The water use efficiencies of five legume green manure species
by Christopher K Wright

A thesis submitted in partial fulfillment of the requirments for the degree of Master of Science in Agronomy
Montana State University

Abstract:
Legume green manures are a potential alternative to summer fallow in dryland crop-fallow farming systems. The objective of this study was to isolate differences in water use efficiency among five legume species including three annuals, Indianhead lentil (Lens Culinaris Medik cv. Indianhead) Austrian Winterpea (Pisum sativum ssp. arvense (L.) Poir. cv. Melrose), and Cahaba white vetch (Vicia sativa L. cv. Cahaba), a biennial, yellow sweetclover (Melilotus officinalis (L.) Desr.), and a short-lived perennial, George black medic (Medicago lupulina L. cv. George). Legumes were arranged with spring wheat (Triticum aestivum L. cv. Pondera) and barley (Hordeum vulgare L. cv. Clark) in a complete randomized block design at Bozeman, MT in 1990 and 1991. Evapotranspiration (ET), canopy biomass accumulation, canopy percent nitrogen (N), and canopy height were measured over both growing seasons. Results were used to generate ET efficiency values in terms of canopy biomass accumulation, canopy N accumulation, and N2-fixation as well as canopy biomass accumulation vs. ET, canopy N accumulation vs. ET, and N2-fixation vs. ET regressions. Relative to 1990 results, poor performance of all legumes in 1991 may have been caused by higher transpirational demand over the growing season, drought over the month of July, and lower NO3-N fertility. In 1990, Indianhead lentil, Cahaba white vetch, George black medic, and yellow sweetclover exhibited similar water use efficiencies while Austrian winterpea exhibited slightly better performance. In 1991, both Austrian winterpea and Indianhead lentil exhibited high performance while slightly lower water use efficiencies were exhibited by Cahaba white vetch, George black medic, and yellow sweetclover.

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Christopher K. Wright

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Christopher Kevin Wright

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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ABSTRACT

Legume green manures are a potential alternative to summer fallow in dryland crop-fallow farming systems. The objective of this study was to isolate differences in water use efficiency among five legume species including three annuals, Indianhead lentil (*Lens Culinaris* Medik cv. Indianhead) Austrian Winterpea (*Pisum sativum ssp. arvense* (L.) Poir. cv. Melrose), and Cahaba white vetch (*Vicia sativa* L. cv. Cahaba), a biennial, yellow sweetclover (*Melilotus officinalis* (L.) Desr.), and a short-lived perennial, George black medic (*Medicago lupulina* L. cv. George). Legumes were arranged with spring wheat (*Triticum aestivum* L. cv. Pondera) and barley (*Hordeum vulgare* L. cv. Clark) in a complete randomized block design at Bozeman, MT in 1990 and 1991. Evapotranspiration (ET), canopy biomass accumulation, canopy percent nitrogen (N), and canopy height were measured over both growing seasons. Results were used to generate ET efficiency values in terms of canopy biomass accumulation, canopy N accumulation, and N_2-fixation as well as canopy biomass accumulation vs. ET, canopy N accumulation vs. ET, and N_2-fixation vs. ET regressions. Relative to 1990 results, poor performance of all legumes in 1991 may have been caused by higher transpirational demand over the growing season, drought over the month of July, and lower NO_3-N fertility. In 1990, Indianhead lentil, Cahaba white vetch, George black medic, and yellow sweetclover exhibited similar water use efficiencies while Austrian winterpea exhibited slightly better performance. In 1991, both Austrian winterpea and Indianhead lentil exhibited high performance while slightly lower water use efficiencies were exhibited by Cahaba white vetch, George black medic, and yellow sweetclover.

Chapter 1

INTRODUCTION

Within a global context, Montana agriculture is representative of agricultural systems in arid and semi-arid cool temperate regions. These regions are generally characterized by long cold winters, cool or cold soils, short growing seasons, high summer insolation, high daytime summer temperatures, persistent winds often high in fall and spring, and potential evapotranspiration (ET) exceeding precipitation for much of the growing season (Ferguson and Krall, 1979). In deference to these climatic constraints, Montana dryland farmers have generally been limited to cultivation of small grains, oil seeds, and forages. To produce annual crops, they have overwhelmingly resorted to the alternate crop-fallow cropping system, e.g. in 1964, 2,310,000 hectares lay fallow in Montana (Ford and Krall, 1979).

The crop-fallow system contains three features that have fostered its widespread adoption. Most importantly, summer fallow allows dryland farmers to stabilize crop yields through the accumulation, on average, of 2.5 cm of soil water from harvest to planting of a subsequent crop. A crop-fallow system can also produce dramatic fertility effects as mineralized nitrate accumulates via the breakdown of soil organic matter over the duration of fallow. Lastly,

the summer tillage operations commonly associated with fallow are an effective method for control of perennial weeds (Ferguson and Krall, 1979).

Unfortunately, the crop-fallow system has several negative features that threaten the long-term sustainability of small-grain agriculture in Montana and the Northern Great Plains. Crop-fallow farming makes inefficient use of the region's most limited resource, precipitation, while degrading the foundation of any agricultural system, the soil. Lastly, the crop-fallow system's dependence on purchased petrochemical inputs, dependence namely on nitrogen-fertilizer and diesel fuel, places Montana farmers at the whim of global markets and events beyond their control, e.g. Arab oil embargoes and Persian Gulf conflicts.

While it is indisputable that summer fallow increases soil water content, the storage efficiency of this practice is low (where storage efficiency equals the percentage of precipitation entering a cropping system that is actually stored in the root zone of the soil profile over the duration of fallow). Over 14 years, a winter wheat (*Triticum aestivum* L.)-fallow cropping system at Sydney, MT exhibited an average fallow storage efficiency of 27.6% (Black et al., 1974).

The relatively low storage efficiency of fallow implies that significant amounts of water move below the root zone when soil water contents reach field capacity. Prior to

cultivation of the Great Plains, native plant communities of the short- and mixed-grass prairies contained a broad spectrum of species with variable rooting depths and growth habits. These heterogenous communities utilized most of the water entering the soil profile before it moved below the root zone (Ferguson and Krall, 1979). However, by removing this vegetation and limiting crop water use to 3 months out of every 2 years, Montana farmers allow approximately 2-3 cm of water to leach below fallow fields annually (Ferguson et al., 1978). This contribution of excess moisture to water tables has created two adverse environmental impacts, saline seep and groundwater contamination.

Saline seep is defined as:

> intermittent or continous saline water discharge, at or near the soil surface downslope from recharge areas under dryland conditions, that reduces or eliminates crop growth in the affected area because of increased soluble salt concentration in the root zone (Brown et al., 1983).

Cropland of eastern Montana is vulnerable to saline seep because soils are underlain by vast Cretaceous marine shale formations that form an impermeable barrier to deep drainage (Long, 1986). Water moving below the root zone of fallow fields solubilizes salts, including nitrates, sodium sulfates, and magnesium sulfates (Ferguson and Krall, 1979). Approximately 81,000 hectares in Montana are affected by saline seeps, resulting in an annual loss of approximately 3 million bushels of wheat and an estimated $12 million in

gross income. In the Northern Great Plains, 810,000 dryland hectares are affected by salinization while an estimated 590,000 square kilometers are vulnerable to future saline seep development (Brown et al., 1983; Bahls and Miller, 1973).

In settings where water tables are deep enough to preclude saline seep formation, summer fallow's contribution of soluble salts may cause groundwater contamination. Groundwater samples near saline seeps commonly contain more than 25,000 milligrams total dissolved solids liter^{-1}. Dissolved constituents commonly include calcium, sodium, magnesium, sulfate, and nitrate (Brown and Krall, 1981).

Nitrate contamination may be of particular concern in the future. Custer (1976) found nitrate at 33-55 ppm in ground water beneath crop-fallow cultivated land at Rapelje, Montana. These fields also contained up to 1,086 kg/ha of nitrate below the root zone, nearly four times the amount of fertilizer-N applied over their cultivated history. In 1990, the Montana Agricultural Extension Service reported that nitrate levels exceeded minimum EPA standards (10ppm) in 6.5% of private well samples obtained from 36 Montana counties (Bauder, 1990)

Leaving ground bare for a 14 or 21 month interval also creates tremendous erosion potential, especially as low residue cover (after a summer of cultivation) coincides with high winds in the fall and spring. The 1982 National

Resources Inventory (NRI) revealed that wind erosion on highly erodible Montana cropland averaged 7,627.2 kg acre^{-1} year^{-1}, well above the average soil loss tolerance (T) value of 4,540 kg acre^{-1} year^{-1} for that land (Soil and Water Conservation Society, 1992). Additionally, crop residue burial during summer fallow tillage may prevent dryland farmers from complying with residue requirements specified in their SCS Soil Conservation Plans. In 1990, the Soil and Water Conservation Society found that crop residue cover fell short of planned levels on 40% of the wheat acreage examined at five Great Plains sites (Soil and Water Conservation Society, 1992).

Lastly, while a fertility effect is linked to summer fallow via the accumulation of mineralized nitrates, this beneficial effect has decreased with the declining organic matter content of Montana soils over the last 75 years. In response, Montana grain farmers have applied increasing quantities of N-fertilizer to obtain profitable yields and high protein contents (Sims and Jackson, 1974; Jackson and Sims, 1977).

A potential alternative to the crop-fallow system is a cereal-legume rotation. Annual legume green manures substituted for summer fallow may ameliorate many of the negative aspects associated with fallow. To improve dryland grain farming in Montana, a legume green manure should: 1. prevent saline seep formation and groundwater contamination

by transpiring water that would otherwise leach below the root zone 2. limit soil erosion by acting as a cover crop and increasing surface residue levels 3. contribute to soil N-fertility by symbiotic association with N_2-fixing *Rhizobium* bacteria 4. improve soil structure by increasing soil organic matter content 5. improve farm profitability by reducing N-fertilizer requirements and eliminating fallow tillage operations.

