams, and reservoirs from soil erosion and surface runoff has prompted researchers to develop and evaluate systems that require less tillage (Sanford et al, 1973). In no-tillage systems, herbicides are used to control existing vegetation and the crop is planted directly into the soil with no plowing or other tillage operations (Clapp, 1972). The key to successful no-tillage is satisfactory control of noncrop vegetation with herbicides without injury to the crop (Young, 1973).

Sanford et al. (1973) reported that management is the keystone to a sound no-tillage program. They reported that no-tillage planting provided the least delay in establishing a second crop, thereby increasing chances for success in double-cropping. They also observed that in Mississippi, when unsatisfactory results were obtained from use of reduced tillage methods, they were usually related to poor weed control, poor management, or lack of knowledge of the complete technology of production. Crops grown under a no-till system generally use more available soil moisture during their life cycles and use it more efficiently than do crops grown with conventional tillage practices (Blevins et al., 1971; Prihar et al., 1979; Shanholtz and Lillard, 1969).

Some of the advantages that can be derived from no-tillage systems include: (1) reduced soil and moisture loss, (2) control of wind and water erosion, (3) ability to plant with higher moisture conditions, (4) reduced labor and production costs, (5) reduced soil compaction, (6) earlier planting, and (7) yields equal to or higher than those produced from conventional tillage (Graffis et al., 1973; Gregory et al., 1970; Hargrove et al., 1982; Stougaard et al., 1984).

Much evidence has accumulated showing that the surface mulch often associated with no-tillage lowers soil temperatures at depths ranging from 2.5 to 10 cm. The mulch reduces the diurnal fluctuation in soil temperature with the greatest difference, compared to bare soil, occurring in the daily maximum temperature (Phillips, 1969; Moody et al., 1963). Moody et al. (1963) concluded that later in the growing season corn growth rates were superior for no-tillage (mulch) compared to bare soil.

Bennett et al. (1973) reported that lower soil temperatures under mulch reduced evaporation rates considerably in no-till plots, and with reduced rainfall runoff, resulted in a significantly greater amount of available soil moisture for plant growth. Mulch also physically absorbs raindrop impact energy; thus, slaking and sealing of soil surface is prevented or retarded. In most instances no-tillage offers surface residues to increase infiltration and decrease erosion (Unger and Phillips, 1973). Unger (1978) reported that soil temperature is affected by many factors, including air temperature, soil water content, soil structure, soil texture, and type and amount of vegetative cover.

Surface residues associated with reduced or no-tillage systems often result in lower spring and summer soil temperatures when compared with fallow soil (Taylor, 1967; Unger, 1978). Therefore, favorable temperatures for germination and emergence may occur up to 7 days later in a no-tillage seedbed. Planting may be delayed 6 or 7 days with no-tillage systems used in northern latitudes of the United States (Unger and Stewart, 1976). Although lower temperatures may delay planting in the spring, lower temperatures under surface residues in the summer may beneficially influence a late-planted crop or crops growing during hot periods (Allen et al., 1975; Rockwood and Lal, 1974). Rockwood and Lal (1974) reported that corn yields were 50% greater with no-tillage compared with conventional tillage because lower temperatures reduced plant water stress.

Smith and Camper (1975) reported that both size and quality of soybean seed are affected by genetic and environmental conditions. Green et al. (1965) and Tyler and Overton (1982) reported that, in a hot dry growing season, soybean seed produced under no-tillage usually appeared to be of greater quality than those produced under conventional tillage. Greater seed quality was attributed to more soil water availability. In Tennessee, Tyler and Overton (1982) found that soybean seed quality from no-tillage systems was improved over soybean grown in conventional tillage systems. This was primarily due to the enhanced availability of soil water under the no-tillage system during dry periods. Seed germination, weight, density, and yield were also superior under drought stress in no-tillage compared with conventional tillage methods.

The purely protective effect of residue cover may influence the rate of evaporation. Bond and Willis (1969) and Papendick and Miller (1977) observed that the evaporation rate decreased as the amount of mulch increased, resulting in a higher mean volumetric moisture content in the upper soil layer when compared with conventional tillage.

Tillage systems may influence the retention and movement of water in the soil profile (Soane and Pidgeon, 1975). Mulch increases the level of soil water storage and conserves water by increasing infiltration and reducing runoff and evaporation (Blevins et al., 1971; Greb et al., 1970; Jones et al., 1969; Robertson et al., 1976). No-tillage is often employed with a heavy surface mulch of plant residues to increase infiltration and decrease erosion hazards (Harrold et al., 1970), but in Britain, the presence of mulch is considered undesirable (Soane and Pidgeon, 1975). On silt loam with an 8 to 10% slope that was planted in row crops using a no-tillage system, reduction of runoff was decreased from 1/2 to 1/6 of the amount observed under clean tillage (Harrold and Edwards, 1972; Jones et al., 1969).

In long term (10-years) tillage study on a Maury silt loam in Kentucky, Frye (1986) found the organic matter content in the surface 5 cm of soil receiving annual applications of 168 kg ha^{-1} fertilizer N was 4.82% for no-tillage and 2.40% for conventional tillage. He reported that the higher amount of organic matter near the soil surface with no-tillage could be attributed to lack of mechanical mixing of plant residues into the soil that resulted in slower decomposition. He also reported that exchangeable potassium (K) in the surface 5 cm was about twice as high under no-tillage compared with conventional tillage. Hargrove et al. (1982) reported that continuous no-tillage resulted in increased nutrient concentrations in the surface soil with a rapid decrease with depth, while conventional tillage resulted in a more homogeneous soil with respect to soil fertility status. Blevins et al. (1977) reported that soil organic matter and organic nitrogen (N) increased significantly in the top 5 cm of soil for corn production under no-tillage, compared with conventional tillage systems.

In the Texas panhandle, under no-tillage, grain sorghum plants emerged faster, grew taller, and matured up to 5 days earlier compared with tilled plots. Slower drying of the soil surface and improved microclimate under no-tillage during seedling emergence, apparently aids in a faster start and resulted in an increased yield average of 5,690 compared with 5070 kg ha^{-1} under conventional tilled grain sorghum production systems (Allen et al., 1975).

Total water use efficiency was higher for no-tillage than for conventional tillage corn populations in West Virginia (Bennett et al., 1973). They reported that greater water use efficiency with no-tillage can largely be attributed to early season residue effects on slowing evaporation loss and increasing growth and yield.

Inadequate seedbed water at planting time is a major limiting factor to early establishment of any crop (Papendick and Miller, 1977). Plant growth and yield responses to a given tillage system depends primarily on water conservation practices. Under no-tillage conditions, the decreased evaporation at the surface and reduced runoff enhances the potential for a given soil to store moisture often results in a water reserve which can carry the crop through periods of short-term drought without detrimental moisture stress developing in the plants (Blevins et al., 1971).

Some disadvantages of no-tillage systems are: (1) poor stands, in some instances which may limit yields; (2) special planting equipment requirements; (3) higher incidence of insect and disease damage due to crop residues, serving as a host habitat; (4) weed control problems due to interference of crop residues with herbicides; and (5) escaped or herbicide-tolerant grassy and broadleaf weeds (Graffis et al., 1973; Gregory et al., 1970; Sanford et al., 1973; Sanford, 1982).

Weeds are the most economically detrimental pest problem for soybean growers using reduced tillage practices (Marra and Carlson, 1983). Thompson (1981) reported that competition for moisture, plant nutrients, and sunlight made weeds the number one soybean yield robber. Triplett (1978) reported that for no-till cropping practices, complete reliance for control of weeds must be placed on the use of herbicides. According to Robinson et al. (1984), weeds have to be controlled in no-till soybeans for 90% of the growing season to avoid yield loss.

In a study by Sanford et al. (1973), competition from weeds in no-till soybean and grain sorghum caused significant yield reductions. In Arkansas, Hinkle (1975) showed that soybean and grain sorghum grown under no-till conditions resulted in yields comparable to conventionally tilled production if good chemical weed control was obtained.

There are many herbicides available for use on no-till cropping systems, but when soybean is grown under no-tillage conditions whether mono- or double-cropped, some weeds may be quite difficult to control (Shurtleff and Coble, 1985). They reported that common cocklebur with a density of 8 weeds per 10 m row reduced soybean yields 11%, while a density of 16 weeds per 10 m row for common ragweed (Ambrosia artemesilfolia) resulted in a 12% reduction in yield.

Johnsongrass (Sorghum halepense), and several morningglory species (Ipomoea spp.) are some of the most serious weed pests in the southern region of the United States (Palmer, 1979). He reported that they were difficult to control due to herbicidal tolerance. The primary factor to the herbicidal tolerance of these weeds is that the seedlings will emerge from depths of up to 15 cm, which is below the zone of herbicide-treated soil in most cases (Chandler et al., 1977). McWhorter and Anderson (1981) reported that various degrees of infestations of johnsongrass reduced soybean yields by 50% or more. Black et al. (1969) considered johnsongrass a very competitive species, in that it fixed carbon dioxide at very high rates and produced large quantities of rhizomes and seeds.

Weed control was a major factor in yield reduction for soybean and grain sorghum (Sanford et al, 1973). In a study in Mississippi, Sanford (1982) reported that the two-year yield average for no-tillage was 3,250 compared with 3,870 kg ha^{-1} for conventional tillage grain sorghum with the difference in yield being attributed mainly to a lack of weed control on no-tilled plots.

Studies conducted in Arkansas double-cropping wheat with soybean or grain sorghum by Hinkle (1975), showed that yields of a second crop planted no-tillage resulted in comparable yields to conventional tillage with good chemical weed control. High yields and improvements in herbicides have become important reasons in the change to no-tillage crop production (Young, 1973). With the continuous development of new and improved herbicides to control grass and broadleaf weed problems, the popularity of no-tillage systems has increased in many areas in the United States (Kapusta, 1979; Whitwell et al., 1985). It has been predicted that 65% of the seven major annual grain crops will be grown by the no-tillage system by the year 2000 (USDA, 1975).

Water Requirements for Crops

Plant water requirements change during the growing season and stress at some growth stages affects crop yield more than at other stages (Stone et al., 1978). Soil water potential, coupled with atmospheric demands and other plant factors, acts indirectly on growth through its influence on plant water potential which, in turn, affects the rate of plant growth (Gandar and Tanner, 1976).

Entz and Fowler (1988) reported that the extent to which water and temperature stresses affected the yield of wheat was dependent on the development stage at which time these stresses occurred and pre-stress conditioning. The influence of temperature and water stresses on wheat yield is generally least during tillering stage and greatest during the period between stem elongation and anthesis (Nix and Fitzpatrick, 1969; Fischer and Maurer, 1976; Doorenbos and Kassam, 1979; Johnson and Kanemasu, 1982).

Water supply at wheat jointing has been shown to influence spike number per unit area (Baier and Robertson, 1967; Day and Intalap, 1970), and post-anthesis drought causes die-back of tillers (Musick and Dusek, 1980). The number of kernels per spike of wheat has been reported to be most severely reduced by water stress during the 15 day period prior to anthesis (Baier and Robertson, 1967; Fischer, 1973). Both water (Baier and Robertson, 1967; Day and Intalap, 1970) and high temperature (daily maximum temperature of 34 vs. 26°C), stress (Fischer and Maurer, 1976) during the grain filling period have been shown to reduce kernel weight.

Schneider et al. (1969) reported that the most critical period for winter wheat was from the booting through the grain filling stages. They found that timing of irrigation was as important as total quantity of water applied. Eck (1980) reported that if limited irrigation was to be used in wheat production in the Southern Great Plains, it could be used more efficiently by preventing stress during tillering and jointing than during heading and grain filling. He also reported that stress during tillering and jointing limited yield potential that was not regained when stress was relieved. Thus, if stress is prevented until heading, the maximum yield of the plant is developed and can be taken advantage of during heading and grain filling.

Under humid or irrigated conditions, narrow row spacings of 0.10 to 0.20 m give highest yields for most small grains (Holliday, 1963; Joseph et al., 1985). Johnson and Davis (1980) reported that winter wheat which did not develop adequate secondary rooting in the fall on a Pullman clay loam soil did not effectively utilize stored soil water from below the 1.0 m depth. Winter and Welch (1987) reported that while using semi-dwarf wheat in wide-row systems was successful in reducing crop water deficit and increasing plant height, grain yield was reduced in wide-row systems compared to narrow-row systems for both tall and semi-dwarf wheat.

In semi-arid regions, yearly differences in yield response to N fertilizer in wheat may be attributed to variability in precipitation and the associated variability in the degree of moisture stress (French and Schultz, 1984). Campbell and Davidson (1979) reported that monitoring moisture stress during the season might provide a guideline for timing N fertilizer application to increase the efficiency of N utilization in wheat. Korentajer and Berliner (1988) reported that over 69% of the variability in wheat yields was due to main seasonal stress index effect.

Withholding irrigation or inducing water stress in wheat has increased water use efficiency (WUE) (Singh and Kumar, 1981; Aggarwal and Sinha, 1983; Misra and Chaudhary, 1985), but others have reported that withholding water decreased WUE (Johnson et al., 1984; Bapna and Khuspe, 1980; Rao and Bhardwaj, 1981). Nicholas et al. (1984) reported that drought and heat stress during the first 10 to 12 days following anthesis reduced kernel weight of wheat.

According to Heatherly (1980) a plant's response to water is evidently more closely related to soil water potential than to any other single factor. He found that for the most rapid vegetative growth and development of soybean, soil moisture potential should be kept above -0.6 bars. He also reported that adequate moisture is the major factor limiting yield in most areas where soybean is grown.

Subjecting soybean to water stress during flower induction shortens the flowering period and causes flower abortion, whereas stress during pod filling reduces seed number and weight (Sionit and Kramer, 1977). When the supply of water and nutrients translocated to the shoot are severely limited, the shoot may slow its rate of terminal growth functions which include photosynthesis and assimilation, leaf expansion, and flower initiation or retention according to Howell (1960) and Levitt (1980). Sojka and Parsons (1983) reported that when significant water stress occurred during the vegetative stages of growth, complete canopy coverage was never achieved for determinate soybean cultivars because vegetative growth tended to cease with flowering.

Soybean is also more sensitive to water deficits during reproductive stages than during vegetative growth stages (Brown et al., 1985; Salter and Goode, 1967; Thompson, 1975; Jung and Scott, 1980; Doss et al., 1974). They reported that pod filling was the critical period when soybean plants needed adequate water for maximum yield. Their results showed that reductions in seed size and seed number were major components responsible for reduced soybean yield in moisture stressed treatments.

Doss et al. (1974) reported that the pod-fill stage, from 15 August to 20 September for "Bragg" soybean at Thorsby, Alabama, was the critical time to have adequate water for maximum yield. Farah (1983) reported that yield reduction from water deficits depends not only on the magnitude of the deficit, but also on the stage of the plant growth. Shipley and Regier (1975) found that withholding a 10 cm irrigation during the six to eight-leaf stage, mid to late bloom stage and early pod set stage in soybean reduced yields 12, 35, and 45%, respectively. The sensitivity of soybean to water stress measured in terms of yield reduction tended to increase dramatically as the crop advanced through its natural sequence of reproductive ontogeny (Kadhem et al., 1985). They reported that sensitivity increased to a maximum during the late pod elongation and subsequent seed enlargement stages. They also suggested that the full pod (R4) stage was a critical "cross-over" point in reproductive ontogeny relative to irrigation timing and its effect on seed size.

Researchers have not agreed upon the growth stage of grain sorghum that is most susceptible to drought stress. Stages identified are boot through bloom (Lewis et al., 1974), heading through bloom (Shipley and Regier, 1975), boot (Inuyama et al., 1976), heading to milk (Plant et al., 1969), and heading through grain filling (Musick and Dusek, 1971). Despite these differences, the consensus is that water stress, just prior to or during reproductive stages of growth, decreases yields.

Eck and Musick (1979a) reported that when grain sorghum plants are stressed at the early boot stage and continued for 27 days or longer, the yields decreased as a result of a reduction in number and size of seed, but when stress was initiated at heading or later, only seed size was decreased. Musick and Dusek (1971) reported that water stress influenced yield primarily by reducing the size and/or number of heads and limiting grain filling. Robins et al. (1967) reported that when sorghum was stressed during the boot to flowering stage, pollination failure or head blast may occur, so grain yield is reduced.

Unger (1988) reported that grain sorghum is adapted to the Southern and Central Great Plains, but water stress at critical reproductive stages could sharply reduce grain yields of the crop on dryland. He also concluded that forage sorghums used water effectively and were not as dependent on adequate water at critical reproductive growth stages as grain sorghum for grain production.

Unger (1984), Unger and Wiese (1979), and Musick and Dusek (1971) reported that although grain sorghum responded to irrigation, it also performed well on dryland provided soil water was not limiting at planting, and rainfall was near normal in the southern High Plains during the growing season. Sorghum grain yields on dryland, however, can be reduced sharply by water stress during critical reproductive growth stages (booting, flowering, and grain filling), even though early growth may provide for near-normal stover production (Unger and Wiese, 1979).

Arkin et al. (1978) reported that water deficits in grain sorghum might also affect canopy development by a reduction in total leaf number, rates of individual leaf emergence from the whorl, and on leaf extension and senescence. All these components are important in determining the surface area available for transpiration and assimilate production (Meyers et al., 1984; Parameswara and Krishnasastry, 1982; El-Sharkawy et al., 1965). Rosenthal et al. (1987) reported that the reduction in leaf extension induced by soil water deficit also reduced leaf area and total biomass and was highly correlated with reduction in cumulative transpiration in grain sorghum. They also reported that reductions of leaf development were closely related to soil water deficits in grain sorghum.

Recent studies (Ogunlela and Eastin, 1984; Saeed et al., 1986) have reported that increases in kernel weight of sorghum were due largely to rate of kernel fill with little difference in duration of growth. While number of kernels per panicle of sorghum is the yield component most variable with environment, final dry weight per kernel is the only component that can change for a panicle after kernel number per panicle has been set (Stickler and Pauli, 1961).

Irrigation

Dillon and Mckibben (1972) reported that drought was probably the major cause of failure in nonirrigated double-cropping systems in

Illinois. When rainfall is inadequate or not properly distributed throughout the growing season, irrigation will usually increase both mono- and double-cropped yields (Ashley and Ethridge, 1978; Boerma and Ashley, 1982). Crabtree and Makonnen (1981) predicted that double-cropping without irrigation would be successful in eastern Oklahoma approximately 60% of the time.

Noori et al. (1985) reported that germination and emergence of winter wheat were critical to crop stand establishment. Low soil water potentials, often found in seedbeds in semi-arid areas, result in slow seed imbibition and germination (Collis-George and Sands, 1959). Slow emergence influences seedling vigor and can affect yield (Lindstrom, 1973). Ward and Shaykewich (1972) and Ashraf and Abu-Shakra (1978) reported that as soil water content decreased, the rate of water uptake by the wheat kernel decreased. Decreasing soil moisture content tends to delay wheat germination (Pawloski and Shaykewich, 1972).

Stark and Longley (1986) reported that tillers in spring wheat which developed under optimal soil moisture conditions were uniform in appearance and reached maximum populations over relatively short degree-day periods. They also reported that soil water deficits decreased the rate of appearance of all main stem tillers, caused tiller appearance to occur over longer intervals, and dry soil conditions severely reduced development of tillers at the coleoptilar node. Klepper et al. (1982) and Rickman et al. (1983) reported that adverse seedbed conditions caused tillers to be omitted or delayed in appearance in winter wheat. Cannell (1969) reported that the time of tiller appearance has a pronounced effect on yield potential. He also reported that the time of appearance was closely linked to tiller survival, size, and productivity. Soil water deficits during vegetative development of wheat can affect leaf area, tiller survival, tiller size, initiation of floral primordia, and the number of grains per spikelet (Aspinall et al., 1964; Slatyer, 1973; Begg and Turner, 1976; Oosterhuis and Cartwright, 1983).

Water is the primary limiting factor to successful soybean production in the semi-arid Great Plains (Korte et al., 1983). Drought stress has been shown to reduce critical growth processes such as photosynthesis, cell enlargement, cell division, and nitrogen fixation. Water stress at critical growth periods appears to be one of the most frequently limiting factors in successful crop production (Brown et al., 1985; Doss and Thurlow, 1974). In a study conducted by Korte et al. (1983) eight soybean cultivars were subjected to either no irrigation or one irrigation applied at three reproductive stages of growth: (1) flowering, (2) pod elongation, and (3) seed enlargement. The flowering irrigation increased yields 20 kg ha^{-1}, pod elongation irrigation increased yields 379 kg ha^{-1}, and seed enlargement irrigation increased yields 384 kg ha^{-1}, compared with nonirrigation.

Ashley and Ethridge (1978) and Kadhem et al. (1985) reported that: (1) a moderate water supply produced about the same yield response as a high supply; (2) irrigation during the vegetative growth period is less important than during flowering, pod set, and pod fill stages; (3) response to irrigation varies with cultivars; and (4) plant lodging is frequently a problem when soybean cultivars are irrigated. Timing rather than quantity of irrigation appears to be more important in determining the effects of irrigation on soybean yields. Results are variable, but most research indicates that irrigation during pod elongation and seed enlargement results in highest seed yields (Brown et al., 1985; Reicosky and Deaton, 1979; Doss et al. 1974).

Research has indicated that grain sorghum yields are reduced if water stress occurs at any time during plant growth (Lewis et al., 1974). Since it is more drought tolerant and highly responsive to added water, it is adapted to both dryland and irrigated conditions (Eck and Musick, 1979a). The greatest response to irrigation has been during the vegetative, vegetative to heading, booting and heading, booting through bloom, and grain filling growth stages (Lewis et al., 1974; Musick and Dusek, 1971; Salter and Goode, 1967; Stewart et al., 1975). Lewis et al. (1974) recorded yield reductions of 17%, 34%, and 10% when the water deficit occurred during the late vegetative to boot stage, boot through bloom stage, and milk through soft dough stage, respectively. Stewart et al. (1975) reported no yield response to irrigation at milk stage or later. Crabtree et al. (1986) reported that irrigation increased the yields of mono- and double-cropped grain sorghum 786 and 1120 kg ha^{-1}, respectively.

Management practices for higher yields such as higher plant populations, increased fertilization, improved varieties, better irrigation timing, and narrower rows are more feasible with irrigation, although maximum response to irrigation comes when other management practices are optimum (Jensen and Musick, 1962).

Double-Cropping

Hovermale et al. (1979) defined double-cropping as the production of two crops grown in succession on the same area of land in one year. According to Hinkle (1975), double-cropping achieves greater utilization of solar energy, reduction of production costs, and better land use efficiency. Phillips and Young (1973) reported that the most widely-used double-cropping program in the United States is small grains and soybean. Wheat following soybean in a double-cropping system is efficient in much of the southeastern United States, extending from Florida and Georgia north to Southern Illinois and west to Oklahoma (Crabtree and Rupp, 1980; McHarry and Kapusta, 1979; Touchton et al., 1980).