This study represents an effort to refine understanding of the legume green manure component of the cereal-legume rotation. Since water is often the greatest limiting factor in Montana dryland agriculture, the objective of this study was to examine the water use efficiency of five legumes including three annuals, Indianhead lentil (*Lens culinaris* Medik cv. Indianhead), Cahaba white vetch (*Vicia sativa* L. cv. Cahaba) , and Austrian winterpea (*Pisum sativium ssp. arvense* (L.) Poir. cv. Melrose), one biennial, yellow sweetclover (*Melilotus officinalis* (L.) Desr.), and one short-lived perennial, George black medic (*Medicago lupulina* L. cv. George).

Chapter 2

REVIEW OF LITERATURE

Legume Green Manures in Dryland Farming Systems

A successful example of a cereal-legume cropping system is found in the Australian ley farming method where small grains are rotated with short-season annual legumes grown for sheep pasture. Interestingly, the historical events leading to widespread employment of ley farming are similar to the evolution of Great Plains agriculture. From 1870 to 1900, Australian wheat yields declined as pre-settlement soil fertility was depleted. Introduction of superphosphate fertilizer, summer fallow, and improved varieties restored crop yields to former levels until nitrogen became severely limiting around 1950. However, instead of using N-fertilizers, Australian farmers shifted to ley farming, alternating small grains with various annual *Medicago* forages (Clarke and Russell, 1977).

After adopting the ley farming system, Australian dryland farmers achieved wheat yields higher than previously obtained on virgin soils (Clarke and Russell, 1977). Additionally, yield benefits associated with the ley system appear to accumulate over time. Elliott et al. (1972) found postive and linear yield increases associated with ley farming practices over a ten year interval while traditional

wheat-fallow cropping sytems produced a 22% yield decline. The contribution of the legume component to nitrogen fertility of the system is equally impressive. An average medic stand in South Australia increased soil nitrogen content by 60 to 70 kg/ha in one season, equivalent to application of approximately 300 kg/ha of sulphate of ammonium (Webber et al., 1976).

Little research has been dedicated to the feasibility of cereal-legume rotations in Montana or within the arid and semi-arid cool temperate zone of agriculture. In Montana, a 38 year study (1914-1951) by Army and Hide (1959) revealed that field pea and sweetclover green manures had a neutral or negative effect (compared to summer fallow) on subsequent small grain yields. These results, combined with the availability of inexpensive N-fertilizer, financial incentives associated with participation in the Federal Farm Program, and increased use of herbicides, largely eliminated further work with legume green manures in Montana until 1978 when Dr. James Sims of Montana State University initiated a reexamination of cereal-legume rotations (Sims and Slinkard, 1991).

Working with rotations of fourteen annual legume species and spring wheat, Koala (1982), demonstrated the adaptability of cereal legume rotations to Montana dryland agriculture. He found that average dry matter yields of five Australian annual medics (*Medicago* spp.) , seven

clovers (*Trifolium* spp.), a medic from Montana (*Medicago lupulina* L.), and one faba bean cultivar (*Vicia faba* L.) were 2,994 Kg/ha, 4,394 Kg/ha, 811 kg/ha, and 2,131 kg/ha, respectively. Soil testing prior to spring grain planting the following year revealed significantly higher ($p<0.05$) levels of NO_3-N in the 0-30 cm soil increment of legume treatments compared to crop-fallow controls. During the cereal phase of the rotation, spring wheat grain yield, protein content, and N uptake were all significantly higher ($p<0.05$) following all legume treatments when compared to spring wheat performance in an alternate crop-fallow treatment.

Additional research in Montana by McGuire et al. (1989) demonstrated that dryland cereal-legume rotations can produce the high grain quality demanded by the malting industry. Reported grain protein content of barley (*Hordeum vulgare* L. cv. Clark) following Austrian winter pea green manure was 11.4% at Bozeman and 10.4% at Huntley without any addition of fertilizer-N. These values are safely within the 10.0 to 12.5% range required by the malting industry.

While the above results reveal that cereal-legume rotations can produce both high grain yield and quality, legume green manures in low precipitation regimes may subject subsequent cereal crops to water deficits. In Koala's study (1982), soil water content in the 0-60 cm depth increment was significantly lower ($p<0.05$) in most

legume treatments compared to fallow controls at the time of legume incorporation. By planting of the subsequent grain crop, fall and winter precipitation replenished soil water content in all legume treatments. However, this restoration of water storage capacity between legume incorporation and cereal planting may not always occur, a possibility that might explain the negative or neutral results reported by Army and Hide (1959). Careful management of annual legumes by fitting green manure evapotranspiration to specific precipitation regimes should allow farmers to overcome this obstacle.

Water Use Efficiency: Definitions, an Historical Context and Theoretical Considerations

Water is the primary component of plant tissue and the solvent in which plant biochemical reactions take place. Despite this important constituitive role, the actual amount of water required for these purposes is very small. Water uptake equivalent to a volume depth of 1 mm would produce record yields of almost any crop (Stanhill, 1986). A much greater volume of water moves through plants from soil to the atmosphere, performing dual functions of nutrient transport and evaporative cooling. On a hot, sunny day, transpiration from a crop surface may exceed 10 kg per square meter of land area (Baker et al., 1992)

The high transpirational demand typical of hot, dry climates presents a dilemma. To produce biomass under these

conditions, plants must reconcile vital, but opposite demands. Synthesis of dry matter requires rapid assimilation of CO_2 through gas exchange with the atmosphere while maintenance of high humidity within the leaf demands minimal gas exchange. Similarly, maximizing absorption of solar radiation to power carbon assimilation conflicts with a need to limit the energy available for latent heat exchange, the energy source driving crop water loss to the atmosphere (Stanhill, 1986). The different means by which plants (through physiological adaptation) and agronomists (through selection and cultural practices) resolve this quandry central to plant growth in arid climates largely determine the wide differences in water use efficiency observed between plant species and cropping systems. Isolating, explaining, and possibly manipulating these differences has become an important focus in the field of plant-water relations.

Definitions

Discussions of plant water use efficiency generally employ a wide range of terms and definitions. Most of this language is not elaborated in any systematic fashion. Of particular confusion are definitions of water use efficiency (WUE) and efficient water use (EWU). Addressing the

nebulous qualities of these terms, Tanner and Sinclair (1983) wrote;

> The phrases "efficient water use" or "water use efficiency" are intrinsically ambiguous in relation to crop production. We may mean saving water from a given supply for crop use; we also may mean increasing production per hectare (yield) per unit of water evaporated from the soil and/or transpired from the plants in the field.

In light of the confusion associated with much of the language encountered in studies of water use efficiency, it seems appropriate to first discuss this language before attempting historical and theoretical discussions of water use efficiency.

Addressing the point made by Tanner and Sinclair, Stanhill (1986) proposed two different definitions of WUE; 1. hydrological water use efficiency, and 2. physiological water use efficiency. He defines hydrological WUE as the ratio of the volume of water used productively, i.e. evapotranspired, to the volume of water available for use, i.e. water reaching a cropping situation via rainfall and irrigation in addition to water available in the soil. Within this hydrological definition, water losses associated with surface runoff, leaching, and irrigation sytems contribute to reductions in efficiency. Stanhill's hydrological definition of WUE also satisfies a formal definition of efficiency in that its value represents a fraction that cannot be less than zero or greater than one.

Physiological definitions of WUE, Stanhill (1986) observes, have typically been expressed as the ratio of crop transpiration to crop yield or total dry matter production. In this context, he argues that use of the word "efficiency" is inappropriate in that a maximum value established by theory or observation does not exist, i.e. values of physiological WUE defined in the above manner do not vary between zero and one. Stanhill, instead, suggests rehabilitation of an older term, the "transpiration ratio" (R_T), to describe the relationship between crop transpiration and growth. In cases where physiological descriptions of WUE are expressed as the ratio of evapotranspiration to crop yield, Stanhill proposes use of the term "evapotranspiration ratio" (R_{ET}).

In addition to avoiding problems with strict definitions of efficiency, Stanhill (1986) prefers use of the terms R_T and R_{ET} because they do not contain the phrase "water use." He writes, "Because transpiration and, to an even greater extent, evaporation from the soil surface are physical processes, often highly correlated but not necessarily causally related to growth or yield, it is hardly appropriate to term them water use.

Tanner and Sinclair (1983) propose a similar separation of water losses associated with runoff, leaching, and irrigation systems from the water requirements linked to crop performance. Along the lines of Stanhill's

hydrological definition of WUE, they define the ratio of crop evapotranspiration to the volume of water available as efficient water use (EWU). They invert R_T and R_{ET} and define the ratio of crop yield to transpiration or evapotranspiration as T efficiency and ET efficiency, respectively. Additionally, they are undisturbed that these terms are not compared to a theoretical or observed maximum.

Since it is common in water use efficiency studies to plot yield versus evapotranspiration, Sinclair and Tanner's term, "evapotranspiration efficiency", will be used herein. While this physiological description of water use efficiency may not satisfy a strict definition of efficiency, its use has become widespread; elimination on strict semantic grounds may lead to unwarranted confusion. Lastly, in light of the importance of transpiration in nutrient transport and temperature regulation, Stanhill's objection to describing transpiration as water use seems questionable and thus the term "water use" will not be stricken from this paper as an occasional substitute for transpiration or evapotranspiration.

History and Theory

Agriculturalists have long recognized the dependence of crop yield on water supply, especially as many early agricultural civilizations arose in arid or semi-arid regions of the world. Indeed, early farmers appear to have

recognized that plants differ in their water requirements. The Artha-sastra (a Sanskrit manual of administration (*ca.* 300 B.C.)) recommends: "According as the rainfall is more or less, the superintendent shall sow the seed which require either more or less water (Stanhill, 1985)."

Woodward, in 1699, was the first scientist to quantitatively correlate increases in plant mass with water use (Stanhill, 1986). From 1890 to 1902, King at the University of Wisconsin, conducted lysimeter studies of field crop "water requirements", the first such research in the United States. In 1902, Widtsoe at the University of Utah, and Kiesselbach at the University of Nebraska, began similar studies (Tanner and Sinclair, 1983).

In 1911, Briggs and Shantz (1914) began their exhaustive study of plant water requirements at Akron, Colorado. Using sealed containers to prevent evaporation, they examined transpirational water use associated with dry matter production in 40 crop, 15 weed, and 6 native grass species. They discovered a linear relationship between transpiration and dry matter gain and introduced the previously discussed transpiration ratio, R_T, where;

R_T = transpiration (g H_2O) / dry matter production (g). [1]

Briggs and Shantz used the slope of the relationship between transpiration and dry matter production to differentiate among plant species on the basis of water use

efficiency. Thus barley, with an R_T of 534, was classified as a more efficient user of water than red clover (*Trifolium repens* L.), with an R_T of 789.