Double-cropping with the use of no-tillage systems requires a high level of management in that each operation must be performed at the most appropriate time (Sanford et al., 1973). They also reported that planting time is critical if the normal maturity date of the preceding crop extends beyond the normal planting range for the succeeding crop. Therefore, no-tillage planting provides the least delay in establishing a second crop. Knapp and Knapp (1978) reported that late-planted wheat produced lower grain yields because it extracted less water from the soil, developed a less extensive root system, fewer tillers, and resulted in fewer heads to harvest when compared with optimal planted dates.

Weather risks associated with double-cropping are reduced through no-tillage practices, largely, because of a reduction in the time required for seedbed preparation and reduction in evaporation loss of soil moisture because of less soil disturbances (Young, 1982). He also reported that harvesting might be easier in a wet season than in conventional tilled fields.

Touchton and Johnson (1982) postulated that climatic conditions, such as number of frost-free days and distribution of rainfall in midsummer, played an important role in the success of double-cropping. They also reported that after wheat harvest, potential soybean yield decreased each day planting was delayed.

McKibben and Pendleton (1968) reported that factors contributing to yield reductions of late-planted, double-cropped soybean were the uncertainty of rainfall in late June and July for good germination and early growth, and frost before crop maturity. Despite the reduction of individual crop yields in the double-cropping system, the total grain yield of the two crops combined is usually higher than either crop grown as a mono-crop (Crabtree and Makonnen, 1981; Rogers et al., 1971; Sanford, 1982). Sanford (1982) also reported that yields of wheat were higher when double-cropped after soybean than when double-cropped after grain sorghum. He attributed the higher wheat yields following soybean to the contribution by soybean to the nitrogen supply and improved tilth.

Dillon and McKibben (1972) reported that perennial weeds caused more problems than annual weeds with double-cropping. A major factor in the occurrence of weed problems is that herbicides with longer residual effects that can be used to effectively control weeds in one crop may cause injury to the subsequent crop and, therefore, are not suitable for use in double-cropping systems (Dillon and McKibben, 1972; Hinkle, 1975; Ndon et al., 1982).

Malcolm (1980) and Mullins et al. (1972) reported that residue interference could reduce crop stands in double-cropping systems, while residue removal or burning over a period of several years might reduce soil productivity, and increase soil erosion and water runoff. Swearingin (1973) found that using weighted fluted coulters in front of planter units helped to overcome the problem of stand establishment in residues by cutting through them and placing the seed deep enough to reach moist soil for good germination and emergence.

Other management practices that increase the chances for successful double-cropping include: (1) excellent stand of small grain to help control weeds; (2) sufficient moisture; (3) adequate fertility for both crops; and (4) planting the summer crop as soon as possible (Crabtree and Rupp,1980; Flannery, 1977; Mederski et al., 1973; Buntley, 1977).

MATERIALS AND METHODS

This study was conducted at the Vegetable Research Station, Bixby, Oklahoma from 1981-88 on a Wynona silt loam soil (Cumulic Haplaquolls) with 0-1% slope.

In the fall of 1980, the seedbed for all wheat was prepared by moldboard plowing plus two tandem diskings. In subsequent years, the same tillage operations were used to prepare the seedbed for monocropped wheat. Two tandem diskings of the double-cropped soybean and grain sorghum stubble were used to prepare the seedbed for double-cropped wheat. From 1980 to 1987, fall soil tests showed phosphorus (P) and potassium (K) to be at the 100% sufficiency levels as determined by the Oklahoma State University soil testing laboratory procedures and recommendations.

Winter wheat, 'TAM-105' was planted on monocropped plots, with a range of 5 October to 21 October planting dates at a rate of 67 kg ha^{-1}. Double-cropped wheat plots were planted with a range of 6 November to 4 December planting dates at a rate of 101 kg ha^{-1}. A hoe drill with 0.25 m row spacings was used to plant the wheat in plots 9.15 x 18.3 m (1981-88). Each year wheat was top-dressed by broadcasting NH_4NO_3 at a rate of 135 kg N ha^{-1} during mid to late February. Wheat grain yields were obtained by harvesting a 3.05 x 18.3 m strip from the center of each plot on dates that ranged from 8 June to 2 July. Wheat yield data were analyzed using a randomized complete-block design consisting of five treatments with four replications.

Seedbed preparation for the conventionally tilled monocropped soybean and grain sorghum treatments consisted of moldboard plowing and two tandem diskings. No-till double-cropped soybean and grain sorghum were seeded directly into standing wheat stubble. All grain sorghum plots received a broadcast application of NH_4NO_3 at 135 kg N ha^{-1} just prior to planting.

Soybean, 'Forrest,' (Maturity Group V) were planted at 296,000 viable seed ha^{-1}. Grain sorghum, cultivars 'Acco BR-Y93' (1981-84) and 'Acco BR-Y90' (1985-88), were planted at 296,000 viable seeds ha^{-1}. Both crops were planted using an eight row, no-till planter equipped with ripple coulters, double-disk openers, 40 mm depth bands, and press wheels. The planter was configured to plant wheel traffic and non-wheel traffic rows in 0.75 and 0.50 m row spacings, respectively. Conventionally tilled monocropped soybean and grain sorghum were planted with a range of 22 May to June planting dates. No-till double-cropped soybean and grain sorghum were planted with a range of 9 June to 3 July planting dates. Soybean and grain sorghum plots were the same size as wheat.

Trifluralin (a,a,a-trifluoro-2,6-dinitro-N-N-dipropyl-p-toluidine) was broadcast on the conventionally tilled, monocropped soybean plots at 1.1 kg ha^{-1} in 234 L ha^{-1} water and incorporated with a Do-all prior to planting. All mono-cropped soybean treatments also received one mechanical cultivation. No-till double-cropped soybean treatments received 1.1 kg ha^{-1} glyphosate [N-(phosphonomethyl) glycine] broadcast in 234 L ha^{-1} water immediately after planting. All soybean plots received a tank-mixed, postemergence application of bentazon (3-isopropyl-1H-2,1,3-benzothiadiazin-4-(trifluoromethyl)phenoxy]-2-nitrobenzoate at 0.56 and 0.42 kg ha^{-1}, respectively, in 234 L ha^{-1} water. Glyphosate was used to control rhizome johnsongrass [Sorghum halepense (L.) Pers.] by spot treating as needed from 1981-83. In 1984 and subsequent years, a separate application of fluazifopbuty(±)-butyl 2-[4-[(5-(trifluoromethyl)-2-pyridinyl)oxy]phenoxy]propanoate at 0.19 kg ha^{-1} along with 0.53 L surfactant in 234 L ha^{-1} water were also applied postemergence to all soybean treatments for continued johnsongrass control.

The above-mentioned postemergence herbicide applications were necessary due to weed pressure from morningglory (Ipomoea purpurea, Ipomoea hederacea var. jacq., and Ipomoea hederaceae var. integriuascula), cocklebur (Xanthium pensylvanicum Wallr.), redroot pigweed (Amaranthus retroflexus L.), common lambsquarters (Chenopodium album L.), and rhizome johnsongrass.

Propazine [2-chloro-4,6-bis(isopropylamino)-s-triazine] was broadcast at 1.34 kg ha^{-1} in 234 L ha^{-1} water, on the conventionally tilled, monocropped grain sorghum plots immediately after planting. Glyphosate and linuron[3-(3,4-dicholorophenyl)-1-methoxy-1-methylurea] were broadcast on the no-till, double-cropped grain sorghum plots as a tank-mixed preemergence application at 1.12 and 0.56 kg ha^{-1}, respectively, in 234 L ha^{-1} water. Conventionally tilled, monocropped grain sorghum plots received one mechanical cultivation. All grain sorghum plots also received a postemergence broadcast application of 0.84 kg ha^{-1} 2,4-Dacamine (N-oleyl-1,3-propylenediamine) in 234 L ha^{-1}

water. Glyphosate was used to spot treat rhizome johnsongrass as needed for control throughout the experiment.

Soybean and grain sorghum yields were obtained by harvesting 2.92 x 18.3 m strip from the center of each plot. Harvest dates ranged from 21 October to 20 November and 13 September to 30 October for monocropped soybean and grain sorghum, respectively. Harvest dates ranged from 25 October to 20 November and 25 September to 20 November for double-cropped soybean and grain sorghum, respectively. Soybean and grain sorghum yield data were analyzed separately using a 2 x 2 factorial. Treatment factors and their respective levels were water (rainfed and irrigated) and cropping systems (monocropped and double-cropped). These constituted the treatments in a randomized complete-block design with four replications.

RESULTS AND DISCUSSION

Rainfall

Monthly distribution and total rainfall amounts from 1 January 1981 to 31 December 1988 and the 30-yr monthly average (1959 to 1988) are given in Table 1. Monthly distributions of rainfall for each year of the eight year study are given in Fig. 1 and 2. Rainfall is generally sufficient to replenish soil water during late winter, spring, and early summer. The last half of July, August, and September remain critical for double-cropped soybean and grain sorghum because of less rainfall and higher atmospheric demand.

Wheat Yields

Total amount of precipitation during the months of February, March, and April was low (63 mm) in 1982 compared with 192, 204, and 258 mm in 1981, 1983 and 1984, respectively. Over the next four-year period (1985-1988) rainfall amounts and distribution were good from February through May of each year with the exception of April and May 1988, when lower than average rainfall was obtained (Figure 2, Table 1).

In 1981 monocropped wheat yielded significantly more ($P < 0.01$) compared with double-cropped wheat (Table 2). Double-cropped wheat yields were significantly higher ($P < 0.05$) where the previous years rainfed and irrigated double-cropped soybeans were grown compared with the rainfed and irrigated double-cropped grain sorghum treatments (Table 2). The 1982 yields for all wheat cropping systems were considerably lower in magnitude compared with other years and can be attributed to an outbreak of tan spot (<u>Pyrenophora</u> <u>triticirepentis</u>). Although tan spot decreased yields, monocropped wheat still significantly ($P < 0.01$) out yielded double-cropped wheat (Table 2). Higher than normal rainfall in May and June, along with lower wheat yields, allowed subsoil water to accumulate in considerable magnitude. Double-cropped wheat yields were not significantly different whether soybean or grain sorghum was grown under rainfed or irrigated conditions in 1981.

In 1983 monocropped wheat yielded significantly ($P < 0.01$) more compared with double-cropped wheat (Table 2). The wheat yield from the rainfed double-cropped wheat and irrigated double-cropped soybean treatment was significantly ($P < 0.05$) higher compared with the two wheat yields double-cropped following grain sorghum in 1982 (Table 2). For the 1984 environment monocropped wheat yielded significantly more ($P < 0.01$) than double-cropped wheat. A wheat yield of 2970 kg ha^{-1} from the rainfed double-cropped wheat and irrigated double-cropped soybean treatment was significantly ($P < 0.05$) higher compared with the rainfed double-cropped wheat and rainfed double-cropped grain sorghum treatment (Table 2).

In 1985 monocropped wheat yielded significantly ($P < 0.01$) more compared with double-cropped wheat. There were no statistically significant differences ($P > 0.05$) between double-cropped wheat treatments (Table 2). The rainfall pattern in 1986 was slightly different from the previous years in that there was zero precipitation in January and well above average precipitation in April, May, September, and October of the same year compared with the 30-yr average. However, the total rainfall in 1986 was lower than total rainfall for 1984 and 1985 (Table 1). Monocropped wheat yielded significantly ($P < 0.05$) more in 1986 compared with double-cropped wheat (Table 2). The drastic yield reduction in 1986 was due to an outbreak of leaf rust (Puccinia recondita Rob. ex Desm F. sp. tritici Eriks).

For the 1987 environment monocropped wheat yielded 2480, significant at ($P < 0.01$), compared with 1910, 1940, 1660, and 1750 kg ha^{-1} for double-cropped wheat (Table 2). Double-cropped wheat yields were not significantly different from one another across all treatments. As with the seven previous years, the 1988 monocropped wheat yielded significantly more ($P < 0.01$) when compared with double-cropped wheat with the 2920 kg ha^{-1} wheat yield from the rainfed double-cropped wheat and rainfed double-cropped grain sorghum treatment being significantly higher ($P < 0.05$) compared with rainfed double-cropped wheat and irrigated double-cropped soybean treatment (Table 2).

When wheat yield data were pooled and analyzed over the 8-yr study period, there was a significant ($P < 0.01$) cropping system, year, and cropping system x year interaction effect. Monocropped wheat yielded an average of 2970 (significant $P < 0.01$) compared with an average of 2400, 2460, 2390, and 2370 kg ha^{-1} for double-cropped wheat (Table 2). These results are similar to those reported by Crabtree and Makonnen (1980) and Crabtree et al. (1987). The higher yields under monocropping were expected as monocropped wheat is planted around the first to third week of October and benefits from more fall growth and tillering compared with early November to early December planting and less tillering of the double-cropped wheat.

Soybean Yields

Rainfall amounts and distribution the last half of July, August, and September remain critical for summer grown crops. During this period supplemental water applications were made on the designated irrigation treatments in either 0, 50, 60, or 70 mm increments (Table 3).

In 1981 there was a highly significant ($P < 0.01$) response to irrigation by both mono- and double-cropped soybean (Table 4). Irrigated monocropped soybean yielded 3200 compared with 1860 kg ha^{-1} for rainfed monocropped soybean, and irrigated double-cropped soybean yielded 2300 compared with 1800 kg ha^{-1} for rainfed double-cropped soybean. The water x cropping system interaction was significant ($P < 0.01$) and can be attributed to the magnitude in increased yield response to irrigation for both mono- and double-cropped soybean (Table 4).

The 1982 soybean yields differed markedly from the 1981 yields. Irrigated monocropped soybean yielded significantly more ($P < 0.05$) compared with rainfed monocropped soybean (Table 4). With the addition of 260 mm of supplemental water, irrigated double-cropped soybean yielded only 1740 compared with 1590 kg ha^{-1} for rainfed double-cropped soybean. The only plausible explanation that can be offered for the failure of double-cropped soybean to show a better response to irrigation is that from middle to late August and during the first half of September high temperatures accompanied low amounts of rainfall which resulted in a high rate of flower abortion and lower pod set.

In 1983, 300 and 360 mm of water were applied to the irrigated monocropped and irrigated double-cropped soybean treatments, respectively. Irrigated monocropped soybean yielded more ($P < 0.05$) 3000 compared with 2610 kg ha^{-1} for rainfed monocropped soybean. Irrigated double-cropped soybean yielded 2680 (significant ($P < 0.05$) compared with 1170 kg ha^{-1} for rainfed double-cropped soybean (Table 4). There was a significant ($P < 0.01$) water x cropping system interaction (Table 4), but unlike 1981, it may be attributed to the magnitude of the yield response of the double-cropped soybean to irrigation, which was much higher (129%) than for the monocropped soybean (15%).

Total rainfall during July, August, and September was somewhat improved over 1983 and was similar in total amount to 1982 (Table 1). With good subsoil moisture and 55 mm of rainfall on 8, 9, 10 August and another 34 mm on 9 September, there was no significant difference in yields of irrigated and rainfed monocropped soybean, although the irrigated treatment had received 120 mm of supplemental water. With the addition of 200 mm water, irrigated double-cropped yielded 1530 compared with 1260 kg ha^{-1} for the rainfed double-cropped soybean (Table 4). The lack of response to irrigation by both soybean cropping systems was similar to that recorded for the 1982 environment.

With the addition of 150 mm of supplemental water to both monocropped and double-cropped soybean treatments in 1985, there was no significant response to irrigation (Table 4). The rainfed monocropped soybean yield of 3240 kg ha^{-1} was not significantly higher ($P > 0.05$) when compared with both rainfed and irrigated double-cropped soybean yields of 2840 and 2760 kg ha^{-1}, respectively. The irrigated double-cropped soybean yield was not significant ($P > 0.05$) when compared with the rainfed double-cropped soybean yield and the irrigated monocropped yield of 3560 kg ha^{-1} was not significant ($P > 0.05$) when compared with 3240 kg ha^{-1} for rainfed monocropped soybean (Table 4).

For the 1986 environment the application of 120 mm supplemental water to both monocropped and double-cropped soybean in June and July did not result in significant higher yields (Table 4). There was adequate precipitation during August, September, and through mid-October and is likely responsible for no significant response to irrigation (Fig. 2). As expected the analysis of variance showed no cropping system, water or water x cropping system interaction effects (Table 4).

In 1987, significantly ($P < 0.01$) higher yields were obtained from mono- compared with double-cropped soybean treatments (Table 4). The rainfall amount and distribution during the summer months were similar to that of 1986 (Table 1). With an application of 110 mm supplemental water irrigated monocropped soybean yielded only 60 kg ha^{-1} more than rainfed monocropped soybean and irrigated double-cropped yielded only 80 kg more compared with rainfed double-cropped soybean (Table 4). There was a significant ($P < 0.01$) cropping system effect on soybean yields in 1987 (Table 4).

There was also a significant cropping system response on soybean yields in 1988 (Table 4). This can be attributed to the replanting of double-cropped soybeans because of the lack of water at the soil surface for adequate first planting stand establishment. The late planting produced small soybeans at harvest. There was no statistically significant difference between the yields of irrigated and rainfed monocropped soybean or irrigated and rainfed double-cropped soybeans (Table 4).

Over the 8-yr period irrigated monocropped soybean yields averaged 3110 compared with 2720 kg ha^{-1} for rainfed monocropped soybean. Monocropped soybean responded significantly ($P < 0.05$) to irrigation in only three out of eight years. Irrigated double-cropped soybean yielded an average of 2250 compared with 1940 kg ha^{-1} for rainfed, double-cropped soybean. Double-cropped soybean responded significantly ($P < 0.01$) to irrigation in only two out of eight years (Table 4). When the data for soybean yields were analyzed over years there were significant ($P < 0.01$) cropping system, water, and year effects. In addition there were significant ($P < 0.01$) water x year, crop x year, and a significant ($P < 0.05$) water x crop x year interactions. The significance of the three-factor interaction implies that the two-factor interaction effect of water x cropping system was not the same for yields over the 8-yr period.

Grain Sorghum Yields

In 1981, 200 and 260 mm of supplemental water were applied to irrigated conventionally tilled monocropped and no-till double-cropped grain sorghum treatments, respectively. Yields of both irrigated grain sorghum treatments were similar (Table 5). Rainfed no-till double-cropped yielded 640 kg ha^{-1} more than did rainfed conventionally tilled monocropped grain sorghum. This demonstrates the erratic differences in environments growers have to contend with in growing summer crops, regardless of the cropping system in the Southern Great Plains.

In 1982 higher than normal rainfall in May and June along with lower wheat yields allowed subsoil water to accumulate prior to planting sorghum. Cooler than normal temperatures and timely distribution and favorable amounts of rainfall during the growing season resulted in no significant yield ($P > 0.01$) differences between treatments, even when 160 and 180 mm of supplemental water were applied to conventionally tilled and no-till double-cropped grain sorghum, respectively (Table 5).

During the summer of 1983, 320 and 360 mm of water were applied to the conventionally tilled monocropped and no-till double-cropped grain sorghum treatments, respectively. Irrigated conventionally tilled monocropped grain sorghum yielded 6160 ($P < 0.01$) compared with 5000 kg ha^{-1} for rainfed no-till double-cropped grain sorghum (Table 5). Irrigated no-till double-cropped sorghum yielded 5330 ($P < 0.01$) compared with 3520 kg ha^{-1} for rainfed no-till double-cropped grain sorghum. Unlike the previous two years, there was a significant ($P < 0.05$) water x cropping system interaction (Table 5) which can be attributed to the increase in yields of both cropping treatments due to irrigation. The increase was significantly higher for irrigated no-till double-cropped (52%) compared with an increase of 23% for conventionally tilled monocropped grain sorghum.

Total rainfall during July, August, and September of 1984 was higher than that in 1983, but similar in total amount to that of 1982 (Table 1). With good subsoil moisture and 55 mm of rainfall on 8, 9, and 10 August and another 34 mm on 9 September, there was no significant difference in yields of irrigated conventionally tilled monocropped and rainfed no-till double-cropped grain sorghum, although the irrigated conventionally tilled monocropped treatment had received 120 mm of supplemental water. With the addition of 200 mm of water, no-till double-cropped grain sorghum yielded 4680 compared with 2700 kg ha^{-1} for the rainfed no-till double-cropped grain sorghum (Table 5). The cropping system x water interaction was significant ($P < 0.01$) and can be attributed to the magnitude in yield difference (37%) between the irrigated no-till double-cropped and rainfed no-till double-cropped grain sorghum treatments.

The highest annual precipitation (1266 mm) during the 8-yr study period was recorded in 1985. Only 70 mm of water were applied to each of the conventionally tilled monocropped and no-till double-cropped grain sorghum treatments (Table 3). Irrigated conventionally tilled grain sorghum yielded significantly more compared with rainfed conventionally tilled monocropped grain sorghum. Irrigated no-till double-cropped grain sorghum yielded 5420 ($P < 0.01$) compared with 4020 kg ha^{-1} for rainfed no-till double-cropped grain sorghum (Table 5). The cropping system x water interaction was significant ($P < 0.01$) and can be attributed to the magnitude in yield difference between the irrigated monocropped and irrigated double-cropped grain sorghum treatments (Table 5).

Total rainfall during July, August, and September, 1986 was higher than that in 1985 (Table 1). With improved adequate distribution and favorable amounts of rainfall during the growing season (Table 1, Fig 2) no significant yield differences between rainfed and irrigated conventionally tilled monocropped grain sorghum or rainfed and irrigated no-till double-cropped grain sorghum treatments, even when 120 mm of supplemental water was applied to conventionally tilled monocropped and no-till double-cropped grain sorghum (Table 5). However, rainfed conventionally tilled monocropped grain sorghum was significantly ($P < 0.01$) higher than rainfed no-till double-cropped grain sorghum and irrigated conventionally tilled monocropped grain sorghum was significantly ($P < 0.05$) higher than rainfed no-till double-cropped grain sorghum treatment. There was a significant ($P < 0.05$) cropping system effect on grain sorghum yield in 1986.

There was adequate precipitation for both mono- and double-cropped grain sorghum and no supplemental water was applied in 1987 (Table 1 and 3). The yield pattern was similar to those obtained in 1986 (Table 5) in that rainfed conventionally tilled monocropped grain sorghum yield was not significantly ($P > 0.05$) different from irrigated conventionally tilled monocropped grain sorghum and rainfed no-till double-cropped grain sorghum was not significantly ($P > 0.05$) different from irrigated no-till double-cropped grain sorghum treatment. However, irrigated no-till double-cropped grain sorghum was significantly ($P < 0.05$) higher compared with irrigated conventionally tilled monocropped grain sorghum yield. There was no significant ($P > 0.05$) cropping system effect on grain sorghum yields in 1987.

In 1988, 150 mm of supplemental water was applied to irrigated conventionally tilled monocropped grain sorghum treatments, respectively. There was no significantly different yield at 0.05 level between rainfed and irrigated monocropped grain sorghum (Table 5). Both the rainfed and irrigated conventionally tilled monocropped yield of 5860 and 5660 kg ha^{-1}, respectively, were significantly different ($P < 0.01$) when compared with 2590 and 3300 kg ha^{-1} yields of rainfed no-till double-cropped and irrigated no-till double-cropped grain sorghum yields, respectively (Table 5). There was a significant ($P < 0.01$) cropping system effect on grain sorghum yield in 1988.

Over the 8-yr study period, irrigated conventionally tilled monocropped grain sorghum averaged 6220 compared with 6010 kg ha^{-1} for rainfed conventionally tilled monocropped grain sorghum. Irrigated no-till double-cropped sorghum yielded an average of 5300 compared with 4360 kg ha^{-1} for rainfed no-till double cropped sorghum (Table 5). When the data for grain sorghum were analyzed over years, there were significant ($P < 0.01$) water x year, crop x year, and water x crop x year interactions. The significance of the three-factor interaction implies that the two-factor interaction effect of water x cropping system was not the same over the 8-yr period. These results are similar to those obtained by Crabtree et al. (1986). In six out of the eight years, supplemental irrigation did not significantly increase grain sorghum yields when monocropped (Table 5). In contrast, irrigation of double-cropped grain sorghum significantly increased yields four out of eight years (Table 4). When the grain sorghum yield data were pooled over the 8-yr period, there was a significant ($P < 0.01$) W x C interaction (Table 5), which can be attributed to the contrasting yield differences between rainfed and irrigated treatments. These interaction effects were due to wide variation in amounts and distributions of rainfall during the 8-yr period (Table 1, Fig. 1 and 2) which often occurs in the southern Great Plains.

SUMMARY AND CONCLUSIONS

Over the 8-yr study period, monocropped wheat yielded an average of 2970 compared with 2400 kg ha^{-1} for double-cropped wheat. During this period, wheat yields from the double-cropping practices were not significantly influenced by the supplemental water applied to the preceding double-cropped soybean or grain sorghum. These results are similar to those reported by Crabtree and Makonnen (1980) and Crabtree et al. (1987). When the data for wheat yields were pooled and analyzed over years there were significant water x year, crop x year, and water x crop x year interactions.

Irrigated monocropped soybean yielded an average of 3110 compared with 2720 kg ha^{-1} for rainfed monocropped soybean. Irrigated double-cropped soybean yielded an average of 2250 compared with 1940 kg ha^{-1} for rainfed double-cropped soybean. When the data for soybean yields were pooled and analyzed over years, there were significant water x year, crop x year, and water x crop x year interactions. The significance of the three-factor interaction implies that the two-factor interaction effect of cropping system x water was not the same for yields in all the eight years. The largest magnitudes in yield deviations from the 8 year mean occurred from 1981 to 1984. When compared with rainfed conditions, the application of supplemental irrigation increased soybean yields in five out of eight years. These results are most likely responsible for the significant interaction effects of C x W x Y.

Irrigated conventionally tilled monocropped grain sorghum averaged 6220 compared with 6010 kg ha^{-1} for rainfed conventionally tilled monocropped grain sorghum. Irrigated no-till double-cropped grain sorghum yielded an average of 5300 compared with 4360 kg ha^{-1} for rainfed no-till double-cropped grain sorghum. When the data for grain sorghum were pooled and analyzed over years there were significant ($P < 0.01$) cropping system x water, water x year, crop x year, and a significant water x crop x year interactions. In six out of the eight years, supplemental irrigation did not significantly ($P > 0.05$) increase grain sorghum yields when monocropped. In contrast, the irrigation of double-cropped grain sorghum significantly increased yields four out of eight years. The significant cropping system x water interaction can be attributed to the contrasting yield differences between rainfed and irrigated treatments. These interaction effects were due to wide variation in amounts and distributions of rainfall during the 8-yr period which is common in eastern Oklahoma.

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Table 1. Rainfall from 1 January 1981 to 31 December 1988 and the 30-yr monthly average (1959-1988) at the Vegetable Research Station, Bixby, Oklahoma.

	Rainfall								
Month	1981	1982	1983	1984	1985	1986	1987	1988	30-yr Avg.[+]
	mm								
January	17	91	65	10	21	00	77	26	39
February	34	12	71	70	102	31	136	35	44
March	50	20	48	125	118	49	56	162	65
April	108	31	85	63	123	114	17	45	96
May	141	199	177	126	74	204	210	30	126
June	96	156	69	89	170	56	67	27	114
July	76	59	26	15	69	12	72	135	86
August	104	58	7	57	57	88	65	22	67
September	100	20	41	55	118	264	78	133	103
October	166	42	260	180	237	178	32	23	85
November	81	159	78	62	144	81	90	148	74
December	4	81	13	268	33	27	177	71	48
Totals	977	928	940	1120	1266	1104	1077	867	947

[+] Rainfall data collected at the Vegetable Research Station.

Table 2. Means and mean squares for estimating the effects of cropping systems and years on the yields of wheat.

Cropping Systems	1981[+]	1982	1983	1984	1985	1986	1987	1988	1981-88
	kg ha^{-1}								
RMCWH[‡]	3580	2570	3490	3520	2660	2190	2480	3310	2970
RDCWH-RDCSB	3210	1980	2990	2770	1860	1870	1910	2630	2400
RDCWH-IDCSB	3160	1940	3080	2970	2190	1860	1940	2530	2460
RDCWH-RDCGS	3060	2070	2770	2550	2100	1980	1660	2920	2390
RDCWH-IDCGS	2940	2150	2700	2820	2150	1730	1750	2760	2370
LSD (0.05)	200	250	180	270	360	280	310	340	93
LSD (0.01)	280	340	250	380	500	390	440	480	123

	MS								
SOURCE	1981	1982	1983	1984	1985	1986	1987	1988	1981-88
Cropping system (C)	** 230820	** 254610	** 390610	** 526860	** 341090	* 118990	** 407500	** 371940	** 2102130
Year (Y)	-	-	-	-	-	-	-	-	** 5350947
C x Y	-	-	-	-	-	-	-	-	** 77180
ERROR	16750	25260	13170	30830	54280	32020	40820	48520	34992

[+] Mean of four replications.
[‡] Rainfed monocropped wheat (RMCWH).
Rainfed double-cropped wheat and rainfed double-cropped soybean (RDCWH-RDCSB).
Rainfed double-cropped wheat and irrigated double-cropped soybean (RDCWH-IDCSB).
Rainfed double-cropped wheat and rainfed double-cropped grain sorghum (RDCWH-RDCGS).
Rainfed double-cropped wheat and irrigated double-cropped grain sorghum (RDCWH-IDCGS).
*,**Significant at the 0.05 and 0.01 probability levels, respectively.

Table 3. Supplemental irrigation applied to soybean and grain sorghum at the Vegetable Research Station, Bixby, Oklahoma.

Cropping system	1981	1982	1983	1984	1985	1986	1987	1988
	mm							
ICT-MCSB[+]	200	200	300	120	150	120	110	150
INT-DCSB	260	260	360	200	150	120	110	150
ICT-MCGS	200	160	320	120	70	120	0	150
INT-DCGS	260	180	360	200	70	120	0	150

[+] Irrigated conventionally tilled monocropped soybean (ICT-MCSB), irrigated no-till double-cropped soybean (INT-DCSB), irrigated conventionally tilled monocropped grain sorghum (ICT-MCGS), and irrigated no-till double-cropped grain sorghum (INT-DCGS)

Table 4. Means and mean squares for estimating the effects of cropping systems and supplemental water on the yields of soybean.

Cropping Systems	1981[+]	1982	1983	1984	1985	1986	1987	1988	1981-88
	kg ha^{-1}								
RCT-MCSB[†]	1860	1820	2620	2560	3240	3440	3380	2860	2720
ICT-MCSB	3200	2310	3000	2800	3560	3450	3440	3150	3110
RNT-DCSB	1800	1590	1170	1260	2840	3410	2560	850	1940
INT-DCSB	2300	1740	2680	1530	2760	3390	2640	980	2250
LSD (0.05)	210	370	270	330	380	180	520	400	310
LSD (0.01)	300	530	390	470	550	260	740	580	400

	MS								
SOURCE	1981	1982	1983	1984	1985	1986	1987	1988	1981-88
Cropping systems(C)	922700**	627230**	3126650**	6685840**	1462980**	6780	2584010**	17550000**	21760000**
Water (W)	3381210**	398450*	3586090**	257790*	61980	60	19920	180960	4031570**
C x W	697410**	113690	1248580**	860	155260	1540	550	23980	43520
Year (Y)	-	-	-	-	-	-	-	-	5562070**
W x Y	-	-	-	-	-	-	-	-	550700**
C x Y	-	-	-	-	-	-	-	-	1600330**
C x W x Y	-	-	-	-	-	-	-	-	314050*
ERROR	16660	53370	29310	42100	57000	12330	104630	63220	47370

[+] Mean of four replications.

[†] Rainfed conventionally tilled monocropped soybeans (RCT-MCSB).
Irrigated conventionally tilled monocropped soybean (ICT-MCSB).
Rainfed no-till double-cropped soybean (RNT-DCSB).
Irrigated no-till double-cropped soybean (INT-DCSB).

Table 5. Means and mean squares for estimating the effects of cropping systems and supplemental water on the yields of grain sorghum.

Cropping Systems	1981[+]	1982	1983	1984	1985	1986	1987	1988	1981-88
	kg ha^{-1}								
RCT-MCGS[†]	3180	6100	5000	7110	7330	6530	6980	5860	6010
ICT-MCGS	4570	5910	6160	7160	7630	6230	6420	5660	6220
RNT-DCGS	3820	5860	3520	2700	4020	5370	7000	2590	4360
INT-DCGS	4670	5960	5330	4680	5420	5950	7070	3300	5300
LSD (0.05)	650	810	450	830	420	710	600	1030	620
LSD (0.01)	940	1170	640	1200	600	1030	860	1480	820

	MS								
SOURCE	1981	1982	1983	1984	1985	1986	1987	1988	1981-88
Cropping systems(C)	554920	34680	5341880**	47620000**	32500000**	2076070*	444250	31790000**	53900000**
Water (W)	5064660**	7110	8890480**	4124640**	2326090**	78580	240190	259780	10130000**
C x W	292740	83040	421040*	3720980**	834520**	781660	403420	841700	4026000**
Year (Y)	-	-	-	-	-	-	-	-	14390000**
W x Y	-	-	-	-	-	-	-	-	1551110**
C x Y	-	-	-	-	-	-	-	-	9493000**
C x W x Y	-	-	-	-	-	-	-	-	479020*
Error	165570	258020	78460	271880	67780	198940	139220	415140	192420

[+] Mean of four replications

[†] Rainfed conventionally tilled monocropped grain sorghum (RCT-MCGS).
Irrigated conventionally tilled monocropped grain sorghum (ICT-MCGS).
Rainfed no-till double-cropped grain sorghum (RNT-DCGS).
Irrigated no-till double-cropped grain sorghum (INT-DCGS).

*,**Significant at the 0.05 and 0.01 probability levels, respectively.

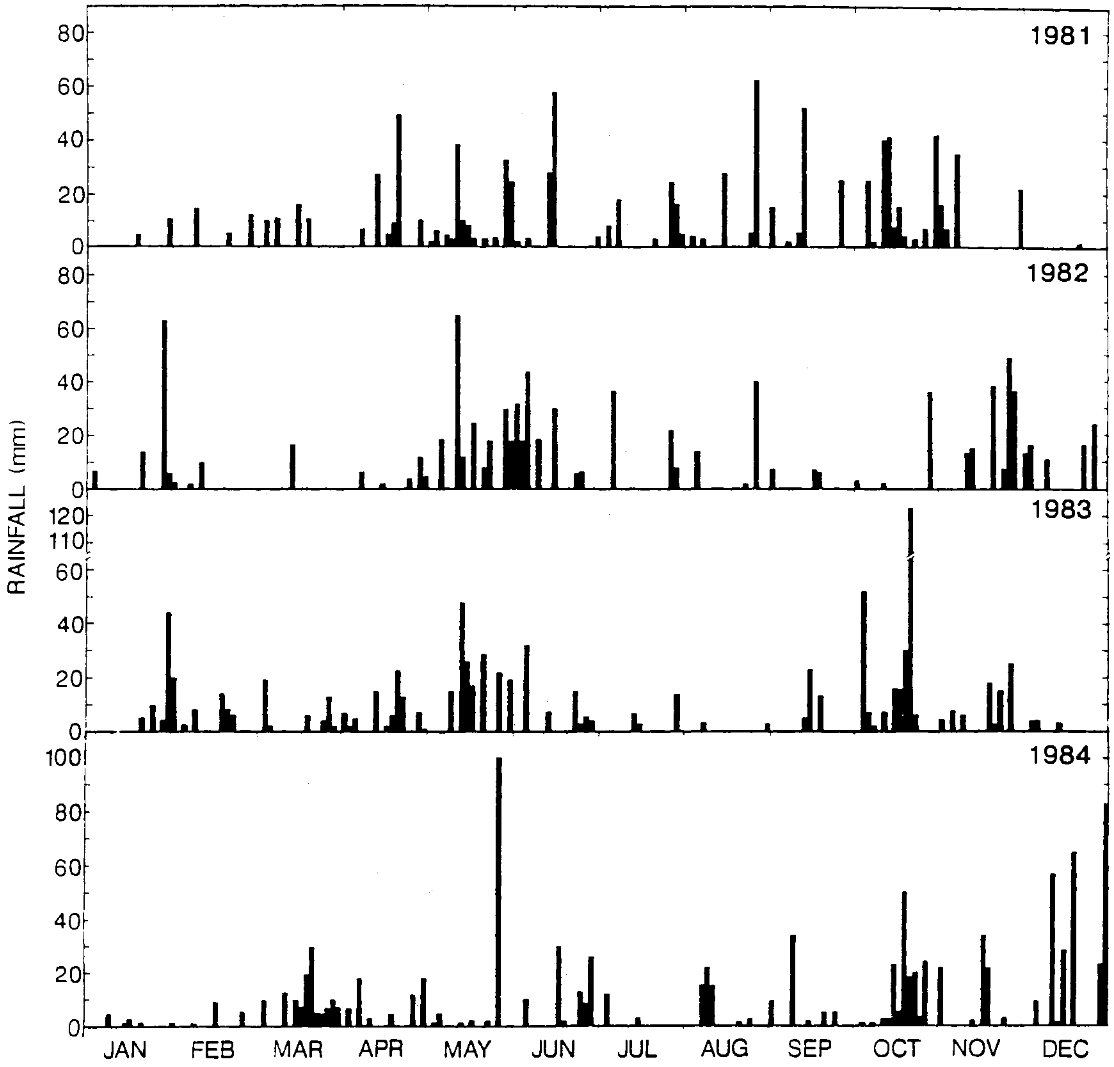

Fig. 1. Rainfall amounts and distribution for 1981-1984 at the Vegetable Research Station, Bixby, Oklahoma.

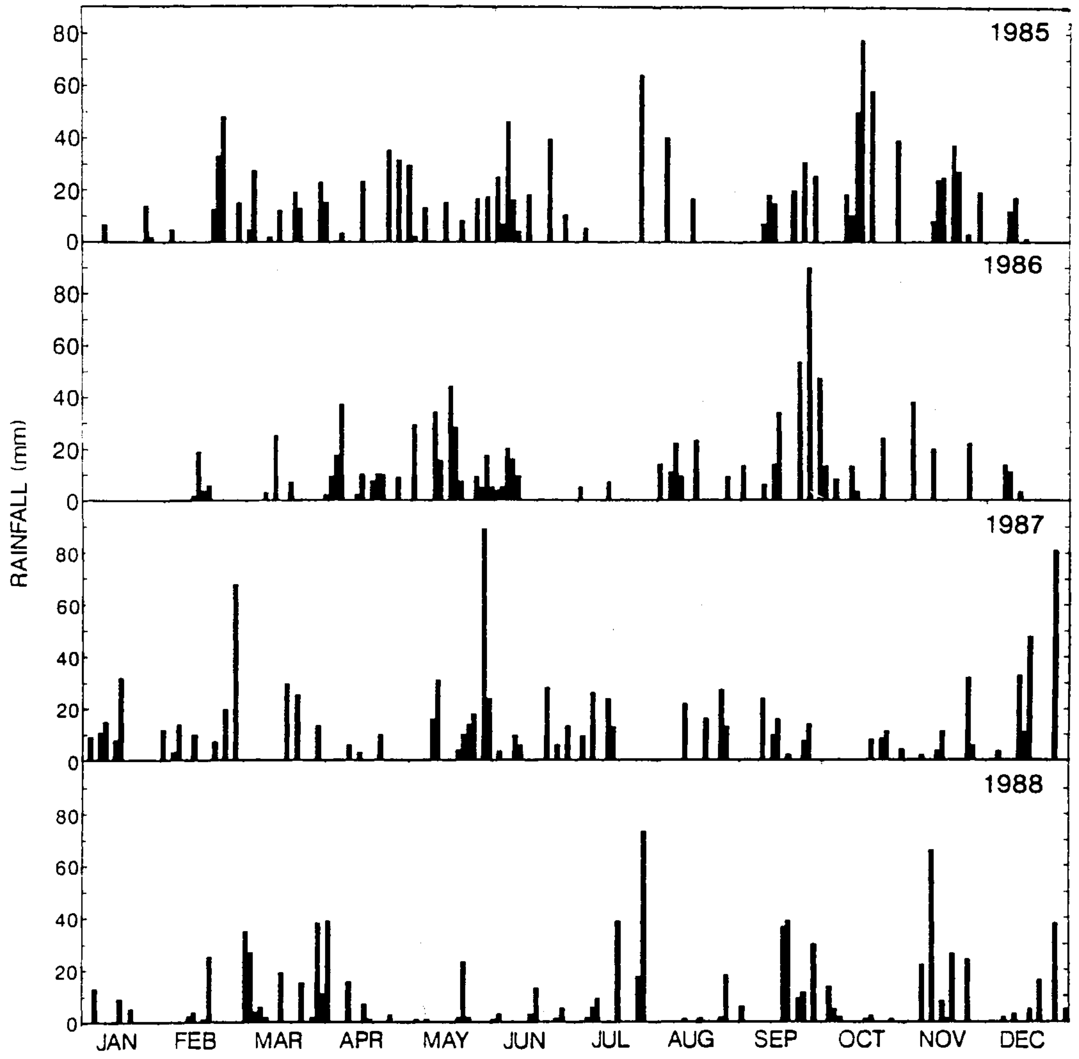

Fig. 2. Rainfall amounts and distribution for 1985-1988 at the Vegetable Research Station, Bixby, Oklahoma.

PART II. EVALUATION OF POTASSIUM QUANTITY-INTENSITY RELATIONSHIPS OF TWO OKLAHOMA SOILS

ABSTRACT

Various studies have been made in the evaluation of the K status of soils by considering the quantity-intensity (Q/I) relationships. These Q/I studies have been used for a better understanding of K release into the soil solution from K-bearing minerals and subsequent uptake by plants. The objective of the greenhouse and laboratory studies was to evaluate the K supplying power of a Kirkland silt loam (Udertic Paleustolls) and a Wynona silt loam (Cumulic Haplaquolls) as affected by previous management and cropping practices using Q/I relationships and to relate these factors to dry matter yields and K uptake by four successive crops of wheat (Triticum aestivum L.) in the greenhouse.

Soil samples were collected from a Wynona silt loam soil which had been field cropped since 1980 without addition of K fertilizer and a Kirkland silt loam soil which had been cropped with wheat from 1893 to present. These soils were further intensively cropped in the greenhouse by growing four successive wheat crops on the Wynona silt loam in a 9 by 9 Latin Square experimental design and in a randomized complete-block design with six treatments and four replications on the Kirkland silt loam. The wheat plants were harvested just prior inflorescence. Dry matter yields were obtained and the K content in the plant dry matter was determined. From each cropping system, a 5 g soil sample was equilibrated to construct typical Q/I curves. The Q/I relation for each

soil treatment was determined by plotting ΔK against the corresponding AR^K value. Potential buffering capacity (PBC^K) was calculated as the slope of the Q/I curve and K-potential values were obtained from the product of ΔK and PBC^K for each Q/I curve. The ΔK, PBC^K, and K-potential values were correlated with dry matter yields and K uptake for four successive wheat croppings. When the data for dry matter yields and K uptake by wheat plants, grown on Kirkland silt loam, were analyzed for each crop, there were significant ($P < 0.01$) treatment differences for three out of the four croppings. When the data were pooled and analyzed over croppings, there were significant ($P < 0.01$) treatment, cropping, and treatment x cropping interaction effects. Correlation coefficients were poor and showed no clear trend of relationship when ΔK, PBC^K, and K-potential were correlated with yields and K uptake by wheat plants grown on the Kirkland silt loam. When the dry matter yields for wheat grown on Wynona silt loam were analyzed for each cropping there was a significant ($P < 0.05$) treatment effect for each of the four croppings, but when the K uptake data were analyzed for each cropping, there was no significant ($P > 0.05$) treatment effect for any of the four croppings. When the dry matter yield data were pooled and analyzed over croppings, this resulted in significant ($P < 0.05$) treatment, cropping, and treatment x cropping interaction effects, however, when the K uptake data were pooled and analyzed over croppings there was only a significant ($P < 0.05$) cropping effect for the Wynona silt loam. Similar to the Kirkland silt loam, the correlation coefficients were poor and showed no clear measure of the intensity of association when ΔK, PBC^K, and K-potential were correlated with dry matter yields and K uptake by wheat plants on Wynona silt loam.

INTRODUCTION

In a very generalized way potassium (K) in a soil system can be characterized as K in soil solution, K exchangeable, K nonexchangeable, and K mineral with equilibrium reactions existing between solution, exchangeable, nonexchangeable, and mineral phases (Mclean and Watson, 1985; Brady, 1984; Tisdale et al., 1985). The rate and direction of the equilibrium reactions determine whether applied K will be leached into lower soil horizons, taken up by plants, converted into unavailable forms, or released as available forms (Brady, 1984; Tisdale et al., 1985).

Nutrient removal in grain year after year by both mono- and double-cropped systems can be substantial. Plant available quantities of soil K are largely a function of the nutrient supplying power of a given soil or fertilizer additions. Geleta (1989) reported that under double-cropped conditions in eastern Oklahoma, whether irrigated or rainfed, response to K fertilization has been marginal after seven years of cropping on a Wynona silt loam soil.

There is a need for an attempt to assess the K supplying power of soils by means other than that of extracting K by the 1 N NH_4OAc, Mehlich III, or by the use of other chemical extracting methods. One such way is by considering the quantity-intensity (Q/I) relationships. The quantity, Q, is usually the gain or loss in exchangeable K after equilibrium of soil and solution and the intensity, I, the activity ratio ${}^{a}K/({}^{a}Ca+{}^{a}Mg)^{1/2}$ in the soil solution. The objective of this greenhouse and laboratory study was to evaluate the K supplying power of two selected Oklahoma soils (Wynona silt loam and Kirkland silt loam) as affected by previous management and cropping practices using Q/I relationships and to relate these factors to dry matter production and uptake of K by four successive crops of wheat grown in the greenhouse.