Despite the fact that Briggs and Shantz demonstrated linear associations between plant growth and water use, they found significant within species variation in the slope of this association from year-to-year and site-to-site (Briggs and Shantz, 1914). This variation cast doubt on the usefulness of the transpiration ratio as a tool to select crop species and cultivars with superior water use efficiencies (Stanhill, 1986).

In 1948, Penman proposed that evapotranspiration be treated as a purely physical process that is only minimally influenced by radiative and aerodynamic characteristics of the crop surface. He demonstrated that ET is largely determined by climatic factors, namely air temperature, dew point, wind velocity, and duration of sunshine (Penman, 1948). Penman and Schofield (1951) extended this physical approach to estimates of crop CO_2 flux and transpiration. Through this work they indirectly rehabilitated the transpiration ratio concept by demonstrating that both components of R_T, yield (carbon assismilation) and transpiration, are dependent on the saturation vapor pressure deficit of air (Penman and Schofield, 1951).

In response to Penman and Schofield's work, de Wit (1958) reexamined the findings of Briggs and Shantz and

their work with R_T. de Wit concluded that site-to-site and year-to-year variation in R_T could be normalized by using free-water evaporation as a climatic correction factor. In this fashion he related yield to water use in dry, high-radiation (semi-arid) climates as:

$$Y = mT/E_o, \quad [2]$$

where Y is dry matter yield, T is transpiration, E_o is free-water evaporation, and m is a crop factor that depends only on species and cultivar. de Wit extended this relationship to humid climates where solar radiation is limiting by dropping E_o to produce the equation:

$$Y = nT, \quad [3]$$

where n is a crop factor dependent only on species and cultivar.

de Wit's equations have survived fairly intact. Arkley (1963) suggested consolidating equations [2] and [3] by substitution of relative humidity for free-water evaporation as a climatic correction factor in equation [2] and applying this equation to all climates. Bierhuizen and Slatyer (1965) proposed a similar consolidation, but instead recommended using the saturation vapor pressure deficit as a

substitute for E_o, producing equation [4],

$$Y \approx k/(e^* - e) \quad [4]$$

where k is a species and cultivar dependent factor similar to m and n in equations [2] and [3] and $(e^* - e)$ equals the saturation vapor pressure deficit.

Although the strong linear associations between yield and transpiration developed in container studies support deWit's equation, field study of the relationship between yield and transpiration is problematic because it is difficult to separate the evaporation and transpiration components of evapotranspiration. Hanks (1983), in his computer model that predicts plant yield as influenced by water use, estimates evaporation as;

$$E = E_{max}t^{-1/2} \quad [5]$$

where t is the time in days since the soil was last wet, and $E_{max} = E_o - T_{max}$. The value of E_o equals class A pan evaporation times an appropriate pan factor and T_{max} is estimated as a function of crop cover and soil water content.

In many field experiments, no attempt is made to separate evaporation from transpiration and, thus, yield is plotted versus ET. In Saskatchewan, Staple and Lehane (1954a, 1954b) conducted two long-term container and field studies (31 and 12 years, respectively) of wheat yield

versus ET and found strong linear correlations between grain yield and ET. Hanks et al. (1969) found a linear association between dry matter production and ET of grain sorghum (*Sorghum vulagre* L.). Walker and Richards (1985) reported a similar relationship in alfalfa (*Medicago sativa* L.).

In the above-mentioned field studies of the relationship between crop yield and ET, linear associations between yield and ET produced positive x-intercepts, i.e. there was no biomass production associated with evapotranspiration until ET reached a certain level. Ritchie (1983) interprets these positive intercepts as cumulative evaporation from the crop surface over the interval from planting to canopy closure at a Leaf Area Index (LAI) value of approximately 1.0.

While deWit's (1958) equation provides a simple description of the relationship between plant dry matter yield and transpiration, more sophisticated approaches describe and isolate physiological and physical characteristics that underlie observed differences in transpiration efficiency. Tanner and Sinclair (1983) estimate the daily rate of canopy biomass accumulation (Y) where

$$Y = bN_c(\text{hexose}) = abcLAI_D C_a \,/\, 1.5(r_b + r_s)_D. \quad [6]$$

N_c equals the rate that hexose is available for supporting

canopy biomass accumulation. The amount of hexose converted to biomass, b, generally ranges from 0.33 to 0.83. a is the ratio (by molecular weight) of leaf hexose to CO_2 uptake. c is equal to 1 - (intercellular $[CO_2]$ / atmospheric $[CO_2]$) and is a measure of the efficiency of carbon assimilation, varying from approximately 0.3 for C_3 plants to 0.7 for C_4 plants. LAI_D is a measure of the leaf area exposed to incident radiation and $(r_b + r_s)$ equals the sum of the boundary layer and stomatal resistance to water vapor diffusion of leaves exposed to incident radiation. This sum is multiplied by 1.5 to derive the sum of the boundary layer and stomatal resistance to CO_2 diffusion.

Tanner and Sinclair (1983) define the daily canopy transpiration rate (T_c) as,

$$T_c \approx L_T(\varrho\varepsilon/P)[(e^* - e)/(r_b + r_s)_D]B \quad [7]$$

where L_T equals the effective transpiration leaf area (dependent on LAI), ϱ is air density, ε equals the ratio of the mole weight of water vapor to air, P is atmospheric pressure, $(e^* - e)$ is the saturation vapor pressure deficit, $(r_b + r_s)_D$ is the sum of boundary layer and stomatal resistance to water vapor diffusion and B is a correction term for mean L_T.

Equations [6] and [7] can be combined in an expression of daily transpiration efficiency where

$$Y/T = (abc/1.5)(P/\varrho\varepsilon)(LAI_D/L_T)[C_a/B(e^* - e)]. \quad [8]$$

While it would not be practical to use equation [8] to describe the relationship between yield and transpiration over an entire growing season, this equation is a useful pedagogical tool for summarizing the biological and environmental factors that determine a plant's water use efficiency. WUE is influenced biologically by LAI, boundary layer properties of leaves, CO_2 uptake rate, efficiency of CO_2 assimilation, and the proportion of hexose converted to biomass. Atmospheric factors that influence WUE include vapor pressure deficit, atmospheric pressure, relative humidity, and air density.

Chapter 3

METHODS AND MATERIALS

Site Description

Field plots were established on June 19, 1990 and May 21, 1991 at the Montana State University Arthur H. Post Field Research Laboratory on fields of Amsterdam silt loam (fine-silty, mixed family of Typic Haploborolls). Both 1990 and 1991 experiments were performed at sites that had been planted to canola (*Brassica campestris* L.) the previous season.

Experimental Design

Two non N_2-fixing species, spring wheat (*Triticum aestivum* L. cv. Pondera) and barley (*Hordeum vulgare* L. Clark) were included with the five legumes. Legumes and cereals were arranged in a completely randomized block design with four blocks. In 1990, plots were 4.6 m x 1.1 m. Plots were slightly larger in 1991, 6.1 m x 2.1 m.

Before planting, seed of each legume species was innoculated with the appropriate *Rhizobium* strain (Liphatech, Inc., Milwaukee, WI). Legumes and cereals were seeded into a firm seedbed at the following rates: Indianhead lentil, 30 kg/ha; Austrian winterpea, 80 kg/ha; Cahaba white vetch, 40 kg/ha; George black medic, 10 kg/ha;

yellow sweetclover, 10 kg/ha; spring wheat, 78 kg/ha; barley 56 kg/ha. Row spacing in all plots was 15 cm.

Meteorological observations

Precipitation and pan evaporation were recorded daily by a U.S. Weather Service Climatological Station located approximately 300 meters from study sites.

Soil, Biomass, and Plant Height Sampling

Initial soil samples to a depth of 107 cm were obtained at emergence of wheat and barley. Two soil cores were hydraulically extracted in each plot and samples were separated into 0-15 cm, 15-61 cm, and 61-107 cm depth increments. Following small grain emergence, subsequent samples were obtained at 7-10 day intervals until all species had reached maturity (seed had ripened).

Biomass sampling was conducted in concurrence with soil sampling. A 1 meter row-strip was randomly selected in each plot and all aboveground biomass was harvested by hand cutting at the soil surface.

At each biomass and soil sampling, plant height was evaluated. Ten individual plants were randomly selected in each plot and measured.

Analyses of Soil and Biomass Samples

Soil samples were weighed and then dried in a forced-air oven at 50° celsius until weight losses were no longer detected. The difference between wet and dry weights was used to calculate soil moisture content. Emergence (first sampling) and maturity (last sampling) soil samples were analyzed for NO_3-N, phosphorus, and organic matter content by the Montana State University Soil Testing Laboratory. Phosphorus concentration was determined by an Olsen method using sodium bicarbonate as an extractant (Olsen and Sommers, 1982), NO_3-N concentration was measured by an automated cadmium reduction method (American Public Health Association, 1981), and soil organic matter content was determined by the colorimetric method of Sims and Haby (1971).

Biomass samples were weighed and then dried in a forced-air oven at 50° celsius until weight losses were no longer detected. A sub-sample of dry matter was analyzed for total nitrogen content by the Montana State University Soil Testing Laboratory using a Kjeldahl method (Bremner and Mulvaney, 1982).

Estimating Legume N_2-fixation

Using the difference method described by Henson and Heichel (1984), spring wheat and barley were employed in estimates of legume N_2-fixation. N_2-fixation was estimated

at each sampling date by subtracting the canopy nitrogen content of spring wheat or barley from the canopy nitrogen content of legumes with the assumption that observed differences resulted from legume assimilation of atmospheric N_2.

Statistical Methods

Statistical analyses were performed using the MSUSTAT statistical package. Results were examined by analyses of variance and sample means were compared using Student's t. Pairs of regression lines were analyzed for coincidence using a method described by Lund (1988). This method produces an F-statistic where;

$$F = \frac{(\text{S.S. Res all} - \text{S.S. Res individuals})/DF}{(\text{S.S. Res individuals})/DF}$$

S.S. Res all equals the residual sum of squares when values from individual regressions are pooled. Residual sums of squares from individual regressions are added to produce S.S. Res individuals.