LITERATURE REVIEW

Evaluation of the K-Supplying Power of Soils

Pratt (1951) reported that exchangeable K provided a good index of K supply to plants. However, several attempts have been made in the past few years to improve the predictability of exchangeable K in assessing the supply of K to plants. Beckett (1964a) suggested the activity ratio of K divided by the square root of Ca + magnesium (Mg) $(^{a}K/(^{a}Ca+^{a}Mg)^{1/2}$ in soil suspensions as a measure of the intensity factor of soil K. He also related the amount of labile soil K quantity (Q) to the intensity (I) and proposed the slope Q/I to represent the potential buffering capacity (PBC), i.e., to define the rate of change in the activity ratio with respect to K removal from the soil. Acquaye and Maclean (1966) reported that the PBC in conjunction with the activity ratio gave a more meaningful description of the K status of soil than did the activity ratio alone.

Availability of labile K is considered to be influenced by the parameters intensity (I) and quantity (Q) of labile K present in soil (Ram and Prasad, 1981). They also reported that all the measured parameters except PBC correlated positively and significantly with each other and also with dry matter yield and K uptake in the soils of Meghalaya. However, they reported that the measured Q/I parameters of K could not show any superiority over the commonly used neutral ammonium acetate for predicting the plant available K in soil. They also reported that a positive and significant relationship existed between cation exchange capacity (CEC) and PBC.

Notable advances have been made in the study of the K status of soils by considering the Q/I relationships. Parra and Torrent (1983) reported that the activity ratio at equilibrium (AR_e^K), and the buffering capacity (dQ/dI) at equilibrium, (PBC_e^K) were the most important parameters of the Q/I curves to predict the K-supplying power of a soil. Fergus et al. (1972) postulated that intensity might be expected to determine short-term uptake, and quantity to be more significant in the case of long-term withdrawals. They also reported that K was a convenient nutrient to choose for tests of the usefulness of the Q/I concept, since the soil supply of labile K could be fairly easily depleted by intensive-cropping. Subba et al. (1984) reported that soil reaction and soluble salt content seemed to influence the Q/I parameters. They reported that the labile K values differed widely (0.04 to 0.43 cmol kg^{-1} soil) which was much smaller than that for exchangeable K, indicating that only a fraction of the latter was readily replaceable with other cations or available to plants.

Bandyopadhyay et al. (1985) reported that the K buffering capacity was higher because of higher content of exchangeable and nonexchangeable K which were in equilibrium with the intensity factor. Potassium Q/I studies of labile K and sodium (Na) of an alluvial soil by Narain and Singh (1979) revealed three exchange sites for K, namely, planar, edge, and interlattice. They also reported that the planar exchange sites were equally accessible to K and Ca while edge and interlattice sites showed a high degree of specificity for K adsorption. Evangelou et al.

(1986) reported that PBC for ammonium (NH_4^+) and K^+ appeared to be a function of the affinity of the exchange phase for each cation and the magnitude of the CEC. Ghelani et al. (1985) observed that high ionic activity ratio of top soil indicated higher availability of K and Mg and the high linear buffering capacity of sub-soil which limited the K uptake by the plant. However, Fergus et al. (1972) reported that the interpretation of soil chemical data in terms of plant uptake of K during exhaustive cropping was limited by the difficulty of achieving complete removal of labile soil K by the plants. They also concluded that Q/I relation characterized only those K ions in rapid equilibrium with Ca and Mg ions.

Ross et al. (1972) reported that attention has shifted to a more comprehensive description, the curvilinear quantity-intensity relationship, which related changes in labile K in the soil to corresponding changes in effective K concentration in the equilibrium solution rather than by a single measurement of the labile K status of soils by the exchangeable K. Beckett's model, according to Ross et al. (1972), assumes that some exchange sites on the soil show no appreciable selectivity for K over Ca and Mg (termed non-specific sites) while others exhibit a distinct specificity for K (termed specific sites).

Previous studies have suggested that the intensity or period of cropping might be important, since the isotherm has been reported unchanged by moderate removal of K by crops (Beckett and Nafady, 1967; Moss, 1967; Addiscott, 1970), but sometimes altered by prolonged cropping (Beckett and Nafady, 1969), or by drastic removal of K from illite by sodium (Na) tetraphenylboron (Beckett and Nafady, 1967). The Q/I studies have been used for a better understanding of K^+ release into the soil solution and consequent uptake by plants (Beckett, 1964a,b; Beckett and Nafady, 1967; Moss, 1967; Rasnake and Thomas, 1976; LeRoux and Sumner, 1968; Sparks and Liebhardt, 1981).

Interpretation and applications of Q/I parameters

Various interpretations have been made on the parameters that can be derived from a Q/I plot. The linear portion of the curve has been ascribed to nonspecific sites for K (Beckett, 1964b), while the curved portion has been attributed to specific sites with a high K affinity (Beckett, 1964b; Rich, 1964; Beckett and Nafady, 1967; LeRoux and Sumner, 1968). The nonspecific sites have been attributed to planar surfaces (Beckett, 1964b; Lee, 1973), while the specific sites have been ascribed to edges of clay crystals and to wedge sites of weathered micas (Rich, 1964; Beckett and Nafady, 1967).

The AR^K value is a measure of availability or intensity of labile K in soil. Beckett and Nafady (1967) found that K fertilization increased AR_e^K values. San Valentin et al. (1973) investigated the effect of cropping on Q/I relations using a Red Bay soil from Florida. They found that before cropping AR_e^K increased with added K and decreased with added lime.

LeRoux (1966) noted that the change in K (ΔK) was a better estimate of soil labile K than normal exchangeable K. He found that higher values of labile K (ΔAK) indicated a greater K release into soil solution resulting in a larger pool of labile K. The labile K pool increased with K fertilization (LeRoux and Sumner, 1968; San Valentin et al., 1973). San Valentin et al. (1973) noted that labile K generally increased with lime additions on cropped soils.

The potential buffering capacity of K (PBC^K) value is a measure of the ability of the soil to maintain the intensity of K in the soil solution and is proportional to CEC (Lee, 1973). LeRoux (1966) noted that a higher soil PBC^K value is indicative of good K availability while a low PBC^K soil would suggest a need for frequent fertilization.

METHODS AND MATERIALS

Greenhouse Procedures

Soil samples (Wynona silt loam) were collected from long term mono- and double-cropped plots located at the Vegetable Research Station, Bixby, Oklahoma. The plots had been cropped from 1981-88 with mono- and double-cropped wheat, soybean, and grain sorghum without additions of P or K fertilizer. The soil samples were air dried and pots containing 2,000 g of soil were planted to 'Bounty 122' wheat (20 plants per pot), then placed in the greenhouse and further intensively cropped by growing four successive wheat crops in a 9 by 9 latin square experimental design.

The nine mono- and double-cropped cropping system treatments were rainfed monocropped wheat (RMCWH), rainfed double-cropped wheat and rainfed double-cropped soybean (RDCWH-RDCSB), rainfed double-cropped wheat and irrigated double-cropped soybean (RDCWH-IDCSB), rainfed double-cropped wheat and rainfed double-cropped grain sorghum (RDCWH-RDCGS), rainfed double-cropped wheat and irrigated double-cropped grain sorghum (RDCWH-IDCGS), rainfed conventionally tilled monocropped soybean (RCT-MCSB), irrigated conventionally tilled monocropped soybean (ICT-MCSB), rainfed conventionally tilled monocropped grain sorghum (RCT-MCGS), and irrigated conventionally tilled monocropped grain sorghum (ICT-MCGS).

Soil samples (Kirkland silt loam) were also collected from the Magruder plots located at the Agronomy Research Station, Stillwater, Oklahoma, which have been cropped with wheat from 1893 to present. These soil samples were also further intensively cropped in the greenhouse by growing four successive wheat crops in a randomized complete-block design with six treatments and four replications.

The six treatments from the Magruder plots consisted of check (no fertilizer), P, NP, NPK, NPK + Lime, and manure. Until 1941 the manure was applied at the rate of 22.4 kg N ha^{-1} every fourth year. Nitrogen was applied annually at the rate of 33.6 kg N ha^{-1} through 1967 at which time the annual rate was increased to 67 kg N ha^{-1} with a fall application since the rate increase. Prior to 1947 sodium nitrate ($NaNO_3$) was the source of N, but amonium nitrate (NH_4NO_3) has been used since that time. Phosphorus and K have been applied at the annual rate of 14 kg P ha^{-1} and 27.9 kg K ha^{-1}, respectively. Lime has been applied when soil analysis indicate a pH of 5.5 or less.

The wheat plants were harvested just prior inflorescence. Four successive crops of wheat were grown in this manner with border pots around each experimental design. Dry matter weight and K content in the plant dry matter were determined.

Soil Potassium Evaluations

Equilibrium solution concentrations of K, Ca, and Mg were determined as given by Beckett (1964a and 1964b). For each greenhouse cropping system treatment and replication, a 5 g sample of soil was equilibrated with 50 ml 0.001 M $CaCl_2$ containing different amounts of KCl. The amounts of KCl used in the equilibrating solutions were 0, 0.000307, 0.001152, 0.002022, and 0.002739 M/L. Samples were kept at constant temperature (25 ± 1°C) for 24 hours and in this period received 8 hours of shaking. After settling, 25 ml of the supernatant solution were removed. Potassium, Ca, and Mg were determined using a Perkin Elmer Model 3030 B atomic absorption spectrophotometer, respectively, using lanthanum (La) to suppress interfering ions (Doll and Christenson, 1966).

Activity ratios were calculated from the composition of supernatant solutions and activity coefficients determined according to the Davies modifications of the Debye-Huckel equation (Butler, 1964). For an ion of charge Z, either positive or negative, the activity coefficient (Y) of the ion is given by

$$-\log_{10} Y = 0.5091\, Z^2 \frac{\sqrt{I}}{1+\sqrt{I}} - 0.2I$$

The constants apply to solutions at 25°C. The ionic strength (I) of the solution is given by

$$I = 1/2 \Sigma\, Ci\, Z^2 i$$

where Ci is the concentration of the ith ion, Zi is its charge and the summation extends over the ions in the solutions.

The gain or loss of K (ΔK) by the soils was obtained by subtracting the K concentrations of the solution before and after equilibration. The quantity-intensity (Q/I) relation for each soil was determined by plotting ΔK against the corresponding AR^K value. The activity ratio at equilibrium (AR_e^K) was obtained from the intersection of the Q/I curve with the $\Delta K = 0$ axis. The AR_e^K represents the ratio ${}^aK/{}^a(Ca + Mg)^{1/2}$ in a solution that upon admixture with soil maintains its numerical value with respect to the activity of K, Ca, and Mg.

The exchangeable K (ΔK) values were determined by extending the linear part of the curve to the $AR^K = 0$ line. Potential buffering capacity (PBC^K) was calculated as the slope of the Q/I curve or $\Delta K/AR_e^K$.

RESULTS AND DISCUSSION

Potassium Quantity-Intensity (Q/I) Parameters

Several interpretations have been made on the parameters that can be derived from a Q/I plot. The linear portion of the curve has been ascribed to nonspecific sites for K while the curved portion has been attributed to specific sites with a high K affinity. The nonspecific sites have been attributed to planar surfaces while the specific sites have been ascribed to edges of clay crystals and to wedge sites of weathered micas. The AR^K value is a measure of availability or intensity of labile K in soil. The gain or loss of K (ΔK) by the soils was obtained by subtracting the K concentrations of the equilibrating solutions before and after equilibration.

These parameters, ΔK, PBC^K, and K-potential, ($\Delta K \times PBC^K$) derived from the Q/I curves (Fig. 1 to 15) were correlated with the whole plant dry matter yields and K uptake by four successive wheat croppings on Kirkland and Wynona silt loam soils.

Dry Matter Yields of Wheat Grown on Kirkland Silt Loam.

The mean whole plant dry matter yields of the four successive crops of wheat are shown in Table 1. There was a significant ($P < 0.01$) treatment effect on dry matter yields of the first cropping and can be attributed to different fertilizer combinations applied to the Kirkland soil.

Yields for the check and P treatments were not significantly different ($P > 0.05$), but yields of both treatments were significantly lower ($P < 0.05$) compared with the NP treatment and most likely can be attributed to the N fertilizer inclusion in the treatment. There was no significant difference ($P > 0.05$) in yield between the NP and NPK treatments, but the yield for the NPK treatment was significantly ($P < 0.05$) lower compared with the NPK + lime treatment. The yield for the manure treatment was significantly ($P < 0.05$) higher compared with the NPK + lime treatment. The high yield of dry matter for the manure treatment could possibly be due to greater release and chelating effect of nutrients during manure decomposition.

Similar to the first cropping, there was a significant ($P < 0.01$) treatment effect on dry matter yields of the second cropping. The yield trend of the second cropping was similar to the first cropping in that the yields of check and P treatments were not significantly ($P > 0.05$) different, but significantly ($P < 0.05$) lower compared with the NP treatment yield. It is interesting to note that there is no significant ($P > 0.05$) difference between the three treatments where N was applied as NH_4NO_3. Although the manure was not significantly different ($P > 0.05$) from NP, NPK, and NPK + lime, the results suggest that N was probably beginning to limit dry matter accumulation in the second cropping.

In the third cropping K deficiency symptoms were observed as the cells at the tips and margins of the wheat leaves died first, and this necrosis spread basipetally toward the younger lower parts at the base of the leaf. Similar to the two previous croppings there was a significantly different ($P < 0.01$) treatment effect on yield. However, unlike the two previous croppings the check yield was significantly ($P < 0.05$) lower compared with the P treatment yield. There was no significant difference ($P > 0.05$) in yields of the P, NP, and NPK treatments and can probably be attributed to the depletion of the N by previous croppings. Similarly, the highest yield was recorded for NPK treatment in the third cropping and can possibly be attributed to a better nutrient balanced under intensive cropping conditions.

The high yields recorded for each of the treatments in the fourth cropping were probably due to the fact that the fourth crop occupied the pots longer than the previous croppings by about 14 days. Unlike the previous croppings, there were no significant ($P > 0.05$) differences due to treatment effects on yield. The check yield was significantly ($P < 0.05$) lower compared with the other five treatments and the P treatment was significantly lower ($P < 0.05$) compared with the NP, NPK, NPK + lime, and the manure treatments The lower dry matter yields can most likely be attributed to N depletion by previous croppings. There was no significant difference ($P > 0.05$) in yields between NP, NPK, NPK + lime, and manure treatments.

When the dry matter yields were pooled and analyzed over croppings the yield response varied with crop and treatments resulting in a significant ($P < 0.01$) treatment x crop interaction (Table 6). The yield of the check treatment was significantly ($P < 0.05$) lower compared with the P treatment yield. However, there was no significant difference ($P > 0.05$) between NP, NPK, NPK + lime, and manure yields when the dry matter yields were pooled over croppings.

The Mean K Uptake by Successive Wheat Crops on Kirkland Silt Loam

The whole plant K uptake by four successive croppings of wheat is shown in Table 2. The main objective of successive wheat croppings on Kirkland silt loam was to crop K out of the soil. There was a significant ($P < 0.01$) treatment effect on K uptake during the first cropping. There was no significant difference ($P > 0.05$) between K uptake by the check and P treatment. However, plant K uptake by the check treatment was significantly ($P < 0.05$) lower compared with K uptake for the NP treatment. The higher plant K uptake by the NP treatment may be due to N fertilizer inclusion in the NP treatment. Plant K uptake by NP, NPK, NPK + lime, and manure treatments were not significantly different ($P > 0.05$). The highest plant K uptake was recorded for the manure treatment in the first cropping.

Plant K uptake by the second cropping was similar to the first cropping in that there was a significant ($P < 0.01$) treatment effect. Unlike the first cropping, there was no significant ($P > 0.05$) difference in plant K uptake between the check and P treatments. The K uptake from the P treatment was lower ($P < 0.05$) than uptake for the NP treatment, but there were no significant ($P > 0.05$) differences in plant K uptake for the NP, NPK, NPK + lime, and manure treatment comparisons (Table 2).

The K uptake by wheat plants during the third cropping was similar to the two previous croppings as there was a significant ($P < 0.01$) treatment effect. As with the first two croppings, the plant K uptake from the check treatment was lower ($P < 0.05$) than K uptake from the P treatment. There was no significant ($P > 0.05$) difference for K uptake for P, and NP, and NPK treatment comparisons, however, plant K uptake for the NP treatment was lower ($P < 0.05$) than K uptake for the NPK + lime and manure treatments. Although there was no significantly different ($P > 0.05$) plant K uptake between NPK + lime and manure treatments, the highest plant K uptake was recorded for the NPK + lime treatment for the third cropping (Table 2).

Marked nitrogen deficiency symptoms were observed in the fourth cropping and the magnitude of K uptake was about one-half compared with the three previous croppings. This resulted in no significantly ($P > 0.05$) different treatment effect for plant K uptake. Plant K uptake for the NP, NPK, NPK + lime, and manure treatments were not significantly different ($P > 0.05$) from each other for the fourth cropping (Table 2).

When the plant K uptake data were pooled and analyzed over croppings the K uptake by the wheat plants varied with crop and treatments resulting in a significant ($P < 0.01$) treatment x crop interaction. There was no significant difference ($P > 0.05$) between plant K uptake for the check compared with the P treatment, but the plant K uptake by the check treatment was significantly ($P < 0.05$) lower than K uptake for the NP treatment. The plant K uptake for the NP, NPK, NPK + lime, and manure treatments were not significantly different ($P > 0.05$) when K uptake data were pooled over croppings (Table 2).

Correlation Coefficients Relating ΔK With Dry Matter Yields and K Uptake of Four Successive Wheat Croppings on Kirkland Silt Loam

While the soil may have a more or less initial uniform distribution of ions, the roots of growing plants alters this uniformity. The influence of the plant root on the ionic conditions of the soil begins when the root starts to force its way through the soil. Since the diameter of the root is frequently larger than the diameter of the majority of soil pores, the root moves soil particles aside and in so doing increases the density of soil in the immediate vicinity of the root so that it has greater than average density. This will also increase the concentration of exchangeable K per unit volume of soil. In addition to pushing the soil aside, the root will intercept K ions in its path and absorption will occur. The root absorbs water and causes movement of water through the soil toward the root. Since this water contains K ions, these ions are transported to the root. The amount reaching the root will depend on the amount of water and the K concentration in the soil.

The correlation coefficients relating ΔK with potassium uptake and yields of successive wheat crops are shown in Table 3. The exchangeable K or the quantity by which the soil gains or loses potassium in reaching equilibrium was poorly correlated ($r = 0.218$) with dry matter yield for the check treatment, $r = 0.388$ for P treatment, and $r = 0.203$ for NPK + lime treatment for the first cropping. There was a negative correlation ($r = -0.606$) between ΔK and dry matter yield for the NPK treatment the first cropping. A better correlation ($r = 0.519$) between ΔK and yield was obtained for the manure treatment and the highest correlation of $r = 0.813$ was obtained for dry matter yield and the NP treatment.

In general there was a poor correlation between ΔK and yield for check, P, NPK, NPK + lime, and manure treatments for the second cropping. However, a better correlation of $r = 0.556$ between ΔK and yield was recorded for NP treatment in the second cropping. In the third cropping there was a poor correlation between ΔK and yield of check ($r = 0.031$), P ($r = 0.488$), NP ($r = 0.173$), and NPK ($r = 0.120$ treatments. However, better correlation coefficients were recorded for the NPK + lime and manure treatments, $r = 0.915$ and $r = 0.867$, respectively.

The correlation coefficients relating ΔK with dry matter yield for the fourth cropping was similar to those obtained for the previous three successive croppings. There were poor correlations between ΔK and dry matter yields for the check ($r = 0.572$), P ($r = -0.520$), NP ($r = 0.406$), NPK + lime ($r = 0.448$), and manure ($r = 0.982$) treatments. Better correlation between ΔK and yield was recorded for NPK treatment ($r = 0.629$). There was a significant ($P < 0.05$) negative correlation between ΔK and dry matter yield ($r = -0.982$) for the manure treatment.

Poor correlation coefficients were also obtained for ΔK and total dry matter yields for the check ($r = 0.474$), P ($r = 0.093$), NP ($r = 0.780$), NPK ($r = 0.261$), NPK + lime ($r = -0.198$), and manure ($r = 0.106$) treatments (Table 3).

There were better correlations between ΔK and K uptake for the first cropping. The correlation coefficients for check, P, NP, and NPK treatments were $r = 0.817$, $r = 0.849$, $r = 0.619$, and $r = 0.962$, respectively, with significant ($P < 0.05$) correlation for the NPK treatment. Although ΔK correlation with K uptake was significant ($P < 0.05$) for the NPK + lime treatment it was negatively correlated. Also there was a negative correlation between ΔK and K uptake for the manure treatment ($r = -0.592$) (Table 3).

Poor correlation coefficients were recorded between ΔK and K uptake for the second cropping. These were $r = 0.420$, $r = 0.181$, $r = 0.079$, $r = 0.205$, $r = -0.109$, and $r = -0.769$ for the check, P, NP, NPK,

NPK + lime, and manure treatments, respectively. Likewise, poor correlation coefficients between $\triangle K$ and K uptake were recorded for the third cropping especially for the check, P, NP, NPK, and NPK + lime treatments, respectively. However, there was a better correlation (r = 0.857) between $\triangle K$ and K uptake for the manure treatment.

For the fourth cropping poor correlation coefficients of r = 0.050 and r = 0.228 were recorded for the check and NP treatments. However, a stronger correlation of r = 0.641 and r = 0.906 were obtained for the P and NPK treatments, respectively. Negative correlation coefficients of r = -0.729 and r = -0.642 between $\triangle K$ and K uptake were recorded for NPK + lime and manure treatments, respectively. Better correlation coefficients were obtained when $\triangle K$ was correlated with total K uptake as indicated by r = 0.639 for check, r = 0.801 for P, r = 0.568 for NP, and r = 0.691 for NPK treatments. As in the fourth cropping negative correlation coefficients of r = -0.682 and r = -0.935 were recorded for NPK + lime and manure treatments, respectively. The wide disparity in correlating $\triangle K$ with yield and K uptake could possibly be explained on the basis that K uptake from soils represented uptake from a dynamic system that was not at equilibrium; therefore, rate processes involved with release and ion movement possibly become the limiting factor in determining absorption rates by plant roots.

Correlation Coefficients Relating PBC^K With Dry Matter Yields and K Uptake of Four Successive Wheat Croppings on Kirkland Silt Loam

The slope of the linear portion of the Q/I relation, $\triangle Q/\triangle I$, gives the amount of labile K that can be removed before AR_e^K changes by a given amount. This represents the Potential Buffering Capacity (PBC^K)

of the soil for K, as defined by Beckett (1964a). The correlation coefficients relating PBC^K with dry matter yields and potassium uptake of successive wheat croppings are shown in Table 4.

There were better correlations between PBC^K and dry matter yields for the check treatment after each cropping than before cropping for each of the croppings under study. The PBC^K correlated poorly with dry matter yields for each of the croppings both before and after cropping for the P treatment. A better correlation between PBC^K and yield was recorded for both before and after cropping for the fourth crop compared with poor correlations for the other three croppings for the NP treatment. Better correlation coefficients after cropping were recorded for both the first and second croppings for the NPK treatment, but poor correlations were recorded for before and after cropping for the third and fourth croppings of the NPK treatment. Unlike the previous treatments, better correlations were observed in the second and fourth cropping for NPK + lime treatment. Better correlations were recorded for the second crop before cropping and for the fourth crop after cropping when PBC^K was correlated with dry matter yields for the manure treatment. However, poor correlations were recorded for both before and after crop for the remaining croppings for the manure treatment. When total dry matter yields were correlated with PBC^K, better correlation coefficients were recorded after cropping for check and NPK + lime treatments. Better, before cropping correlations, were recorded for NP, NPK + lime, and manure treatments, however, none were statistically significant (Table 4).

When PBC^K was correlated with K uptake there was no uniform relationship or trend detected for the various treatments before or after cropping for any of the four croppings (Table 4). When PBC^K was correlated with total K uptake there were significant ($P < 0.05$) correlations, before cropping, for the NP ($r = 0.985$) and, after cropping, for the manure ($r = 0.984$) treatments (Table 4).

Correlation Coefficients Relating K-Potential With Dry Matter Yields and K Uptake of Successive Wheat Crops Grown on Kirkland Silt Loam

The AR_e^K indicates the status of the immediately exchangeable K and, therefore, should represent exchange of K ions from the soil complex; the $\triangle K$ denotes the amount of exchangeable K and supposedly rate at which the activity of K on the exchange complex decreases as K is removed from the complex as indicated by the PBC^K. As the activity ratio of K is reduced, the diffusion gradient away from the complex is also reduced, and K supply to the plant root may be insufficient. By multiplying the $\triangle K$ by the PBC^K measurements, the Q/I relation could be defined in a single parameter in which the $\triangle K$ value of the soil is related to a standard PBC^K. This product, the K-potential, is supposedly the amount of exchangeable K ($\triangle K$) multiplied by the ease of release of the K.

Correlation coefficients relating K-potential to dry matter yields and uptake are shown in Table 5. There was no general trend or conclusions that could be drawn when these correlations were studied for all treatments or croppings. When K-potential was correlated with total dry matter yields and total K uptake, no correlations were statistically significant (Table 5). These results suggest that the typical Q/I relationship failed to measure different long term effects of soil fertility amendments relative to dry matter production and total plant K uptake when intensively cropped with wheat in pots.

Dry Matter Yields of Successive Wheat Crops Grown on Wynona Silt Loam

The mean whole plant dry matter yields of four successive crops of wheat are shown in Table 6. There was a significant ($P < 0.05$) treatment effect on dry matter yield of the first cropping. This can most likely be attributed to different cropping system treatments applied to the Wynona soil in 1981. The yields for rainfed monocropped wheat (RMCWH), rainfed double-cropped wheat and rainfed double-cropped soybean (RDCWH-RDCSB), and rainfed double-cropped wheat and irrigated double-cropped soybean (RDCWH-IDCSB) treatments were not significantly ($P > 0.05$) different, but the yield of RMCWH was significantly ($P < 0.05$) higher compared with the rainfed double-cropped wheat and rainfed double-cropped grain sorghum (RDCWH-RDCGS) treatment. The rainfed double-cropped wheat and irrigated double-cropped grain sorghum (RDCWH-IDCGS) yield was significantly ($P < 0.05$) higher compared with the rainfed conventionally tilled monocropped soybean (RCT-MCSB), irrigated conventionally tilled monocropped soybean (ICT-MCSB), rainfed conventionally tilled monocropped grain sorghum (RCT-MCGS), and irrigated conventionally tilled monocropped grain sorghum (ICT-MCGS) treatments.

Similar to the first cropping there was a significant ($P < 0.05$) treatment effect on dry matter yields for the second cropping. Unlike the first cropping the RDCWH-RDCSB yield was significantly ($P < 0.05$) higher than RMCWH, RDCWH-IDCSB, and RDCWH-RDCGS yields in the second cropping. The RDCWH-IDCGS yield was not significantly different (P >

0.05) compared with RCT-MCSB yield. However, the RCT-MCSB yield was significantly ($P < 0.05$) higher than ICT-MCSB and ICT-MCGS yields.

For the third cropping there was a significant ($P < 0.05$) treatment effect on dry matter yields. Similar to the first cropping the RMCWH yield was not significantly different ($P > 0.05$) compared with RDCWH-RDCSB and RDCWH-IDCSB yields. The RDCWH-RDCGS yield was lower ($P < 0.05$) compared with RDCWH-IDCGS yield. Also the RCT-MCSB yield was significantly ($P < 0.05$) lower compared with ICT-MCSB yield, but RCT-MCGS and ICT-MCGS yields were not significantly different ($P > 0.05$).

Similar to Kirkland silt loam, N deficiency symptoms were observed in the wheat plants in the fourth cropping and can be attributed to the depletion of N by the previous croppings. There was a significant ($P < 0.05$) treatment effect on dry matter yields as in the three previous croppings. Similar to the third cropping the yields of the RMCWH, RDCWH-RDCSB, and RDCWH-IDCSB treatments were not significantly different ($P > 0.05$). The RDCWH-RDCGS yield was significantly ($P < 0.05$) higher compared with the RDCWH-IDCGS yield and the RCT-MCSB yield was significantly ($P < 0.05$) lower compared with the ICT-MCSB yield, but there was no significant difference ($P > 0.05$) when the RCT-MCGS yield was compared with the ICT-MCGS yield. A general decline in dry matter yield in almost all treatments was observed with the exception of the RDCWH-RDCGS treatment in which the highest yield was recorded for the fourth cropping.

When the dry matter yields were pooled and analyzed over croppings the yield response varied with crop and treatments resulting in a significant ($P < 0.05$) treatment x crop interaction. The RMCWH yield was not significantly different ($P > 0.05$) compared with the RDCWH-RDCSB yield, but RDCWH-RDCSB yield was significantly ($P < 0.05$) higher compared with the RDCWH-IDCSB yield. The RDCWH-RDCGS was significantly ($P < 0.05$) lower compared with RDCWH-IDCGS yield. However, there were no significant differences ($P > 0.05$) between the ICT-MCSB, RCT-MCGS, and ICT-MCGS yields when the dry matter yields were pooled over croppings (Table 6).

The Mean K Uptake by Successive Wheat Crops on Wynona Silt Loam

The whole plant K uptake by four successive croppings of wheat is shown in Table 7. The objective of successive wheat croppings was to crop K out of the Wynona silt loam soil. Unlike Kirkland silt loam, there was no significant ($P > 0.05$) treatment effect on K uptake during the first cropping.

The trend of plant K uptake by the second and third cropping was similar to the first cropping in that there was no significant ($P > 0.05$) treatment effect. Substantial K had been removed from the soils as reflected in much lower plant K uptake by all treatments under study in the fourth cropping. However, as in the first three croppings, there was no significant treatment effect on K uptake. When the plant K uptake data were pooled and analyzed over croppings, the K uptake by the wheat plants did not vary with treatment and there was no treatment x crop interaction, but there was a significant ($P < 0.05$) crop effect on plant K uptake when K uptake data were pooled over croppings (Table 7).

Correlation Coefficients Relating ΔK With K Uptake and Yields of Successive Wheat Croppings on Wynona Silt Loam

The correlation coefficients relating ΔK with potassium uptake and yields of successive wheat crops are shown in Table 8. The exchangeable K (ΔK) or the quantity by which the soil gains or loses K in reaching equilibrium had correlations of ($r = 0.544$, $r = 0.604$, and $r = 0.669$) with dry matter yields for the RCT-MCSB, RCT-MCGS, and ICT-MCGS treatments, respectively, for the first cropping. There was a significant ($P < 0.05$) correlation between ΔK and dry matter yield of ICT-MCGS, but correlations were poor between ΔK and dry matter yields of the other treatments.

For the second cropping a significant ($P < 0.05$) negative correlation was obtained between ΔK and dry matter yield for the RDCWH-RDCGS treatment, and a significant correlation ($r = 0.676$) was obtained for the RCT-MCSB treatment. Poor correlation coefficients between ΔK and yields were obtained for the other treatments under study. For the third cropping significant ($P < 0.05$) correlation coefficients ($r = 0.657$, $r = 0.666$) were recorded for RDCWH-RDCSB and RDCWH-IDCSB treatments, respectively. Poor correlation coefficients were obtained for all other treatments when ΔK was correlated with dry matter yields.

Significant ($P < 0.05$) correlation coefficient was recorded for RMCWH ($r = 0.790$) treatment between ΔK and dry matter yield in the fourth cropping. However, ΔK was poorly correlated with yields of the other treatments under study in the fourth crop. When the total dry matter yield was correlated with ΔK, a significant ($P < 0.05$) correlation coefficient ($r = 0.667$) was recorded for only the RMCWH treatment while poor correlation coefficients were obtained for the other treatments under study (Table 8).

In general there was a poor correlation between ΔK and K uptake for all treatments for the first crop. However, there was a significant ($P < 0.05$) correlation between ΔK and K uptake ($r = 0.812$) for the RCT-MCGS treatment. Relative poor correlations were obtained for the other treatments for the second cropping. Similar to the two previous croppings poor correlation coefficients were recorded for all the treatments for the third cropping. Significant ($P < 0.05$) correlation coefficients ($r = 0.784$ and $r = 0.676$) were obtained for the RDCWH-RDCSB and RDCWH-IDCSB treatments, respectively, for the fourth cropping. Poor correlations were obtained for the other treatments in the fourth crop. Generally, there was a poor correlation between ΔK and dry matter yields and ΔK and K uptake for all treatments under study.

Correlation Coefficients Relating PBC^K With Dry Matter Yields and K Uptake of Four Successive Wheat Crops Grown on Wynona Silt Loam in the Greenhouse

The correlation coefficients relating PBC^K with dry matter yields and K uptake of successive wheat croppings are shown in Table 9. For the most part there were poor correlations between PBC^K and dry matter yields of all the treatments for each cropping and total dry matter whether PBC^K was determined before or after the completion of the fourth cropping. Similar to the yield data, poor correlations were obtained for all treatments before and after cropping when PBC^K was correlated with K uptake (Table 9).

Correlation Coefficients Relating K-Potential With Dry Matter Yields and K Uptake of Four Successive Wheat Crops Grown on Wynona Silt Loam In the Greenhouse

Correlation Coefficients relating K-potential to K uptake and yields are shown in Table 10. Potassium-potential is the product of ΔK x PBC^K and since these two parameters did not correlate well as previously reported one would predict poor correlations with dry matter yields and K-uptake. Such was the case and most likely this can be attributed to the failure of the typical Q/I relationship to measure the dynamics of K release from all four phases of K, particularly from the primary mineral form of K in the Kirkland and Wynona silt loam soils.

SUMMARY AND CONCLUSIONS

When the data for dry matter yields and K uptake by wheat plants, grown on Kirkland silt loam, were analyzed for each cropping, there was significant ($P < 0.01$) treatment effect for three out of the four croppings. When the data were pooled and analyzed over croppings, there were significant ($P < 0.01$) treatment, cropping, and treatment x cropping interaction effects. The dry matter yield of the check treatment was significantly ($P < 0.05$) lower compared with the P treatment. However, there were no significant ($P > 0.05$) differences in dry matter yields of the NP, NPK, NPK + lime, and manure treatments.

When the wheat plant K uptake data were pooled and analyzed over croppings the K uptake varied with treatment and cropping resulting in a significant ($P < 0.01$) treatment x cropping interaction effect. There was a significant ($P < 0.05$) difference between the check and P treatments. Potassium uptake by wheat for the check treatment was significantly ($P < 0.05$) lower compared with the NP treatment. Uptake of K by wheat for the NP, NPK, NPK + lime, and manure treatments was not significantly different ($P > 0.05$) when K uptake data were pooled and analyzed over croppings for Kirkland silt loam. In general, correlation coefficients were poor and showed no clear trend of relationship when ΔK, PBC^K, and K-potential were correlated with yields and K uptake by wheat plants grown on the Kirkland silt loam.

When the dry matter yields for wheat grown on Wynona silt loam were analyzed for each cropping, there was a significant ($P < 0.05$) treatment effect for each of the four croppings, but when the K uptake data were analyzed for each cropping, there was no significant ($P > 0.05$) treatment effect for any of the four croppings. When the dry matter yield data were pooled and analyzed over croppings, a significant ($P < 0.05$) treatment, cropping, and treatment x cropping interaction effects resulted, however, when the K uptake data were pooled and analyzed over croppings there was only a significantly ($P < 0.05$) cropping effect for the Wynona silt loam. The RMCWH treatment dry matter yield was not significantly different ($P > 0.05$) compared with the RDCWH-RDCSB yield, but the RDCWH-RDCSB treatment yield was significantly ($P < 0.05$) higher compared with the RDCWH-IDCSB yield. The RDCWH-RDCGS dry matter yield was significantly ($P < 0.05$) lower compared with the RDCWH-IDCGS treatment yield. There were no significant differences ($P > 0.05$) between the ICT-MCSB, RCT-MCGS, and ICT-MCGS yields when the dry matter yields were pooled over croppings.

Similar to the Kirkland silt loam, the correlation coefficients were poor and showed no clear measure of the intensity of association when $\triangle K$, PBC^K, and K-potential were correlated with dry matter yields and K uptake by wheat plants grown on Wynona silt loam. These poor correlations may be attributed to the failure of the Q/I relationship to measure the dynamics of K release for all phases of K, particularly from the primary mineral form(s) of K in both the Kirkland and Wynona silt loam soils.

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Table 1. Means and mean squares for dry matter yields of wheat from successive croppings on Kirkland silt loam.

Treatments	Croppings				
	1	2	3	4	1-4
	g pot^{-1}				
Check[†]	1.142	2.374	2.132	4.247	2.474
P	1.285	2.318	2.723	6.041	3.092
NP	2.252	3.671	3.776	4.614	3.578
NPK	2.428	3.824	4.050	4.445	3.687
NPK + Lime	2.162	3.499	3.486	5.108	3.564
Manure	2.508	3.246	3.133	5.269	3.539
LSD (0.05)	0.293	0.666	0.545	1.343	0.316

	MS				
Source	Crop 1	Crop 2	Crop 3	Crop 4	Crop 1-4
Trt.[+]	1.416**	1.721**	2.006**	1.744	3.445**
Crop	--	--	--	--	36.387**
Trt. X Crop	--	--	--	--	1.147**
Error	0.038	0.195	0.131	0.794	0.364

[+] Treatment.

[†] Mean of four replications.

**Significant at 0.01 probability level.

Table 2. Means and mean squares for K uptake by wheat plants from successive croppings on Kirkland silt loam.

Treatments	Croppings				
	1	2	3	4	1-4
	mg K g^{-1}				
Check[†]	38.097	32.742	42.297	21.840	33.744
P	43.032	36.260	49.787	18.235	36.829
NP	47.302	44.975	47.337	19.547	39.791
NPK	49.087	48.352	53.952	19.112	42.626
NPK + Lime	47.460	44.152	55.107	20.370	41.772
Manure	50.067	43.997	54.442	18.147	41.664
LSD (0.05)	6.022	7.967	5.853	3.068	3.753

Source	MS				
	Crop 1	Crop 2	Crop 3	Crop 4	Crop 1-4
Trt.[+]	161.615[**]	281.747[**]	202.370[**]	15.686	43.825[**]
Crop	--	--	--	--	208.520[**]
Trt. X Crop	--	--	--	--	14.489[**]
Error	31.936	55.892	30.170	8.291	3.286

[+] Treatment.
[†] Mean of four replications.
[**] Significant at 0.01 probability level.

Table 3. Correlation coefficients relating ΔK with dry matter yields and K uptake of four successive wheat crops grown on Kirkland silt loam in the greenhouse.

		Check	P	NP	NPK	NPK+Lime	Manure
Dry matter	Crop 1	0.218	0.388	0.813	-0.606	0.203	0.519
"	Crop 2	-0.537	0.228	0.556	-0.600	0.097	-0.038
"	Crop 3	-0.031	0.488	0.173	0.120	0.915	0.867
"	Crop 4	-0.572	-0.520	0.406	0.629	-0.448	-0.982*
Total dry matter		-0.474	-0.093	0.780	0.261	-0.198	0.106
K uptake	Crop 1	0.817	0.849	0.619	0.962*	-0.968*	-0.592
"	Crop 2	0.420	0.181	0.079	0.205	-0.109	-0.769
"	Crop 3	0.308	-0.273	0.345	-0.054	0.283	0.857
"	Crop 4	-0.050	0.641	0.228	0.906	-0.729	-0.642
Total K uptake		0.639	0.801	0.568	0.691	-0.682	-0.935

*Significant at 0.05 probability level.

Table 4. Correlation coefficients relating PBC^k with dry matter yields and K uptake of four successive wheat crops grown on Kirkland silt loam in the greenhouse.

		Check before	Check after	P before	P after	NP before	NP after	NPK before	NPK after	NPK+L before	NPK+L after	Manure before	Manure after
Dry matter	Crop 1	0.380	0.855	0.309	0.622	0.263	-0.275	-0.875	0.632	-0.965*	-0.700	-0.978*	-0.815
"	Crop 2	-0.116	0.554	0.332	-0.962*	-0.305	-0.774	-0.888	0.605	0.792	0.400	0.891	0.426
"	Crop 3	-0.058	0.608	0.486	0.434	-0.165	-0.871	0.166	-0.052	-0.568	-0.960*	-0.200	-0.718
"	Crop 4	-0.147	0.687	-0.521	-0.394	0.683	0.600	0.456	-0.676	0.871	0.801	0.427	0.900
Total dry matter		-0.093	0.929	-0.074	-0.765	0.557	0.066	-0.130	-0.283	0.883	0.634	0.601	0.188
K uptake	Crop 1	0.975*	0.403	0.822	-0.802	0.951*	-0.040	0.822	-0.976*	0.379	0.888	-0.447	0.233
"	Crop 2	0.277	0.349	0.339	0.087	0.280	-0.447	-0.173	-0.231	0.432	0.342	0.814	0.917
"	Crop 3	-0.062	-0.232	-0.158	0.561	-0.041	0.178	-0.482	0.076	-0.127	-0.287	-0.287	-0.741
"	Crop 4	-0.028	-0.620	0.599	-0.845	0.895	0.579	0.706	-0.924	0.511	0.807	0.969*	0.897
Total K uptake		0.343	-0.100	0.906	-0.513	0.985*	0.126	0.361	-0.710	0.583	0.817	0.694	0.984*

*Significant at 0.05 probability level.

Table 5. Correlation coefficients relating K-potential with dry matter yields and K uptake of four successive wheat crops grown on Kirkland silt loam in the greenhouse.

		Check before	Check after	P before	P after	NP before	NP after	NPK before	NPK after	NPK+L before	NPK+L after	Manure before	Manure after
Dry matter	Crop 1	0.299	-0.165	-0.222	0.266	-0.507	0.520	-0.620	-0.928*	0.327	0.417	0.905	0.727
"	Crop 2	0.123	-0.914*	-0.418	-0.686	0.057	0.968*	-0.503	-0.853	-0.145	-0.012	-0.965*	-0.299
"	Crop 3	0.140	0.221	-0.422	-0.110	0.161	0.555	-0.398	-0.118	-0.177	0.745	-0.060	0.784
"	Crop 4	0.170	-0.954*	0.460	0.146	-0.723	-0.459	0.006	0.623	-0.677	-0.881	-0.154	-0.946*
Total dry matter		0.152	-0.773	0.002	-0.185	-0.734	0.126	-0.527	-0.028	-0.822	-0.742	-0.697	-0.090
K uptake	Crop 1	-0.953*	-0.200	-0.837	-0.409	-0.896	-0.330	-0.177	0.836	0.325	-0.695	0.676	-0.357
"	Crop 2	-0.212	0.497	-0.349	-0.666	-0.148	-0.051	-0.472	-0.051	0.446	0.193	-0.650	-0.884
"	Crop 3	0.090	0.904	0.170	-0.215	-0.163	0.269	-0.877	-0.533	-0.754	-0.237	0.045	0.798
"	Crop 4	-0.054	-0.219	-0.626	-0.273	-0.774	-0.790	-0.248	0.744	0.431	-0.400	-0.857	-0.826
Total K uptake		-0.313	0.788	-0.923*	-0.841	-0.920*	-0.453	-0.460	0.423	0.365	-0.401	-0.464	-0.987*

*Significant at 0.05 probability level.

Table 6. Means and mean squares for dry matter yields of wheat from successive croppings on Wynona silt loam.

Treatments	Croppings				
	1	2	3	4	1-4
	----------	----------	g	----------	----------
RMCWH[†]	3.635	4.613	3.404	2.923	3.644
RDCWH-RDCSB	3.382	5.009	3.621	3.265	3.819
RDCWH-IDCSB	3.471	4.581	3.179	2.957	3.547
RDCWH-RDCGS	3.233	3.711	2.809	4.033	3.446
RDCWH-IDCGS	4.412	5.336	3.339	2.707	3.949
RCT-MCSB	3.116	5.203	2.840	2.204	3.341
ICT-MCSB	3.088	4.262	3.801	3.029	3.545
RCT-MCGS	3.184	5.227	3.085	2.564	3.515
ICT-MCGS	3.114	4.797	3.503	2.655	3.518
LSD (0.05)	0.381	0.294	0.475	0.491	0.210

	MS				
Source	Crop 1	Crop 2	Crop 3	Crop 4	Crop 1-4
Trt.[+]	1.597*	2.487*	1.034*	2.392*	1.267*
Crop	--	--	--	--	51.558*
Trt. x Crop	--	--	--	--	2.081*
Error	0.163	0.097	0.253	0.270	0.199

[+] Treatment

[†] Mean of 9 replications.

*Significant at 0.05 probability level.

Table 7. Means and mean squares for K uptake of wheat plants from successive croppings on Wynona silt loam.

Treatments	Croppings				
	1	2	3	4	1-4
	------------------- mg K g^{-1} -------------------				
RMCWH†	27.642	25.620	26.444	16.116	23.956
RDCWH-RDCSB	28.902	26.071	26.273	16.987	24.558
RDCWH-IDCSB	28.404	26.024	26.553	16.862	24.461
RDCWH-RDCGS	28.124	25.356	27.582	16.644	24.427
RDCWH-IDCGS	28.311	25.293	26.896	16.769	24.317
RCT-MCSB	28.529	25.387	26.553	16.162	24.158
ICT-MCSB	27.129	25.931	26.771	16.971	24.201
RCT-MCGS	27.331	26.833	27.144	16.489	24.449
ICT-MCGS	27.160	26.431	26.927	16.644	24.291
LSD (0.05)	1.307	1.384	0.976	0.613	0.572

	MS				
Source	Crop 1	Crop 2	Crop 3	Crop 4	Crop 1-4
Trt.+	3.808	2.478	1.442	0.923	1.254
Crop	--	--	--	--	2184.454*
Trt. x Crop	--	--	--	--	2.466
Error	1.915	2.147	1.069	0.422	1.469

+Treatment
†Mean of 9 replications.
*Significant at 0.05 probability level.