Measures of crop performance over time (ET, canopy biomass accumulation, canopy nitrogen accumulation, and N_2-fixation) were fit to a logistic equation of the form $y=a/(1+be^{-cx})$ where a, b, and c are constants. The logistic equation is generally accepted as a good descriptor of aspects of plant growth that approach a limit (Milthorpe and

Moorby, 1974). All curve fitting operations were performed using TableCurve (Jandel Scientific, San Rafael, CA) curve fitting software.

Chapter 4

RESULTS

Direct Measures of Crop Performance: Evapotranspiration, Canopy Biomass Accumulation, and Canopy % Nitrogen

Measurements of evapotranspiration, canopy biomass accumulation, and canopy % N over the 1990 and 1991 growing seasons are summarized in Figures 1 through 7. Canopy biomass and ET means are fit to the logistic equation while canopy % N means are fit by standard linear regression.

The 1990 Indianhead lentil evapotranspiration curve fit approaches a limit of 18.84 cm while the 1991 ET curve fit reaches a plateau just short of 15 cm (Fig. 1). Mean canopy biomass accumulation peaked at 6,413 kg/ha in 1990 while the 1991 biomass curve fit approaches a limit of 4,021 kg/ha. Poorer performance in 1991 appears to be associated with a shorter growth period, 80 days in 1991 versus 109 days in 1990. Mean canopy %N ranged from 4.18% to 2.65% in 1990 and from 4.05% to 2.17% in 1991.

In both 1990 and 1991 curve fits, Austrian winterpea ET plateaus at just over 14.5 cm (Fig. 2). However, the 1991 ET curve fit reached that limit more rapidly. In 1990, mean canopy biomass accumulation reached a maximum value of 7,000 kg/ha while the 1991 canopy biomass curve fit approaches a limit of 3,770 kg/ha. Mean canopy %N declined from 4.18% to 2.65% in 1990 and from 4.41% to 2.65% in 1991.

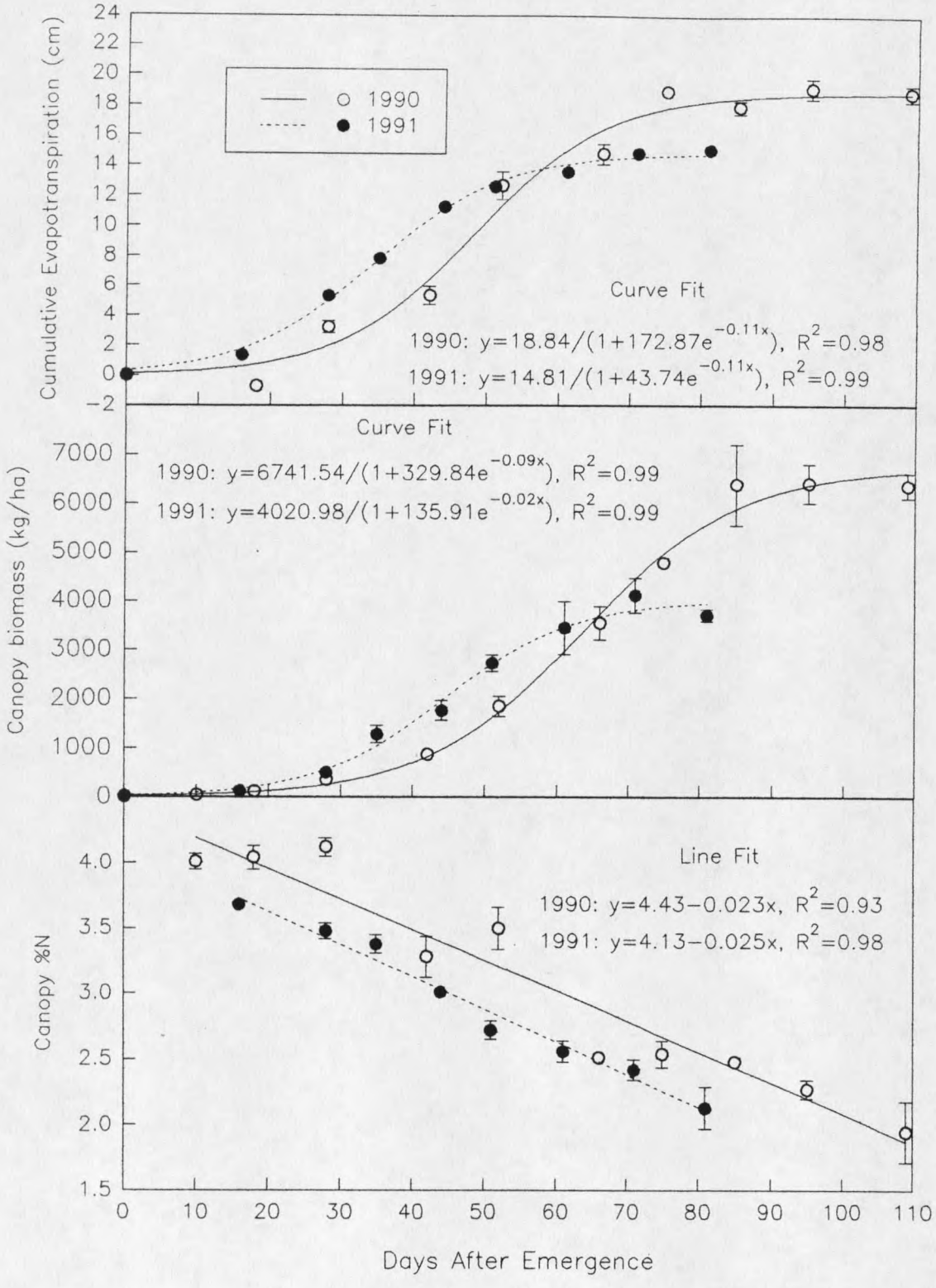

Fig. 1. Indianhead lentil ET, canopy biomass accumulation and canopy %N after emergence in 1990 and 1991. Values are means of 4 replicates ± standard error.

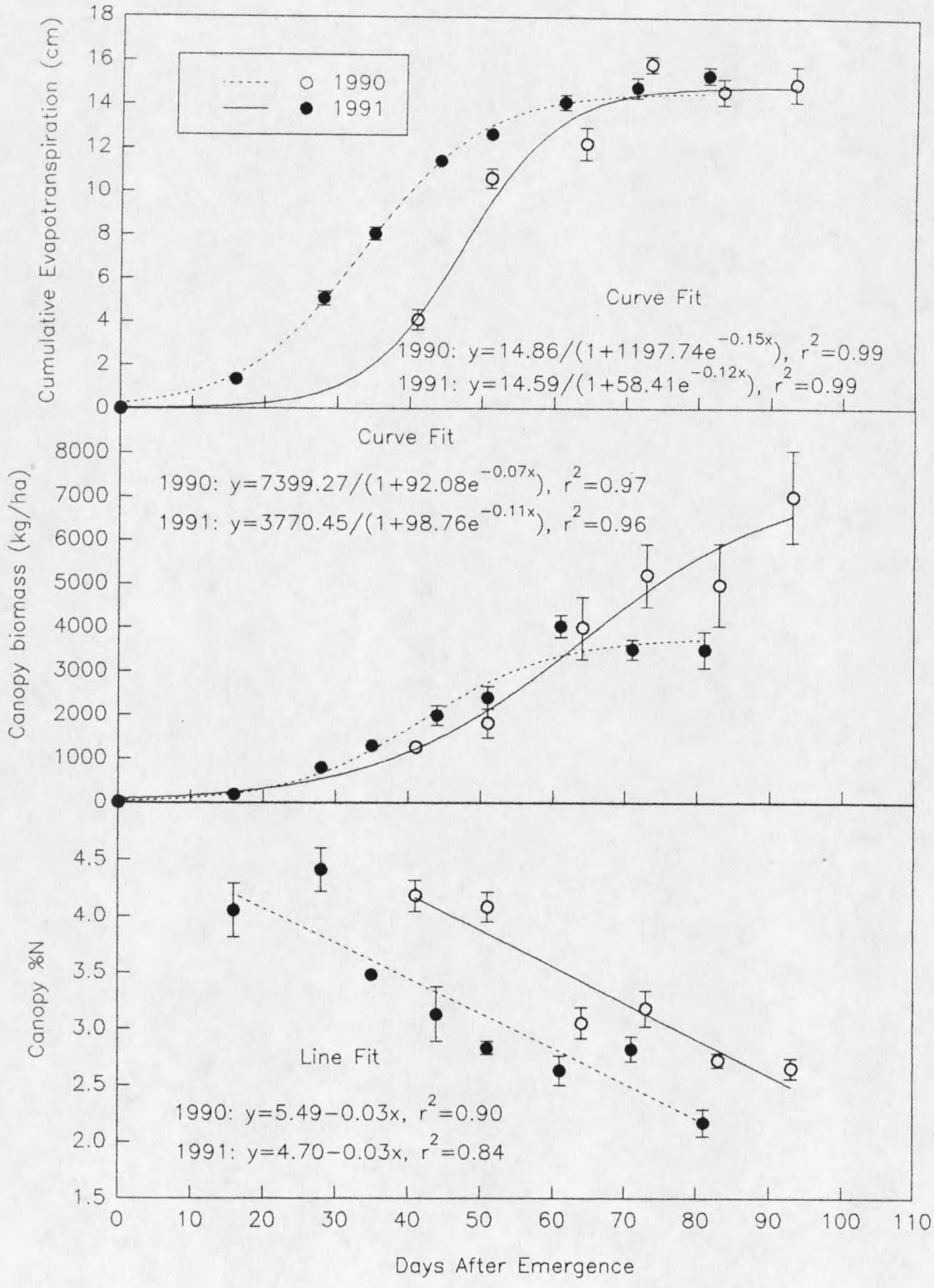

Fig. 2. Austrian winterpea ET, canopy biomass accumulation and canopy %N after emergence in 1990 and 1991. Values are means of 4 replicates ± standard error.

The George black medic growth period was considerably longer in 1990, 106 days in 1990 versus 70 days in 1991 (Fig. 3). The 1990 ET curve fit approaches a plateau of 19.17 cm while the 1991 ET curve fit plateaus at approximately 14 cm. In 1990, mean canopy biomass accumulation reached a maximum value of 7,420 kg/ha. Biomass production was dramatically worse in 1991, reaching a maximum mean of only 2,523 kg/ha. In 1990, mean canopy %N values ranged from 3.92% to 2.58%. Additionally, the 1990 %N linear regression produces a relatively low R^2 value of 0.70. In 1991, %N means declined from 3.49% to 2.56%.

Growth of Cahaba white vetch occupied a 99-day period in 1990 and a 71-day period in 1991 (Fig. 4). Evapotranspiration over time curves for both years are similar until the 1991 curve fit plateaus at approximately 15 cm. The 1990 ET curve approaches a limit of 18.28 cm. In 1990, mean canopy biomass reached a maximum of 7,402 kg/ha. In 1991, biomass production was poor, reaching a maximum mean of only 2,500 kg/ha. In 1990, canopy %N means ranged from 4.08% to 2.59%. In 1991, %N values declined from 3.55% to 2.03%. The 1991 %N regression is not particularly strong with an R^2 value of 0.79.

Yellow sweetclover ET was similar in 1990 and 1991 (Fig. 5). The 1990 ET curve fit plateaus just short of 19 cm while the 1991 ET curve fit approaches a limit of 17.33 cm. The 1990 canopy biomass curve fit approaches a

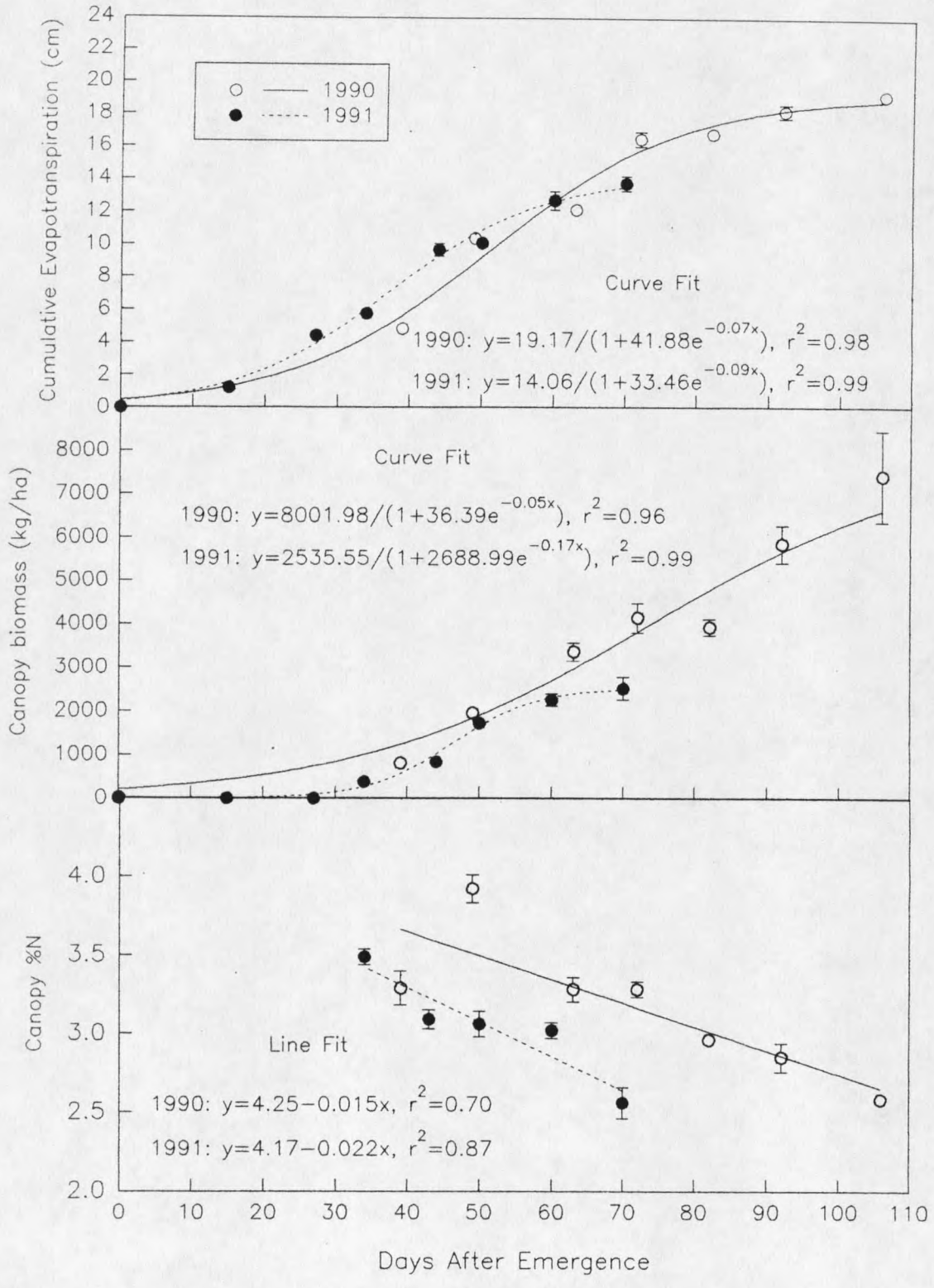

Fig. 3. George black medic ET, canopy biomass accumulation and canopy %N after emergence in 1990 and 1991. Values are means of 4 replicates ± standard error.

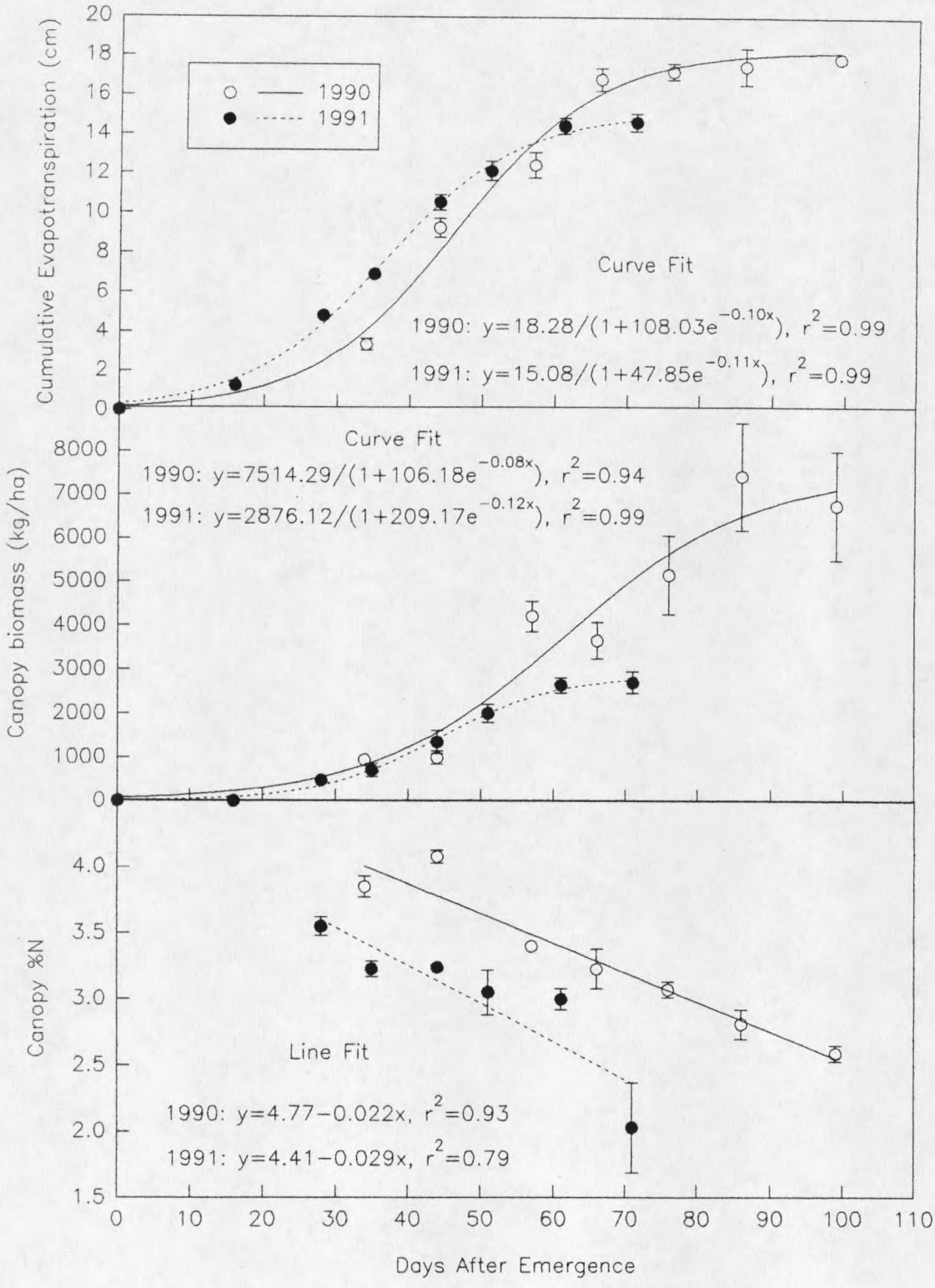

Fig. 4. Cahaba white vetch ET, canopy biomass accumulation and canopy %N after emergence in 1990 and 1991. Values are means of 4 replicates ± standard error.