Table 8. Correlation coefficients relating ΔK with dry matter yields, and K uptake of four successive wheat crops grown on Wynona silt loam in the greenhouse.

Treatment	Dry matter Crop 1	Dry matter Crop 2	Dry matter Crop 3	Dry matter Crop 4	Total Dry Matter	K uptake Crop 1	K uptake Crop 2	K uptake Crop 3	K uptake Crop 4	Total K uptake
RMCWH	0.445	-0.152	0.070	0.790*	0.667*	-0.171	0.624	0.395	-0.094	0.644
RDCWH-RDCSB	-0.161	0.299	0.657*	0.098	0.473	-0.135	-0.126	0.277	0.784*	0.112
RDCWH-IDCSB	-0.309	0.205	0.666*	0.397	0.422	-0.451	0.350	0.364	0.676*	0.173
RDCWH-RDCGS	0.187	-0.852*	0.144	0.170	-0.057	-0.045	0.570	0.575	0.236	0.631
RDCWH-IDCGS	0.125	-0.187	-0.093	0.162	0.086	0.143	0.107	0.146	-0.160	0.141
RCT-MCSB	0.544	0.676*	-0.541	0.411	0.335	0.448	-0.557	-0.235	0.185	0.009
ICT-MCSB	0.289	0.336	-0.295	-0.259	-0.068	-0.397	-0.602	-0.281	0.406	-0.755*
RCT-MCGS	0.604	-0.192	-0.282	0.493	0.508	-0.076	0.812*	0.266	-0.058	0.519
ICT-MCGS	0.669*	-0.172	0.146	0.072	0.277	-0.518	0.127	0.144	0.119	-0.228

*Significant at 0.05 probability level.

Table 9. Correlation coefficients relating PBC^K with dry matter yields and K uptake of four successive wheat crops grown on Wynona silt loam in the greenhouse.

	Dry matter crop 1 Before	Dry matter crop 1 After	Dry matter crop 2 Before	Dry matter crop 2 After	Dry matter crop 3 Before	Dry matter crop 3 After	Dry matter crop 4 Before	Dry matter crop 4 After	Total dry matter Before	Total dry matter After	K uptake crop 1 Before	K uptake crop 1 After	K uptake crop 2 Before	K uptake crop 2 After	K uptake crop 3 Before	K uptake crop 3 After	K uptake crop 4 Before	K uptake crop 4 After	Total K uptake Before	Total K uptake After
RMCWH	0.217	-0.293	-0.181	-0.455	-0.077	-0.049	0.299	-0.461	0.185	-0.531	-0.414	-0.083	0.252	-0.527	0.691*	0.189	-0.357	-0.162	0.185	-0.492
RDCWH-RDCSB	0.161	0.231	-0.164	-0.236	-0.098	-0.779*	-0.645	-0.435	-0.340	-0.660*	-0.282	-0.072	0.176	0.223	0.629	-0.086	0.123	-0.684*	0.187	-0.079
RDCWH-IDCSB	-0.692*	0.189	0.095	-0.153	-0.036	-0.435	0.095	-0.137	-0.232	-0.230	-0.015	0.270	0.211	-0.394	-0.302	-0.188	0.245	-0.450	0.004	-0.178
RDCWH-RDCGS	0.356	-0.112	-0.741*	-0.066	-0.362	-0.412	0.370	0.391	-0.061	-0.042	0.493	0.406	0.413	-0.138	0.206	-0.163	0.068	0.039	0.524	0.003
RDCWH-IDCGS	-0.463	-0.042	-0.026	0.269	-0.635	-0.700*	0.024	-0.312	-0.752*	-0.642	-0.796*	-0.379	-0.067	-0.231	0.086	-0.381	0.700*	0.744*	-0.037	-0.214
RCT-MCSB	-0.165	0.213	0.510	-0.411	-0.572	0.218	-0.222	-0.612	-0.344	-0.272	-0.817*	0.010	-0.058	0.618	0.164	0.497	0.460	0.043	-0.444	0.553
ICT-MCSB	0.350	-0.201	0.157	0.024	-0.886*	-0.445	-0.546	-0.165	-0.644	-0.460	-0.728*	-0.285	-0.261	0.277	0.577	0.496	0.132	0.003	-0.425	0.282
RCT-MCGS	0.179	-0.071	0.056	-0.039	0.171	0.065	-0.006	-0.237	0.345	-0.220	0.081	0.369	0.722*	-0.650*	-0.227	0.102	0.332	0.047	0.533	-0.119
ICT-MCGS	-0.148	-0.279	0.124	0.240	-0.335	0.045	-0.574	-0.022	-0.734*	0.039	0.068	0.256	0.042	0.021	-0.173	0.067	-0.372	-0.032	-0.060	0.192

*Significant at 0.05 probability level.

Table 10. Correlation coefficients relating K-potential with dry matter yields and K uptake of four successive wheat crops grown on Wynona silt loam in the greenhouse.

	Dry matter crop 1 Before	Dry matter crop 1 After	Dry matter crop 2 Before	Dry matter crop 2 After	Dry matter crop 3 Before	Dry matter crop 3 After	Dry matter crop 4 Before	Dry matter crop 4 After	Total dry matter Before	Total dry matter After	K uptake crop 1 Before	K uptake crop 1 After	K uptake crop 2 Before	K uptake crop 2 After	K uptake crop 3 Before	K uptake crop 3 After	K uptake crop 4 Before	K uptake crop 4 After	Total K uptake Before	Total K uptake After
RMCWH	-0.307	0.233	0.256	0.295	0.136	0.397	-0.629	0.259	-0.382	0.525	0.290	0.252	-0.377	0.465	-0.612	-0.412	0.071	-0.064	-0.441	0.401
RDCWH-RDCSB	-0.237	-0.242	0.162	0.287	0.411	0.730*	0.729*	0.457	0.545	0.650*	0.431	0.111	-0.250	-0.247	-0.389	0.001	0.190	0.708*	-0.016	0.061
RDCWH-IDCSB	0.407	0.971*	-0.214	0.070	-0.412	0.353	-0.476	0.075	-0.305	0.211	0.235	-0.258	-0.136	0.256	-0.165	0.244	-0.484	0.320	-0.086	0.124
RDCWH-RDCGS	-0.241	-0.058	0.868*	0.007	0.022	0.269	-0.464	-0.544	-0.080	-0.262	-0.125	-0.278	-0.463	0.236	-0.425	0.262	-0.397	-0.281	-0.585	0.114
RDCWH-IDCGS	0.140	0.234	0.330	0.096	0.509	0.457	-0.025	0.163	0.503	0.601	0.465	0.635	-0.087	0.038	-0.266	-0.014	-0.554	-0.781*	-0.226	-0.038
RCT-MCSB	0.128	0.657*	-0.572	0.307	0.603	-0.126	0.025	0.466	0.218	0.523	0.567	0.886*	0.228	-0.415	0.142	-0.150	-0.476	-0.151	0.451	0.339
ICT-MCSB	-0.225	0.205	-0.485	-0.048	0.719*	0.424	0.441	0.148	0.413	0.431	0.694*	0.282	0.487	-0.287	-0.057	-0.533	-0.540	-0.041	0.632	-0.334
RCT-MCGS	-0.517	0.575	0.289	-0..096	0.049	-0.478	-0.092	0.785*	-0.245	0.617	0.339	0.191	-0.553	0.844*	-0.550	-0.041	0.035	-0.076	-0.269	0.625
ICT-MCGS	-0.638	0.345	0.107	-0.128	-0.458	-0.410	-0.068	-0.028	-0.495	-0.249	0.233	-0.536	-0.271	-0.083	-0.137	0.056	-0.182	-0.109	-0.071	-0.442

*Significant at 0.05 probability level.

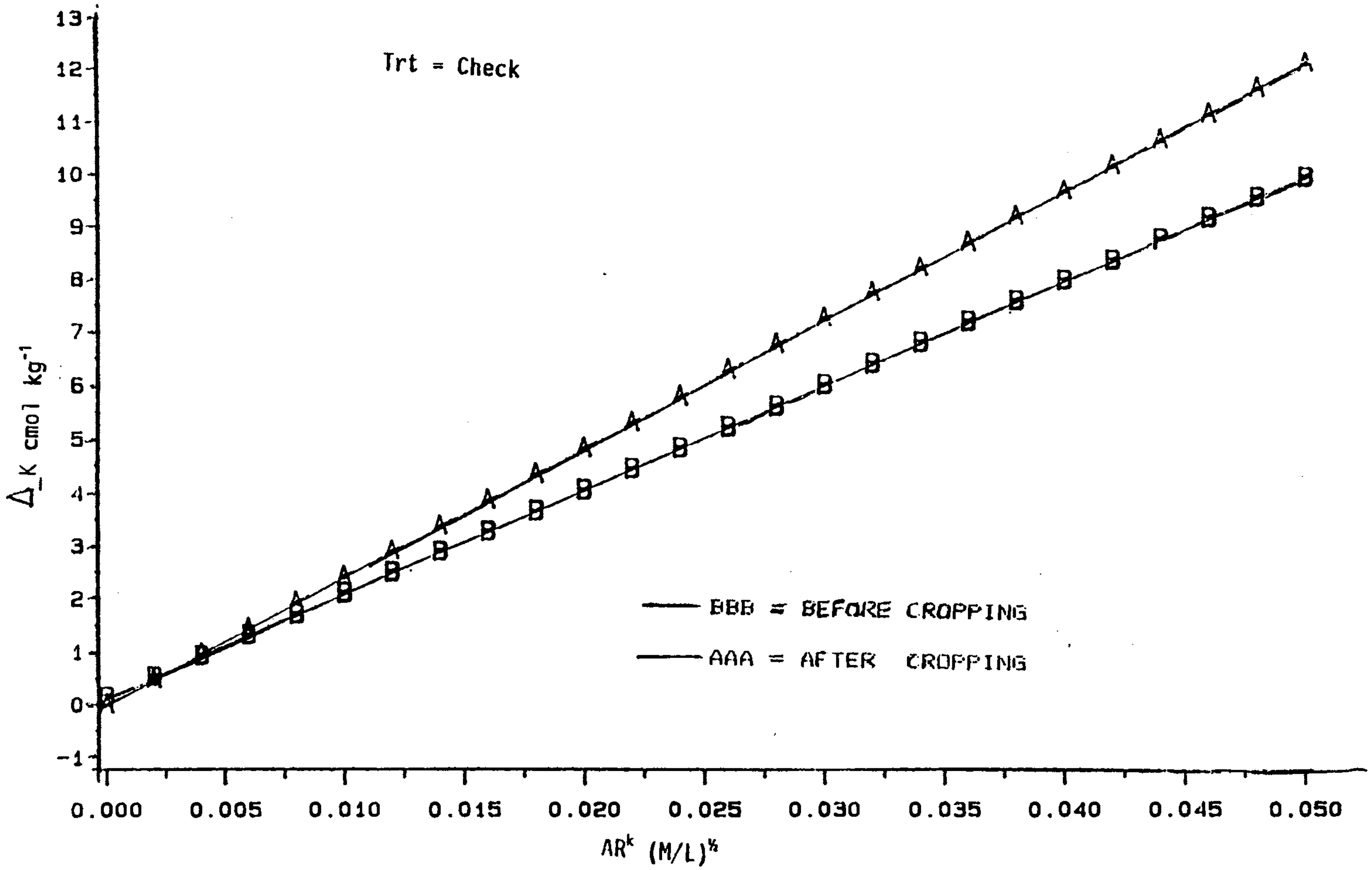

Fig. 1 Relation of Potassium Activity Ratio (AR_e^K) to $\underline{\Delta}K$ Before and After Cropping on Kirkland Silt Loam.

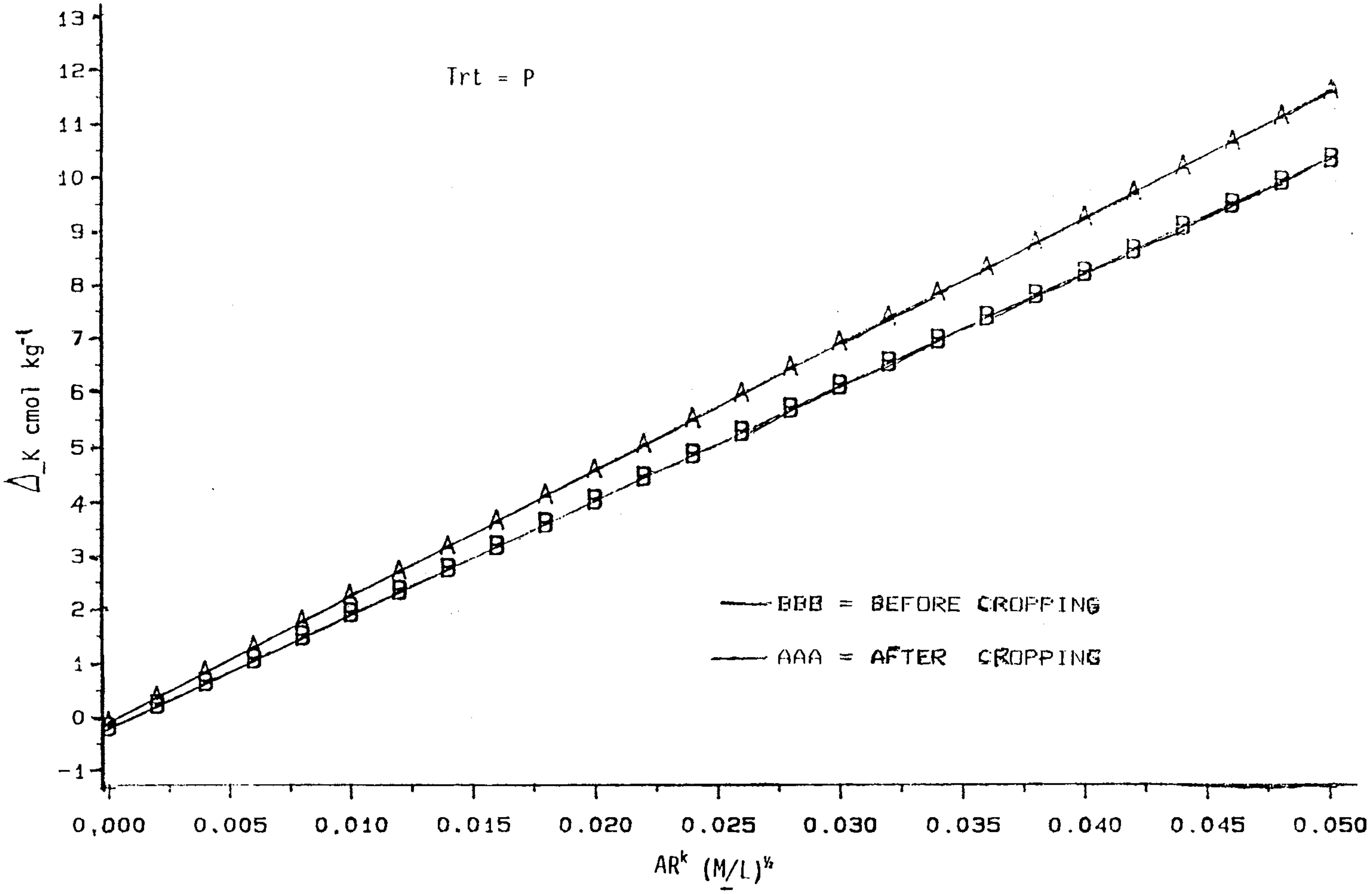

Fig. 2 Relation of Potassium Activity Ratio (AR_e^k) to ΔK Before and After Cropping on Kirkland Silt Loam.

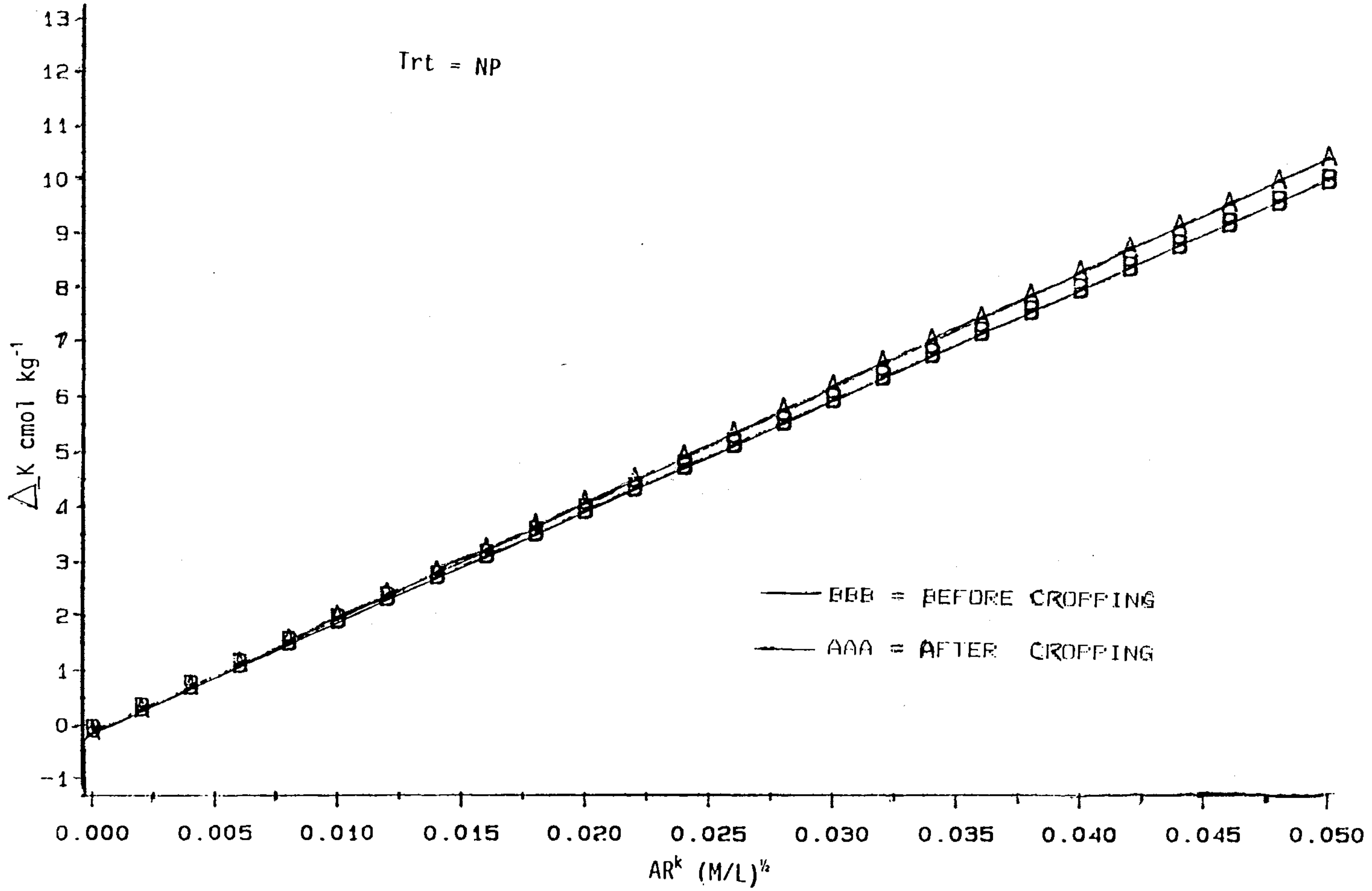

Fig. 3 Relation of Potassium Activity Ratio (AR_e^K) to ΔK Before and After Cropping on Kirkland Silt Loam.

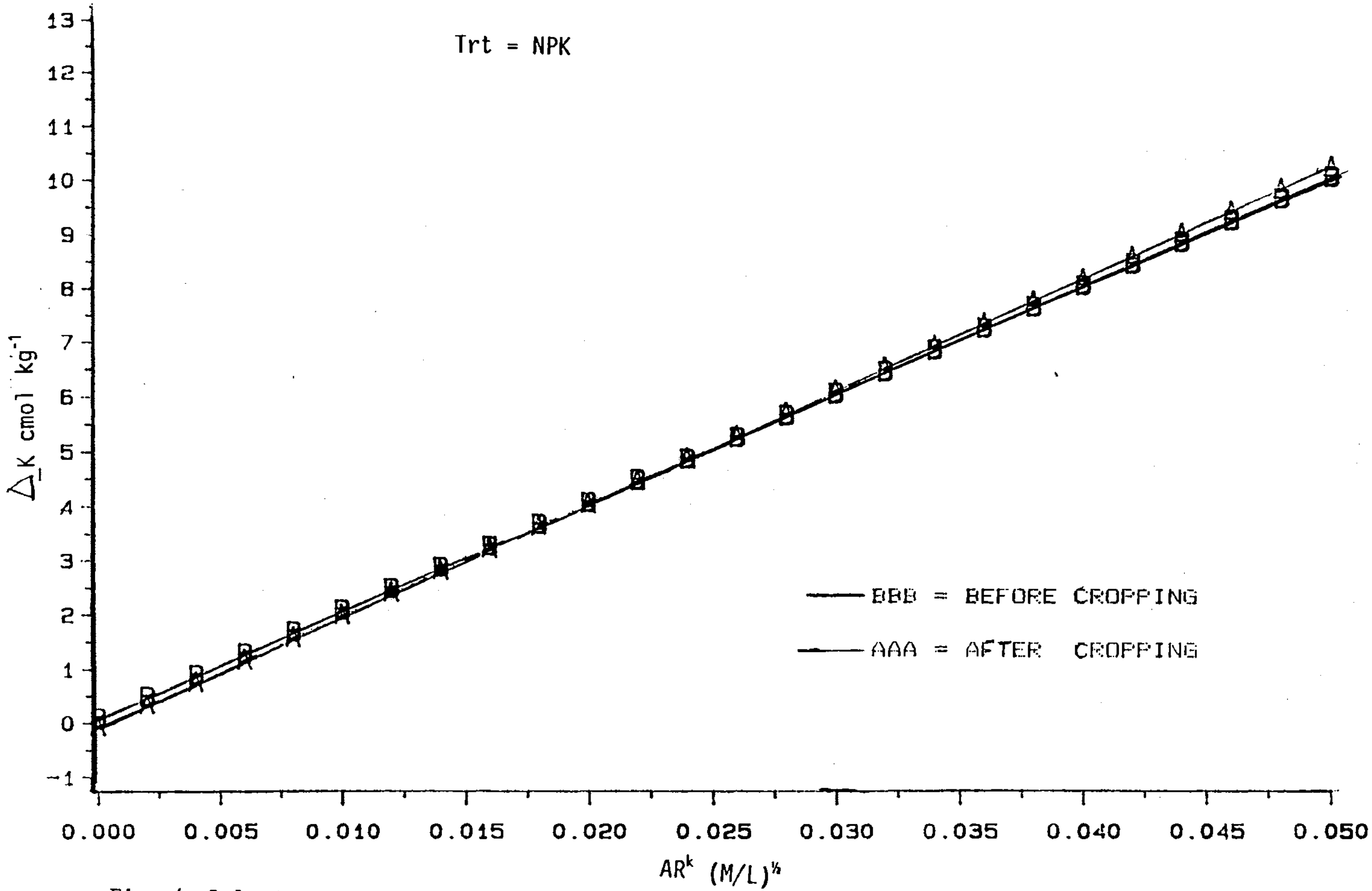

Fig. 4 Relation of Potassium Activity Ratio (AR$_e^K$) to ΔK Before and After Cropping on Kirkland Silt Loam.