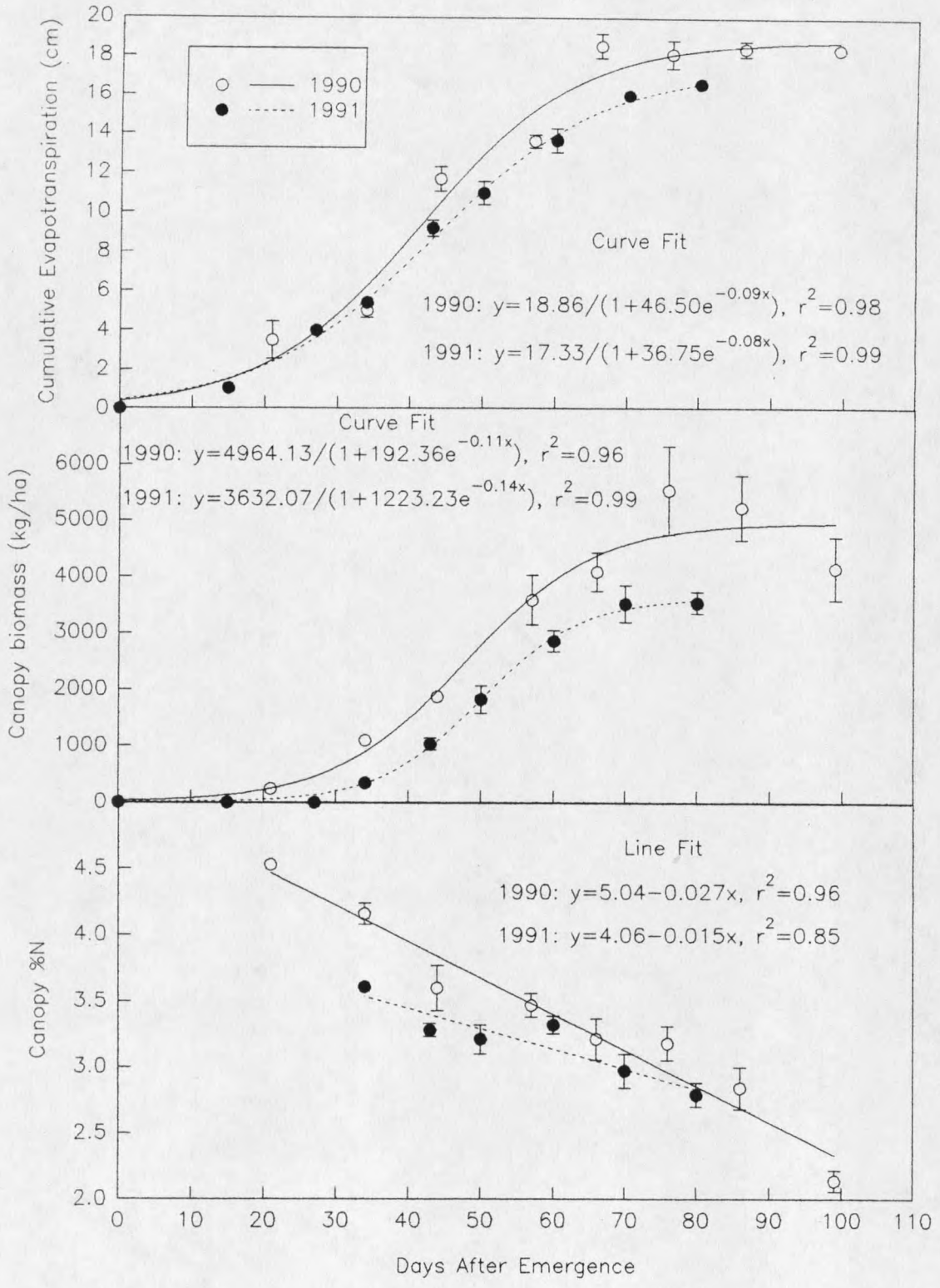

Fig. 5. Yellow sweetclover ET, canopy biomass accumulation and canopy %N after emergence in 1990 and 19991. Values are means of 4 replicates ± standard error.

limit of 4,964 kg/ha while the 1991 curve fit plateaus at approximately 3,600 kg/ha. Mean canopy %N declined from 4.53% to 2.14% in 1990 and from 3.61% to 2.79% in 1991.

Curve fits of barley ET in 1990 and 1991 approach limits of 16.51 and 15.07 cm, respectively (Fig. 6). In 1990, mean canopy biomass accumulation reached a maximum value of 5,930 kg/ha. Biomass accumulation was more rapid in 1991, reaching a maximum mean of 6,616 kg/ha. Mean canopy %N declined from 4.95% to 1.62% in 1990 and from 3.19% to 1.04% in 1991.

Spring wheat ET and canopy biomass accumulation were similar in both 1990 and 1991 (Fig. 7). Evapotranspiration curve fits approach limits of 15.01 and 14.94 cm in 1990 and 1991, respectively. The 1990 canopy biomass curve fit approaches a limit of 4,618 kg/ha while the 1991 curve fit approaches a limit of 4,994 kg/ha. Mean canopy %N ranged from 4.81% to 1.63% in 1990 and from 3.24% to 1.07% in 1991.

Derived Measures of Crop Performance: Canopy Nitrogen Accumulation and N_2-Fixation

Canopy biomass and %N values were multiplied to produce estimates of canopy nitrogen accumulation. Canopy nitrogen means are fit to the logistic equation.

In 1990, mean Austrian winterpea canopy N reached a maximum value of 184.4 kg/ha (Fig. 8). In 1991, performance was noticeably lower. The 1991 canopy N curve fit plateaus at approximately 90 kg/ha.

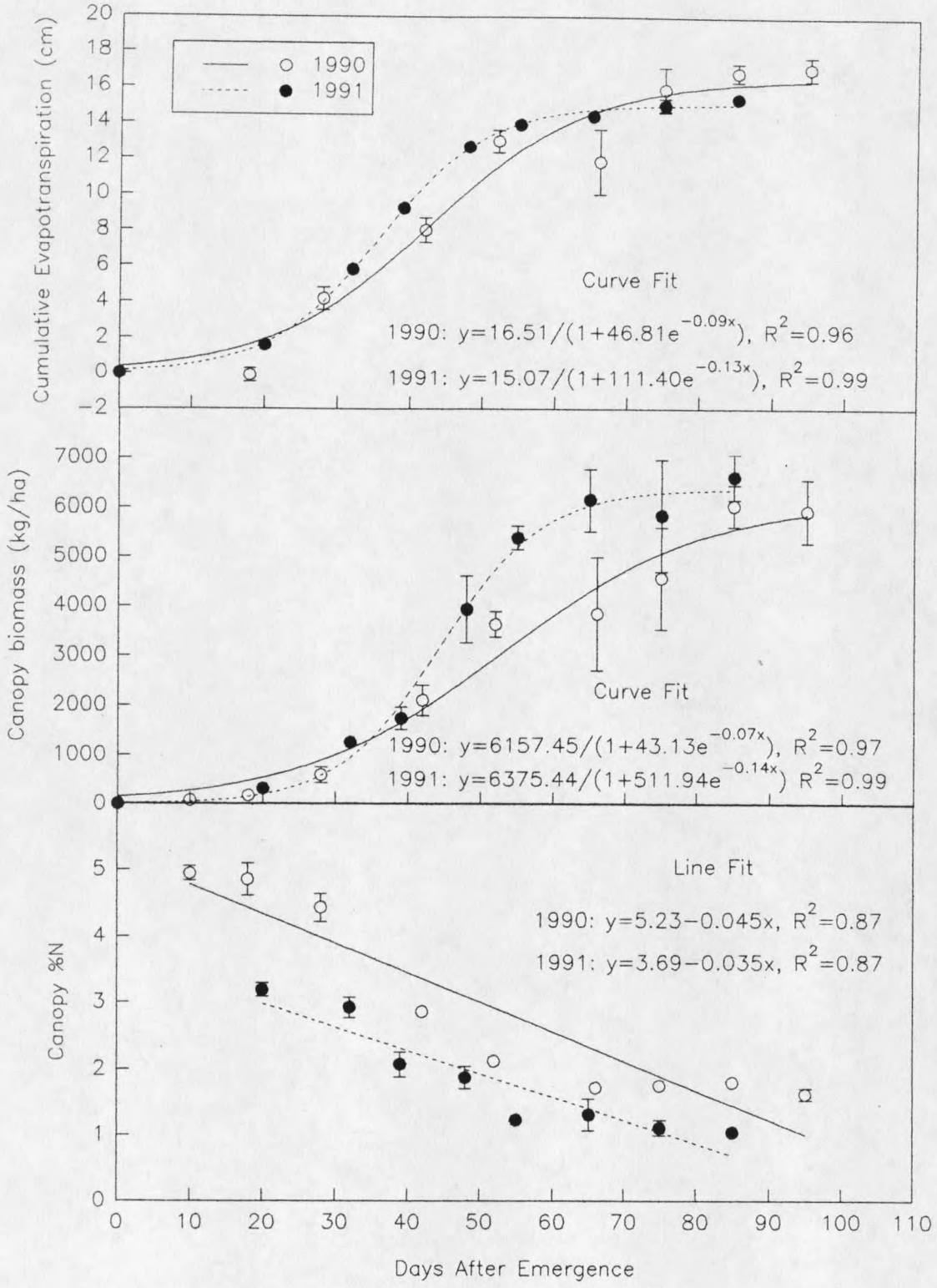

Fig. 6. Barley ET, canopy biomass accumulation and canopy %N after emergence in 1990 and 1991. Values are means of 4 replicates ± standard error.

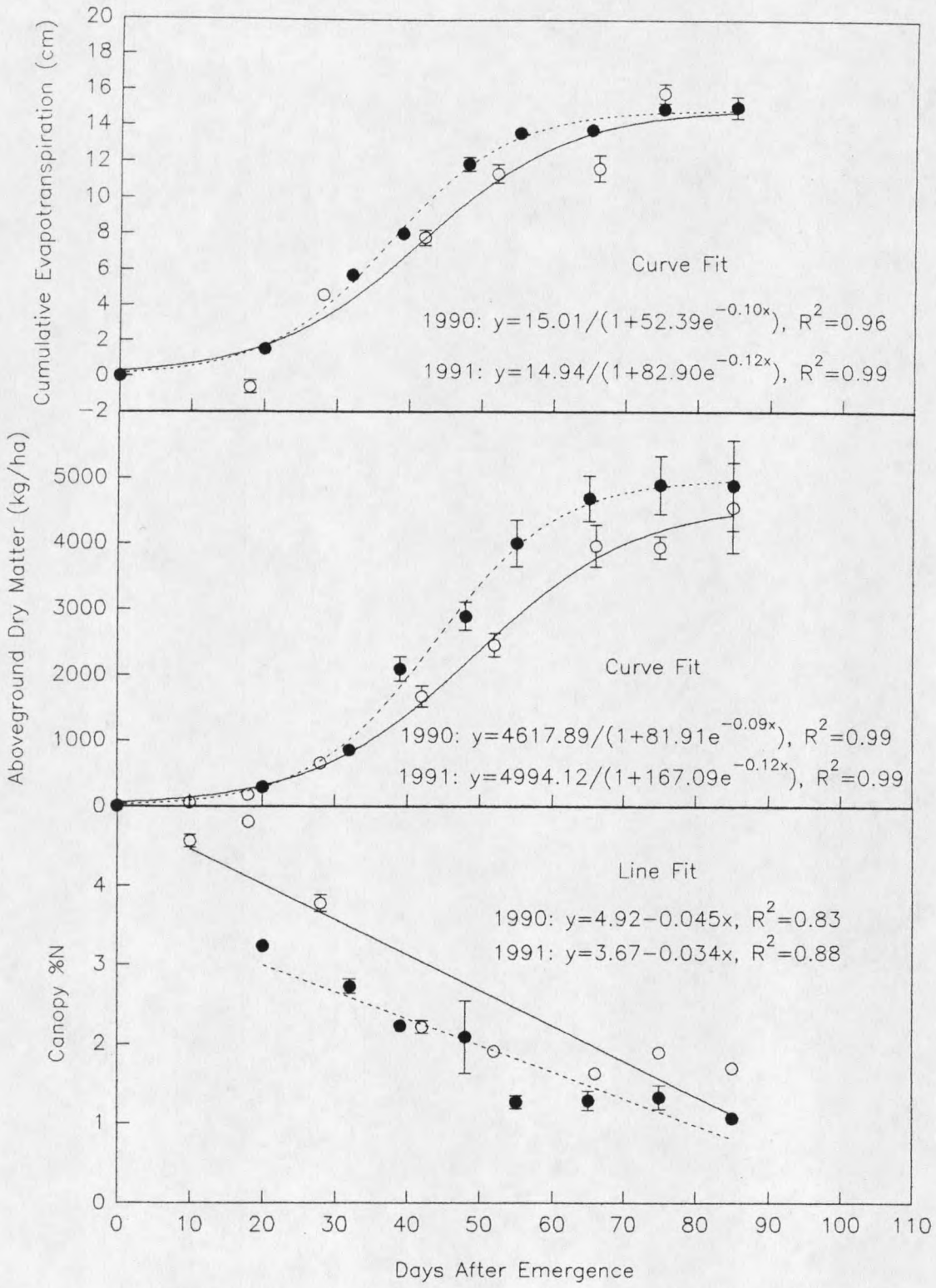

Fig. 7. Spring wheat ET, canopy biomass accumulation and canopy %N after emergence in 1990 and 1991. Values are means of 4 replicates ± standard error.

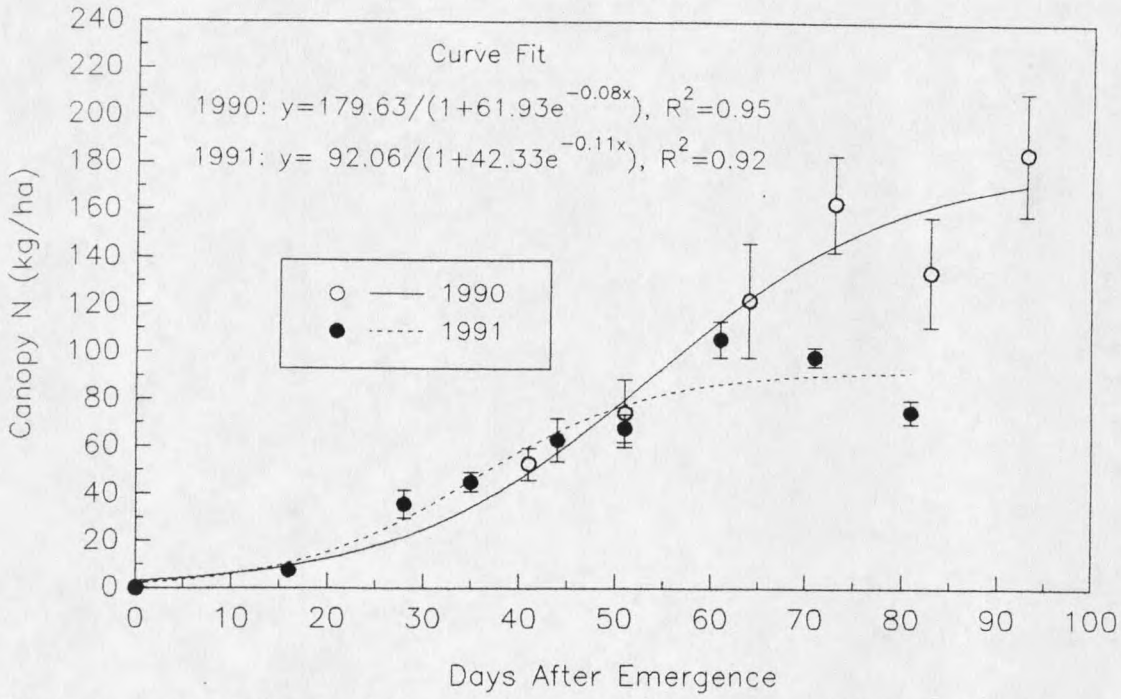

Fig. 8. Austrian winterpea canopy nitrogen accumulation after emergence in 1990 and 1991. Values are means of 4 replicates ± standard error.

Indianhead lentil accumulated more canopy nitrogen in 1990, despite higher values in 1991 through 60 days after emergence (Fig. 9). The 1990 canopy N curve fit approaches a limit of 143.8 kg/ha while the 1991 curve fit approaches a limit of 90.6 kg/ha. Lower values in 1991 appear to be associated with a shorter growth period, 80 days in 1991 versus 109 days in 1990.

The George black medic growth period was also substantially longer in 1990, 106 days in 1990 versus 70 days in 1991. In 1990, canopy nitrogen accumulation reached a maximum mean of 191.0 kg/ha (Fig. 10). The 1991 canopy N curve fit approaches a limit of 68.1 kg/ha.

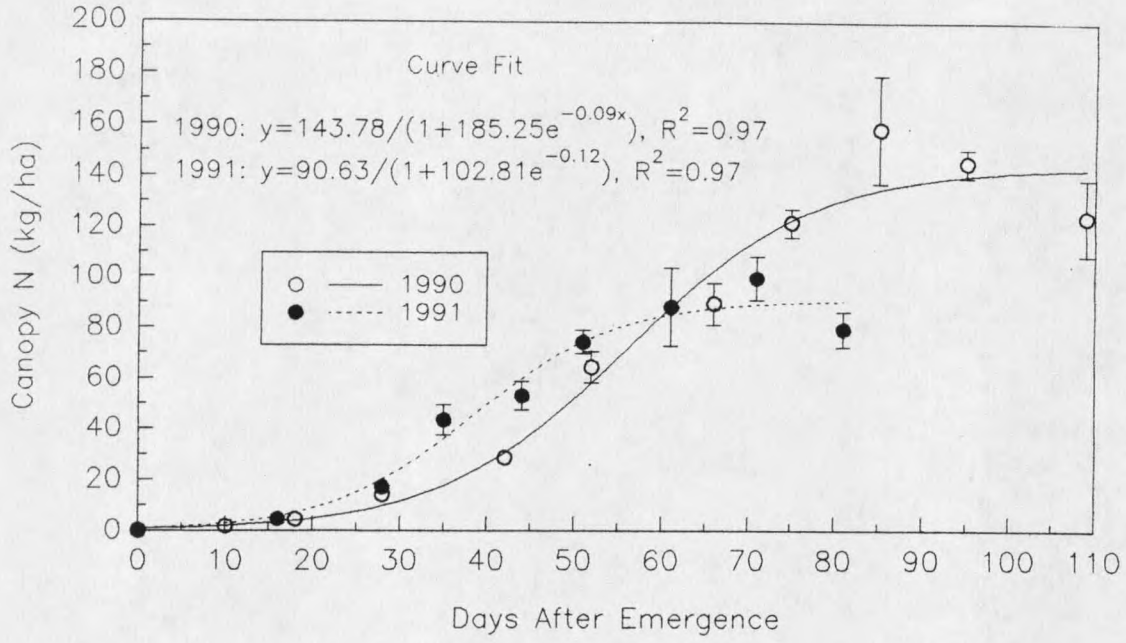

Fig. 9. Indianhead lentil canopy nitrogen accumulation after emergence in 1990 and 1991. Values are means of 4 replicates ± standard error.

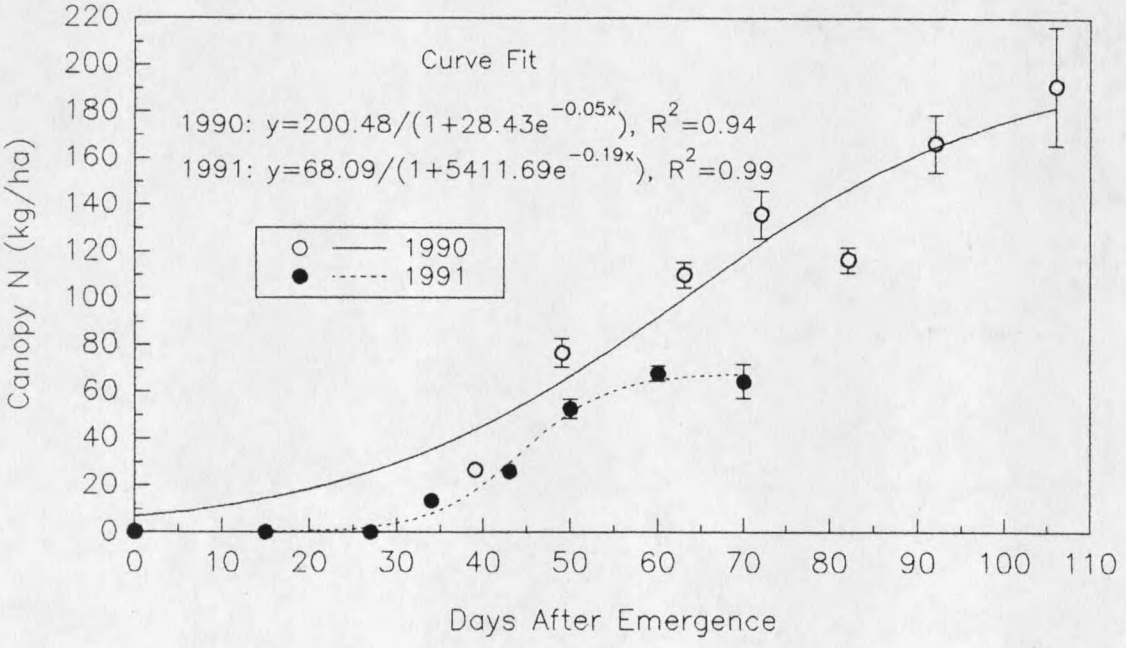

Fig. 10. George black medic canopy nitrogen accumulation after emergence in 1990 and 1991. Values are means of 4 replicates ± standard error.