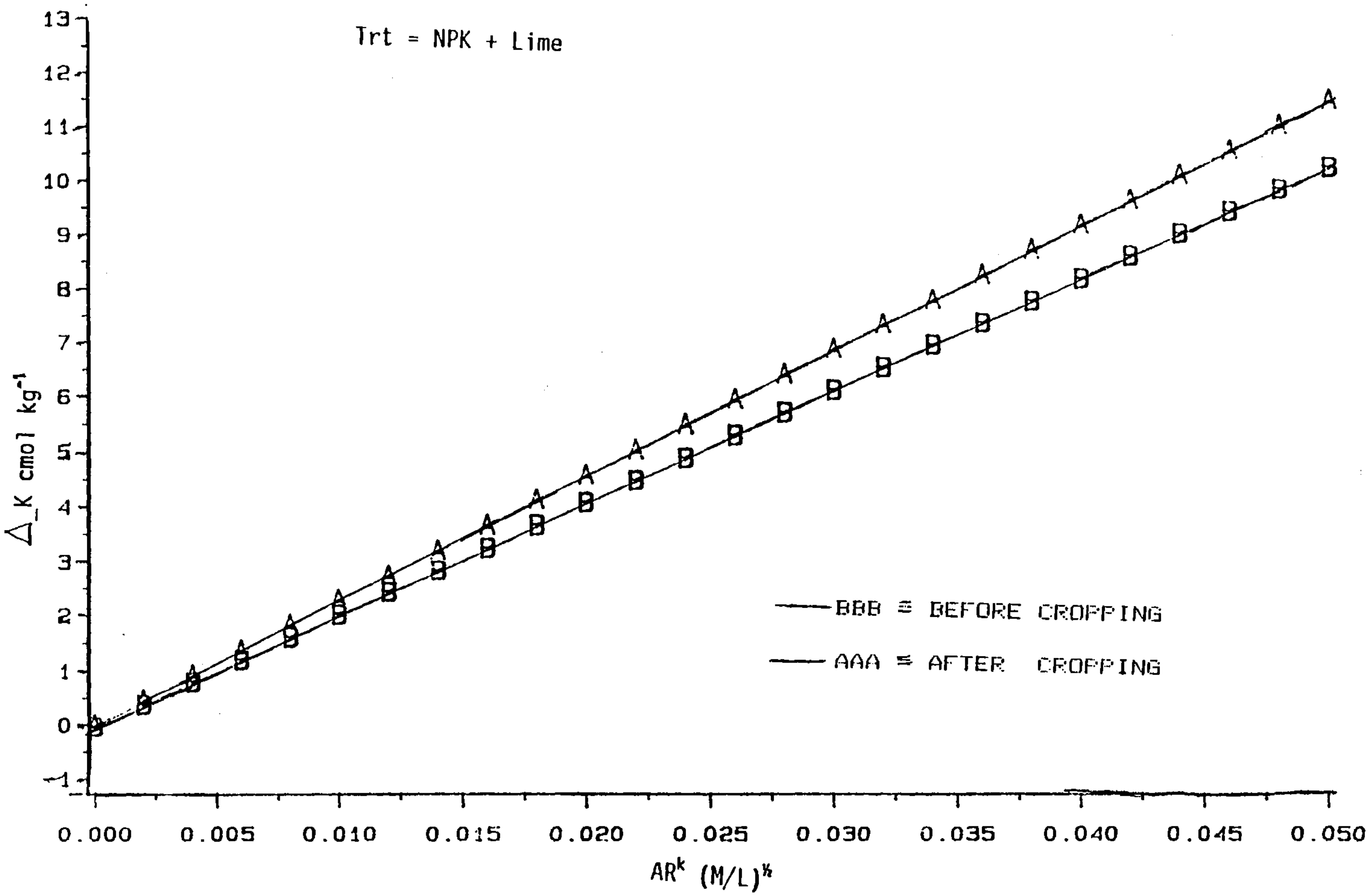

Fig. 5 Relation of Potassium Activity Ratio (AR_e^K) to $\underline{\Delta}$K Before and After Cropping on Kirkland Silt Loam.

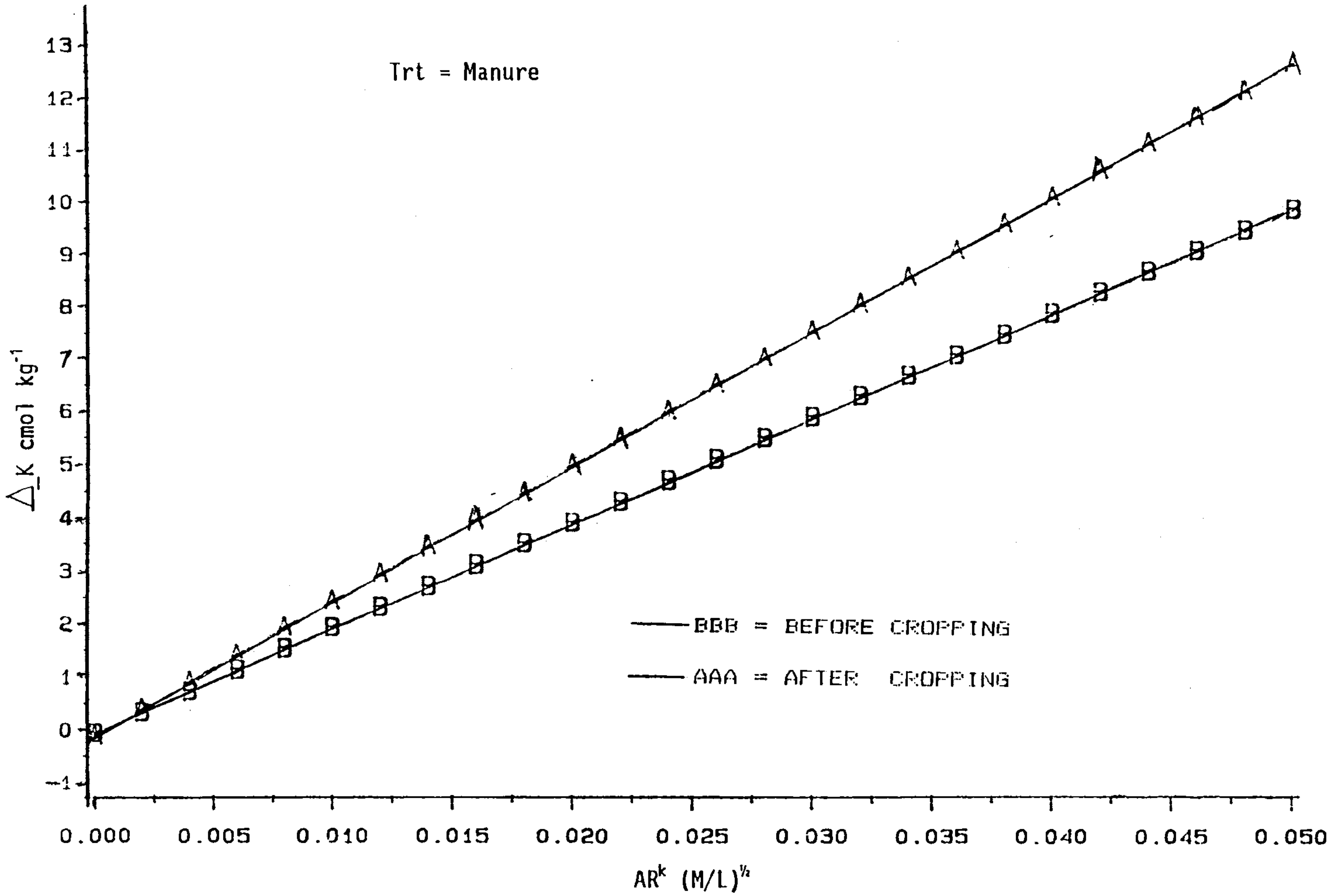

Fig 6 Relation of Potassium Activity Ratio (AR_e^K) to ΔK Before and After Cropping on Kirkland Silt Loam.

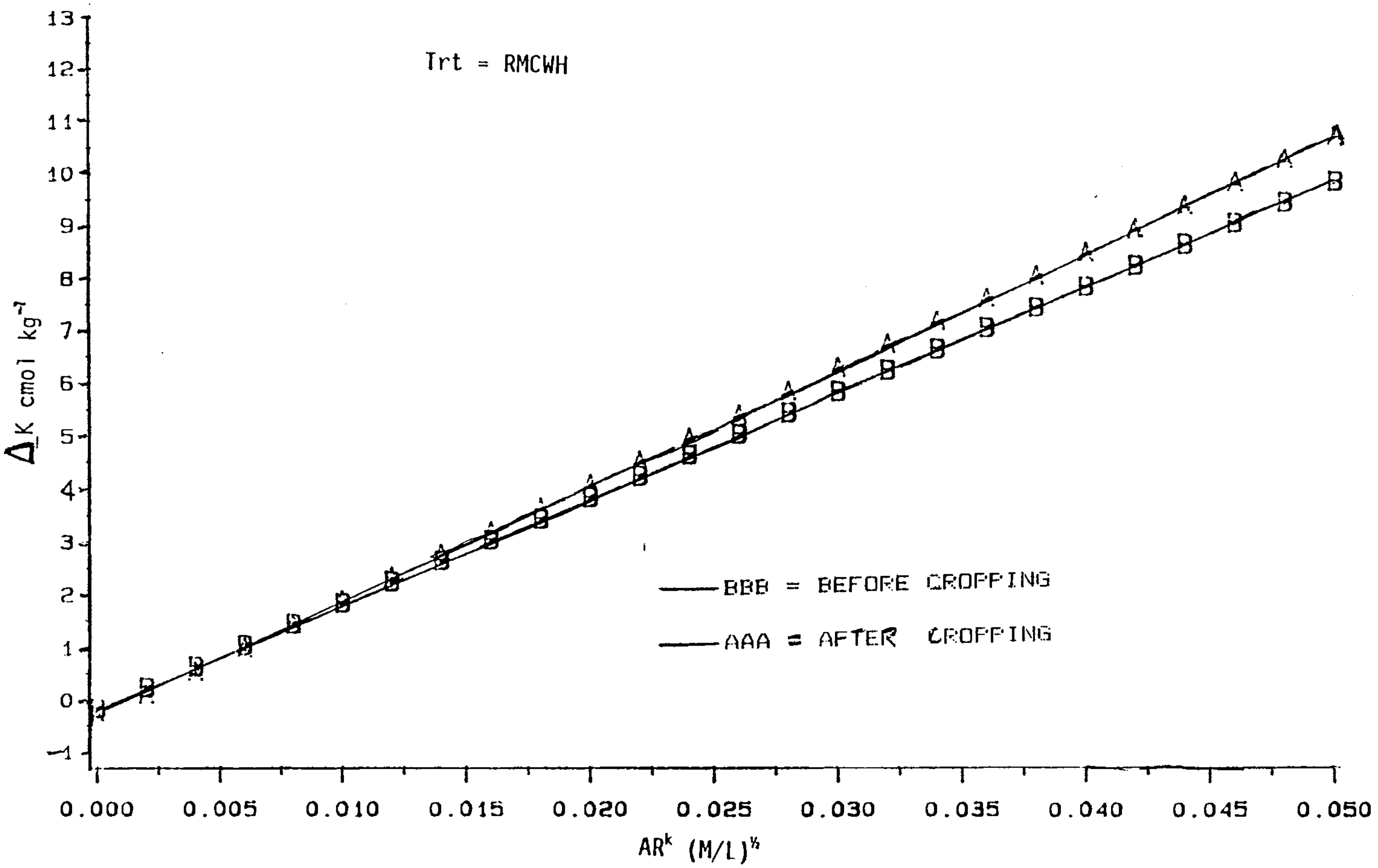

Fig. 7 Relation of Potassium Activity Ratio (AR_e^K) to ΔK Before and After Cropping on Wynona Silt Loam.

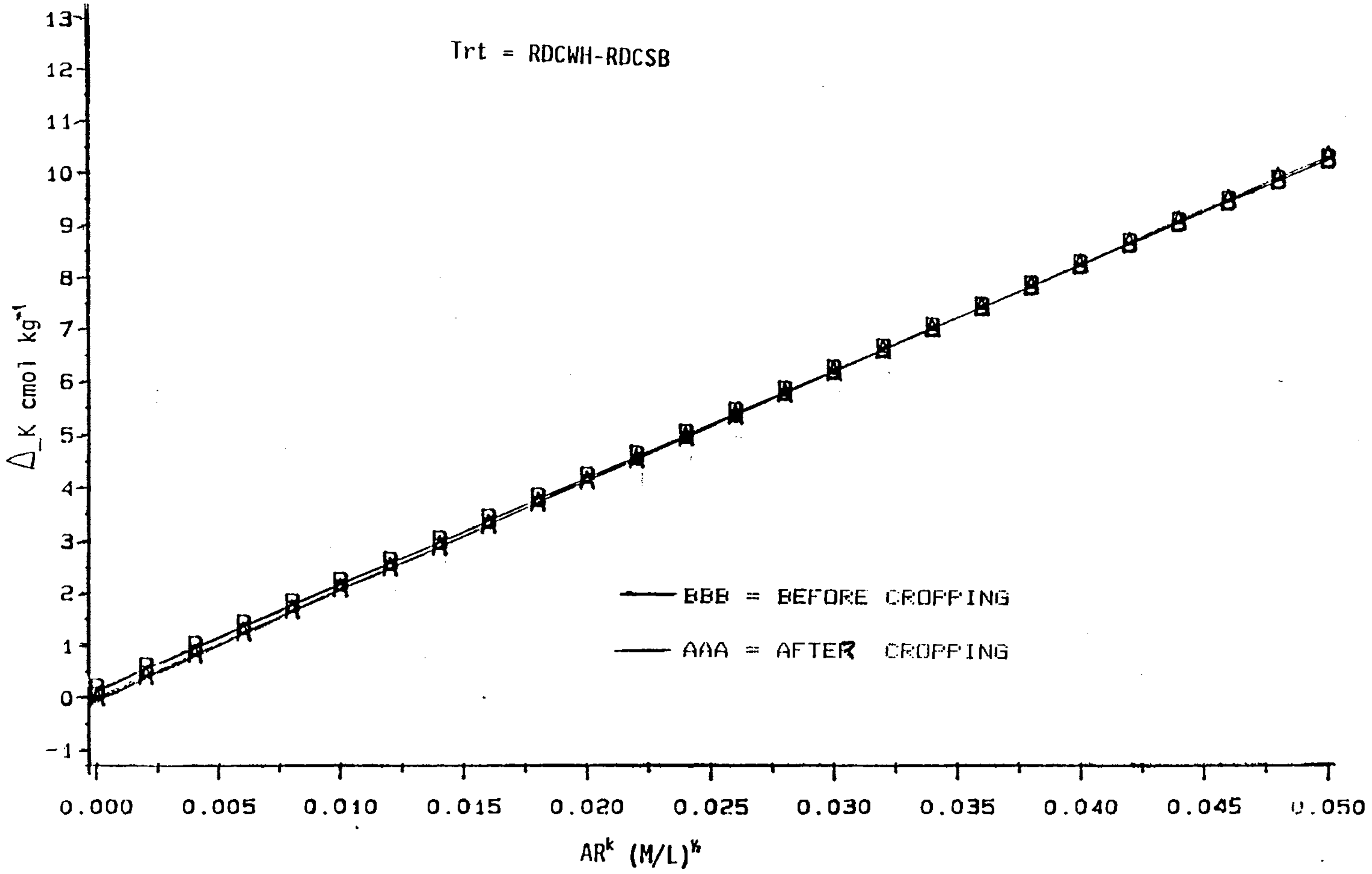

Fig. 8 Relation of Potassium Activity Ratio (AR_e^K) to ΔK Before and After Cropping on Wynona Silt Loam.

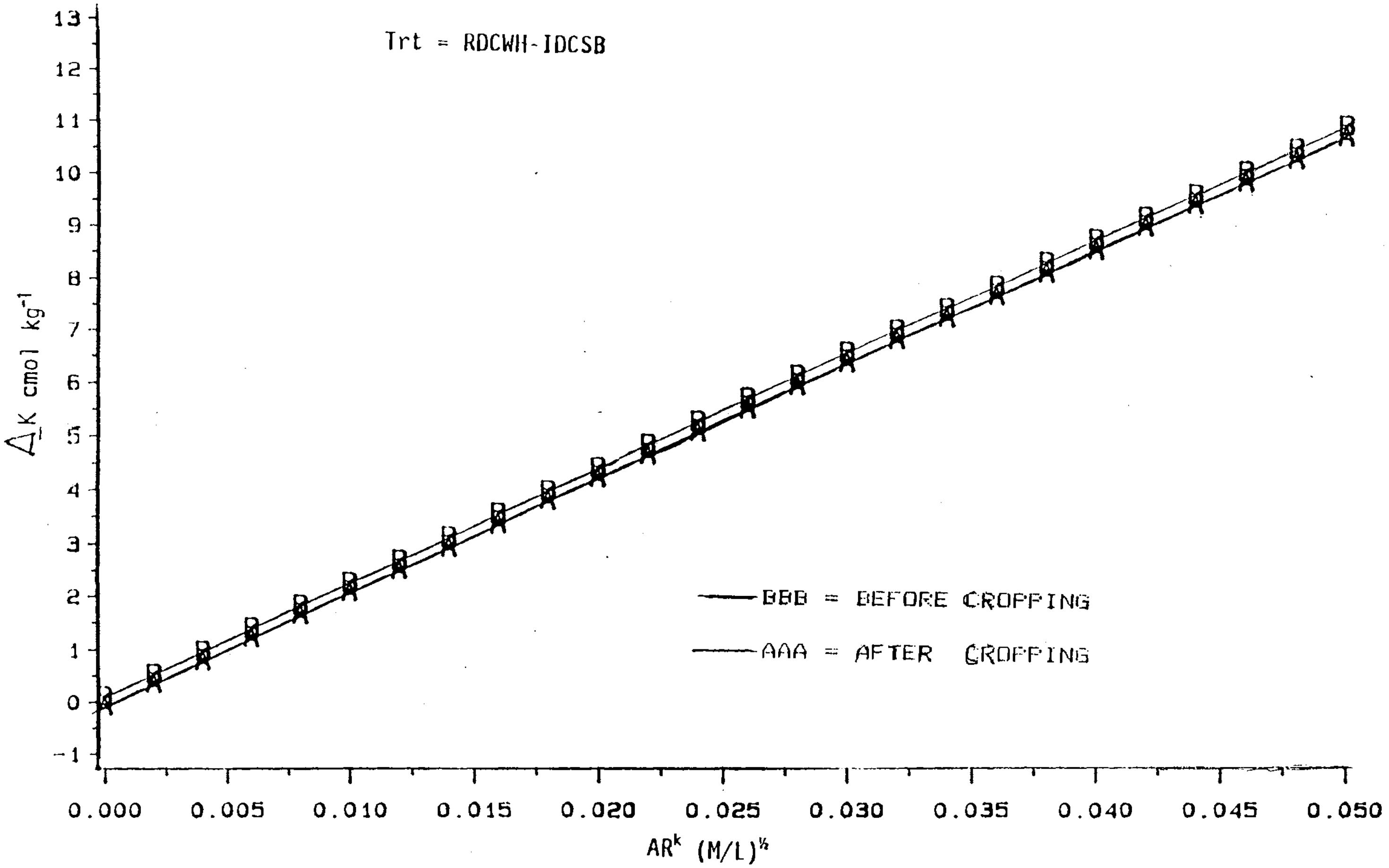

Fig. 9 Relation of Potassium Activity Ratio (AR_e^K) to $\underline{\Delta}$K Before and After Cropping on Wynona Silt Loam.

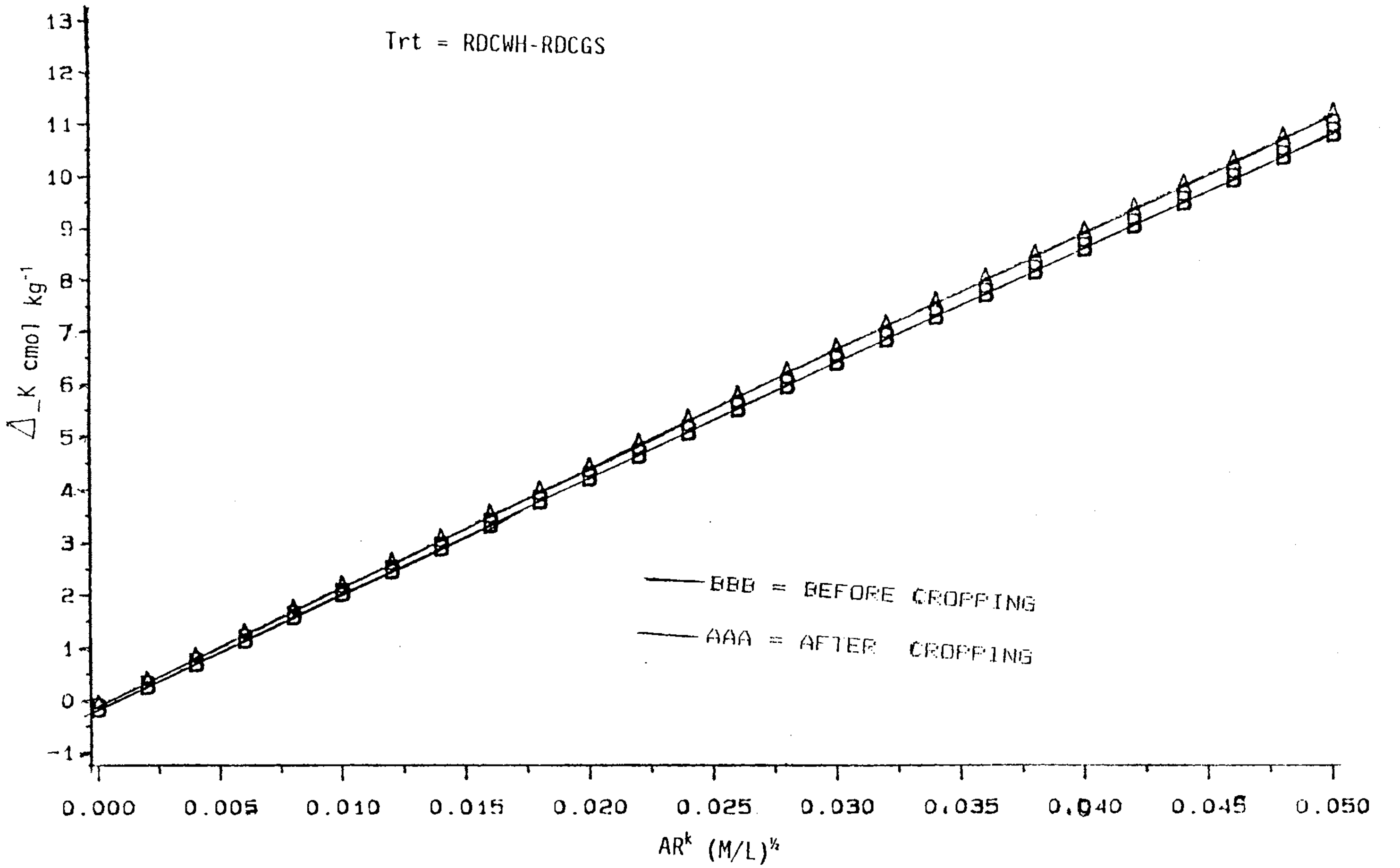

Fig. 10 .Relation of Potassium Activity Ratio (AR_e^K) to ΔK Before and After Cropping on Wynona Silt Loam.

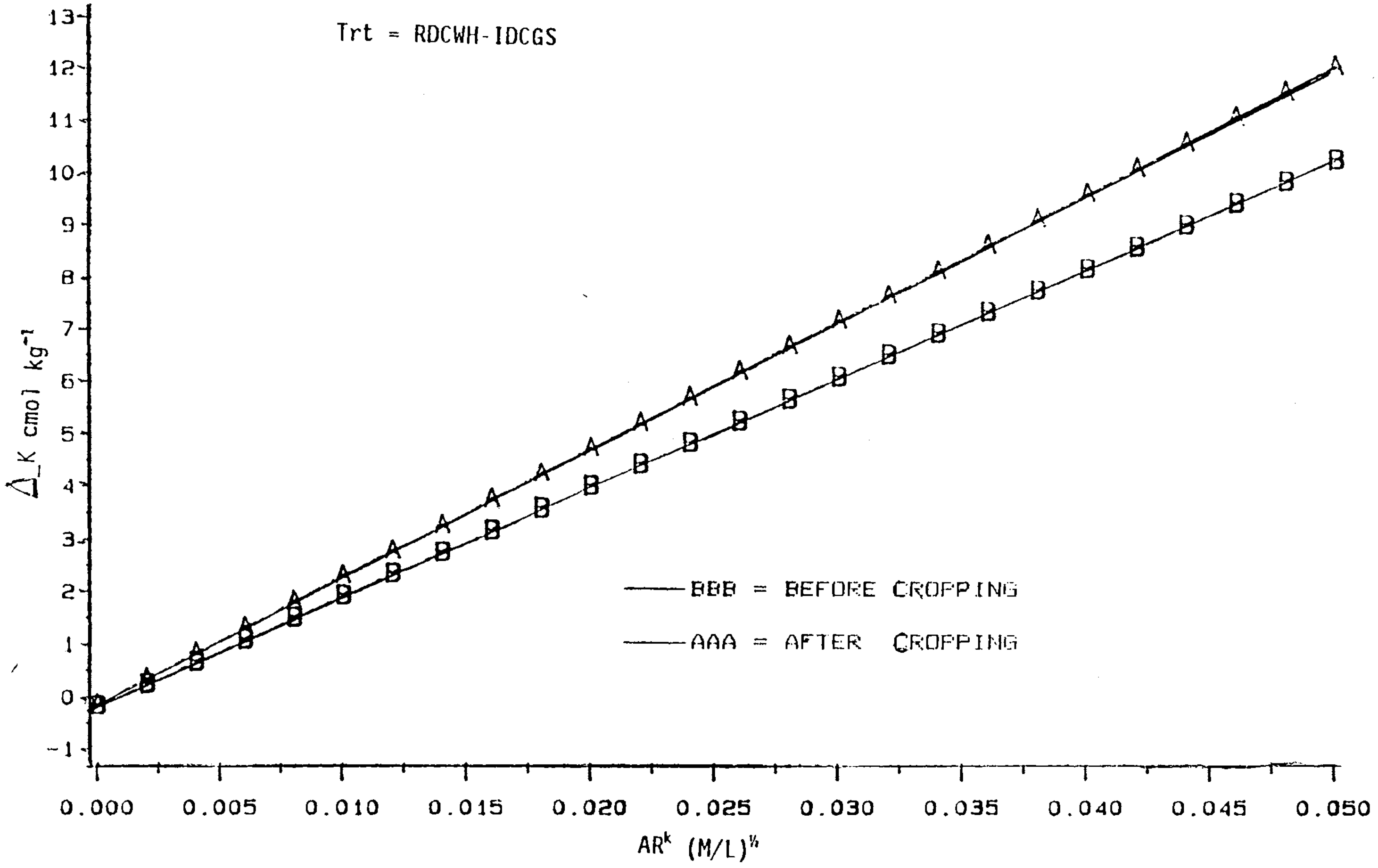

Fig. 11 Relation of Potassium Activity Ratio (AR_e^K) to ΔK Before and After Cropping on Wynona Silt Loam.

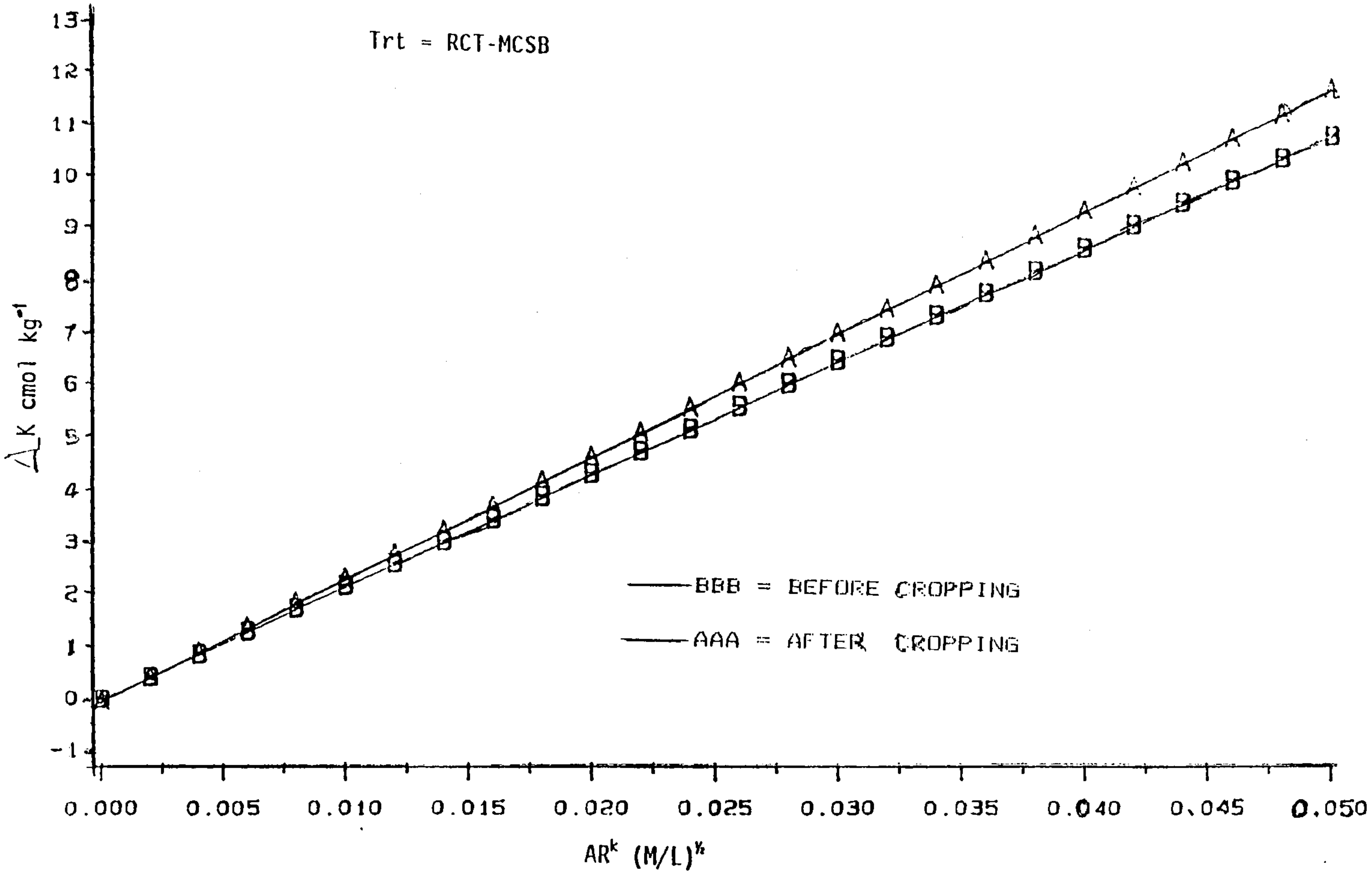

Fig. 12 Relation of Potassium Activity Ratio (AR_e^K) to ΔK Before and After Cropping on Wynona Silt Loam.

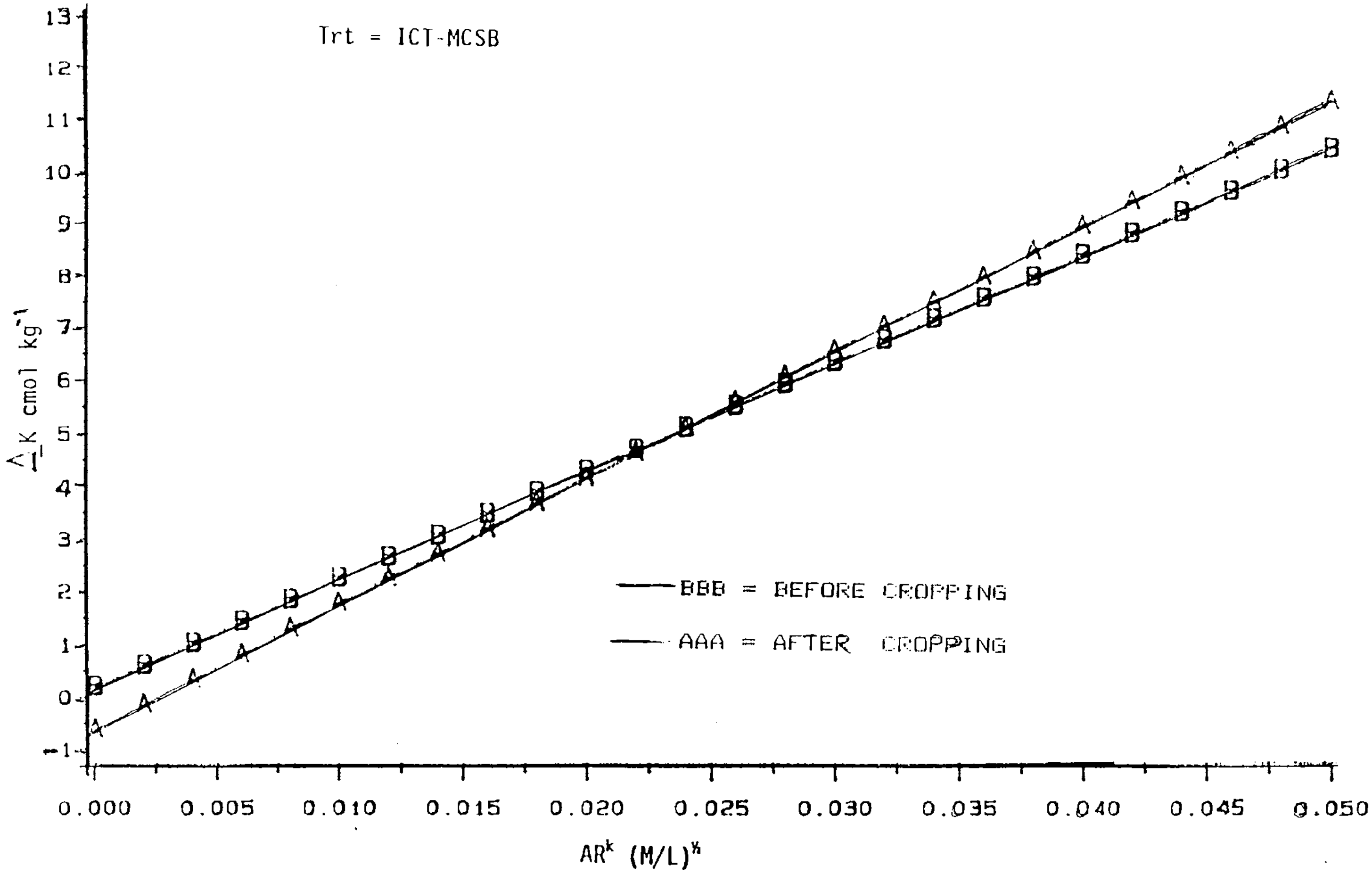

Fig. 13 Relation of Potassium Activity Ratio (AR$_e^K$) to ΔK Before and After Cropping on Wynona Silt Loam.

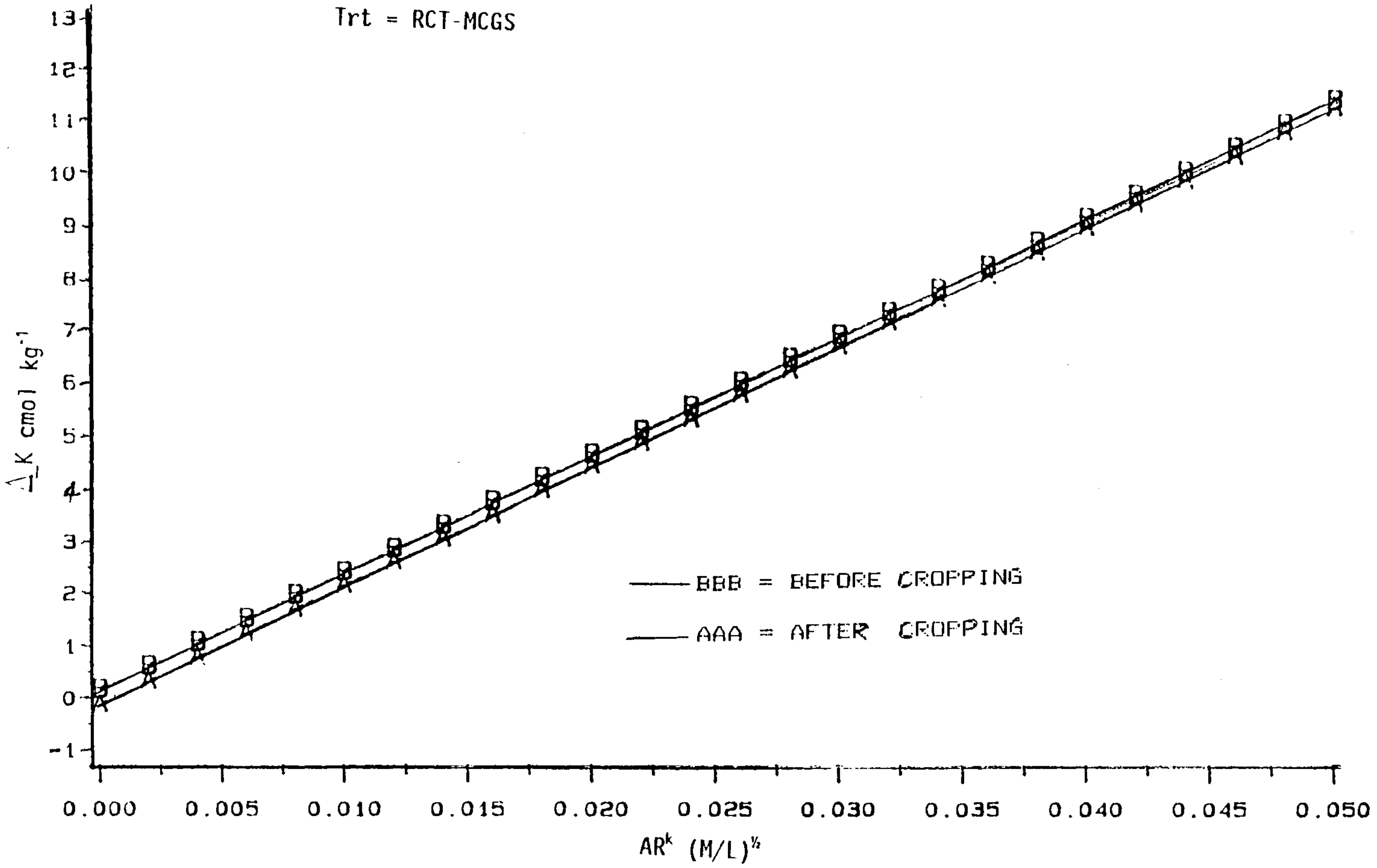

Fig. 14 Relation of Potassium Activity Ratio (AR$_e^K$) to$\underline{\Delta}$K Before and After Cropping on Wynona Silt Loam.

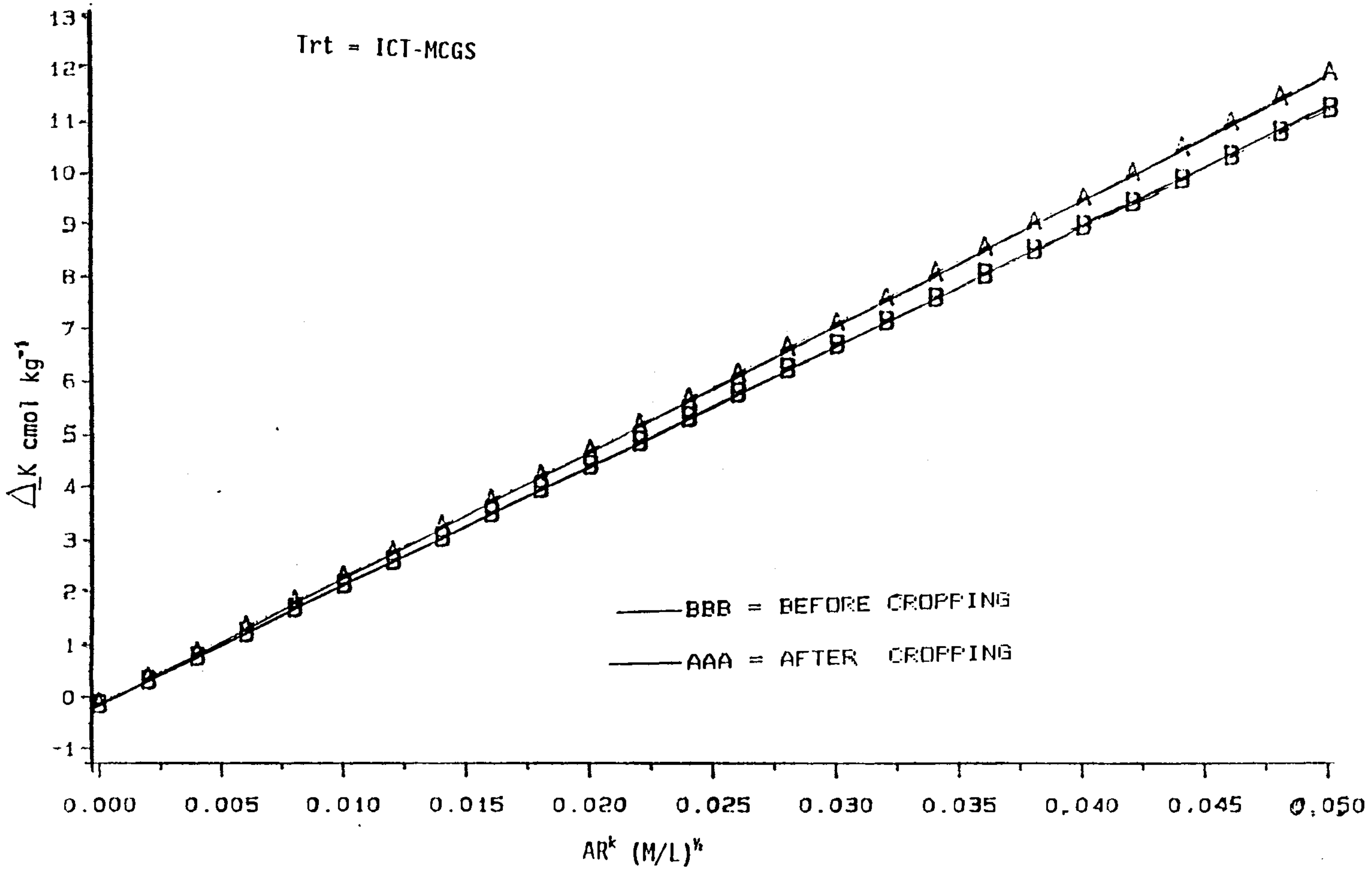

Fig. 15 Relation of Potassium Activity Ratio (AR_e^K) to ΔK Before and After Cropping on Wynona Silt Loam.

VITA

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Doctor of Philosophy

Thesis: LONG TERM MONO- AND DOUBLE-CROPPING WHEAT, SOYBEAN, AND GRAIN SORGHUM UNDER RAINFED AND IRRIGATED CONDITIONS AND EVALUATION OF POTASSIUM QUANTITY-INTENSITY RELATIONSHIPS OF TWO OKLAHOMA SOILS

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Biographical:

Personal Data: Born in Imesi-Ile, Obokun Local Government Council, Oyo State, Nigeria, January 14, 1947, to Ojo, Isaiah, and Tolani, Adesina.

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Professional Experience:

Laboratory Assistant, Agronomy Department, Oklahoma State University, Stillwater, Oklahoma, processing and grading of peanut varieties, 1988-1989.

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Research Associate, International Institute of Tropical Agriculture (I.I.T.A), Ibadan, Nigeria, conducting soil fertility and water management research in the Farming Systems Program; coordinated fertilizer and fertility research with Tennessee Valley Authority (TVA), Potash and Phosphate Institute, University of Ife and Ahmadu Bello University, Agronomy Departments, Nigeria; coordinating, collecting and analyzing data from experimental plots and cooperative program, teaching agricultural officers from African countries during rice and corn production and grain legume improvement training courses; also trained technicians in the Farming Systems Program at I.I.T.A. outstations, supervised and assisted in the recruitment and orientation of new staff, and evaluated them periodically for promotion, 1971-1982

Agricultural Officer, Ministry of Agriculture and Natural Resources, Western State of Nigeria, Ibadan, Organized Young Farmers Club, involved in training farm settlers and agricultural extension workers; organized Cooperative Unions, 1967-1971.

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PUBLICATIONS:

Crabtree, R.J., R.G. Greenland, J.D. Prater, J.O. Adesina, and P.L. Claypool. 1987. Mono- and double-cropped wheat and soybeans under rainfed and irrigated conditions. Soil Sci. 144:53-60.

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