Differences in yellow sweetclover performance do not appear to be associated with variation in growing period length. Over the duration of the two growing seasons examined, 1990 canopy N means were consistently higher (Fig. 11). In 1990, mean canopy N reached a maximum value of 179.1 kg/ha. The 1991 canopy N curve fit approaches a limit of 103.9 kg/ha.

The 1990 logistic fit of Cahaba white vetch canopy nitrogen accumulation approaches a limit of 188.3 kg/ha (Fig. 12). Canopy N accumulation in 1991 was lower; the 1991 curve fit plateaus at approximatley 67 kg/ha. Poor 1991 performance appears to be related to a shorter growth period, 71 days in 1991 versus 99 days in 1990.

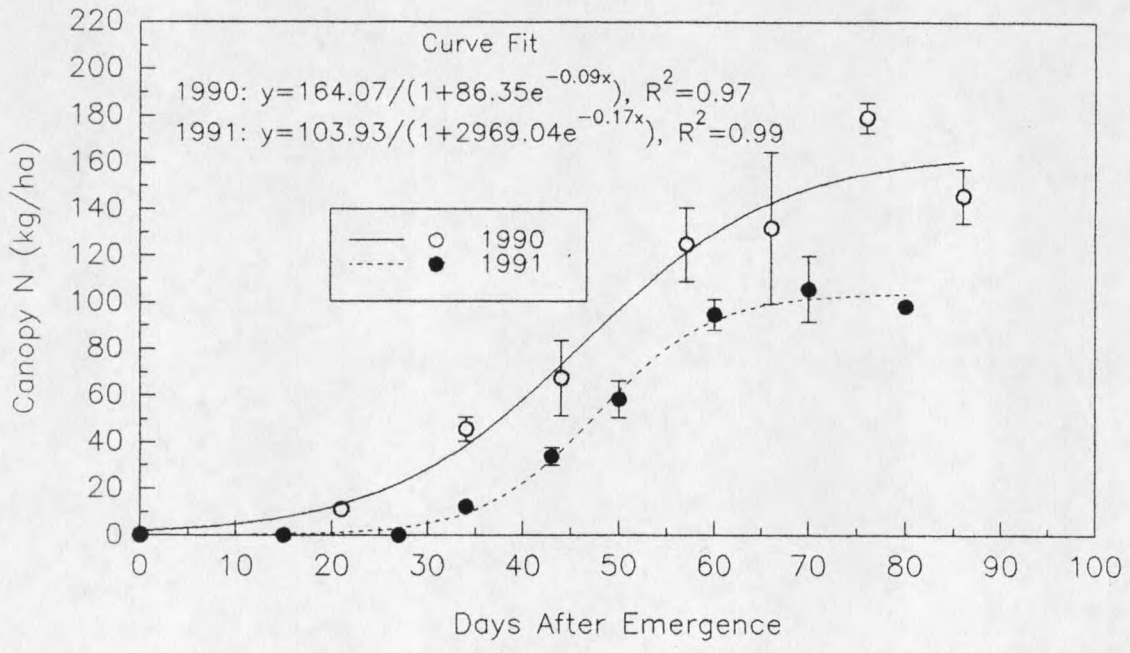

Fig. 11. Yellow sweetclover canopy nitrogen accumulation after emergence in 1990 and 1991. Values are means of 4 replicates ± standard error.

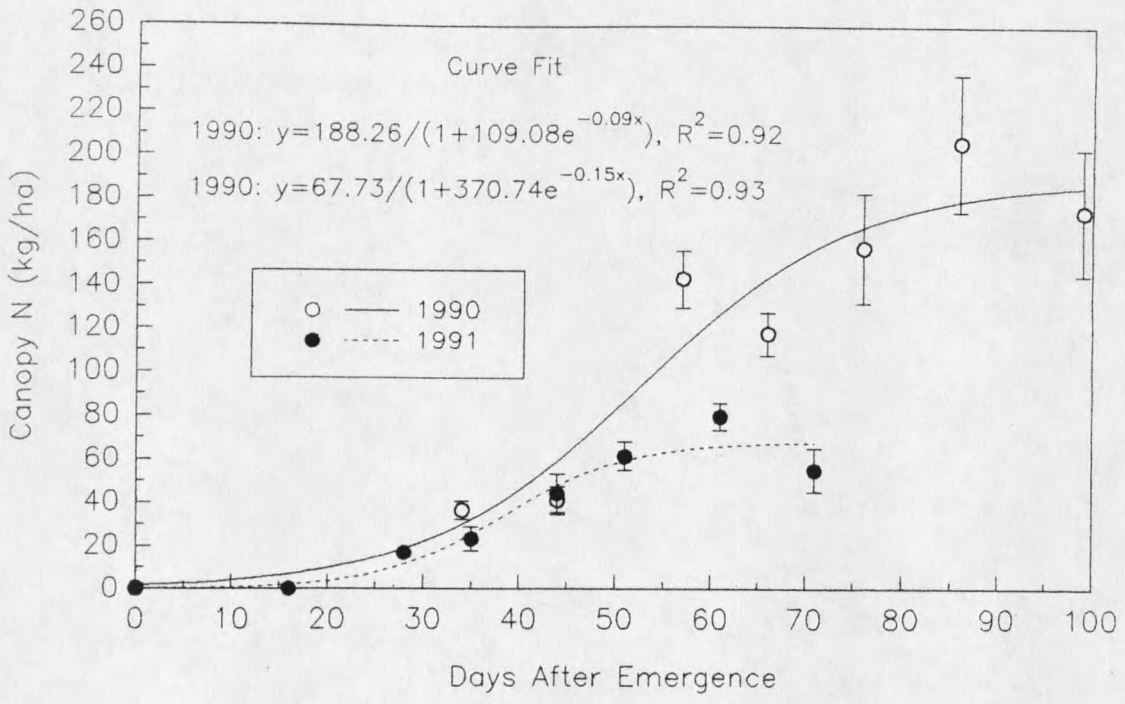

Fig. 12. Cahaba white vetch canopy nitrogen accumulation after emergence in 1990 and 1991. Values are means of 4 replicates ± standard error.

Barley canopy nitrogen accumulation was similar in 1990 and 1991 (Fig. 13). The 1990 canopy N curve fit approaches a limit of 93.1 kg/ha while the 1991 curve fit plateaus at approximately 73 kg/ha.

Spring wheat performance was also similar in 1990 and 1991 (Fig. 14). In 1990, mean canopy N reached a maximum value of 77.3 kg/ha. The 1991 canopy N curve fit plateaus at approximately 60 kg/ha.

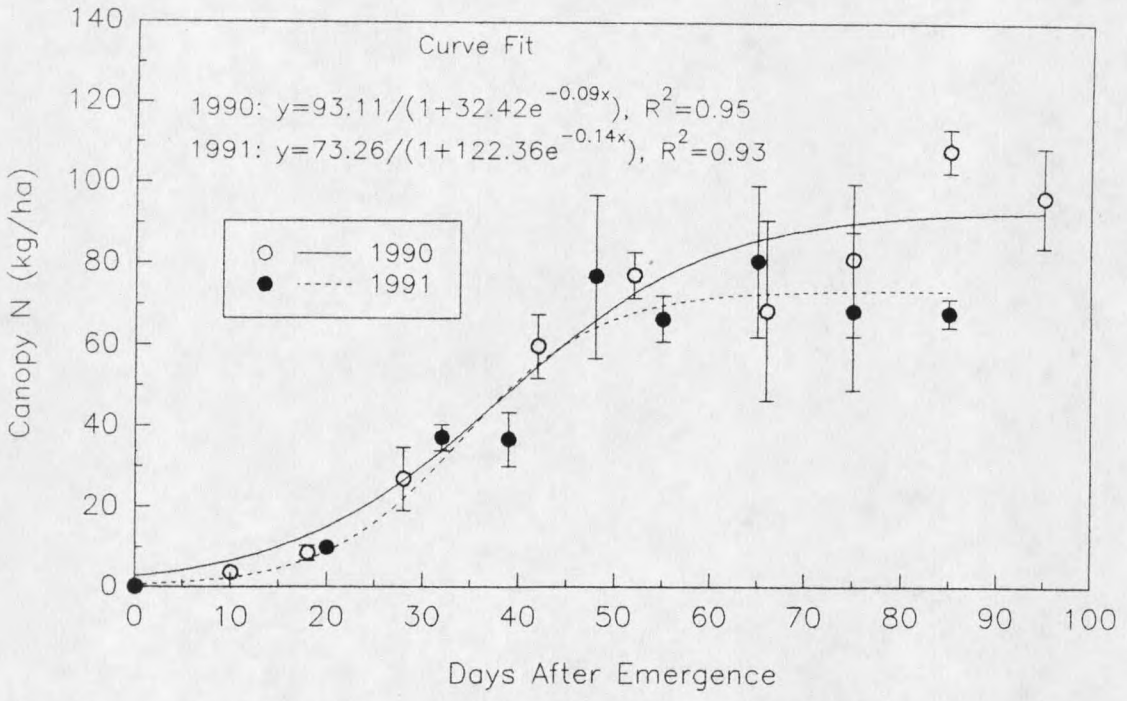

Fig. 13. Barley canopy nitrogen accumulation after emergence in 1990 and 1991. Values are means of 4 replicates ± standard error.

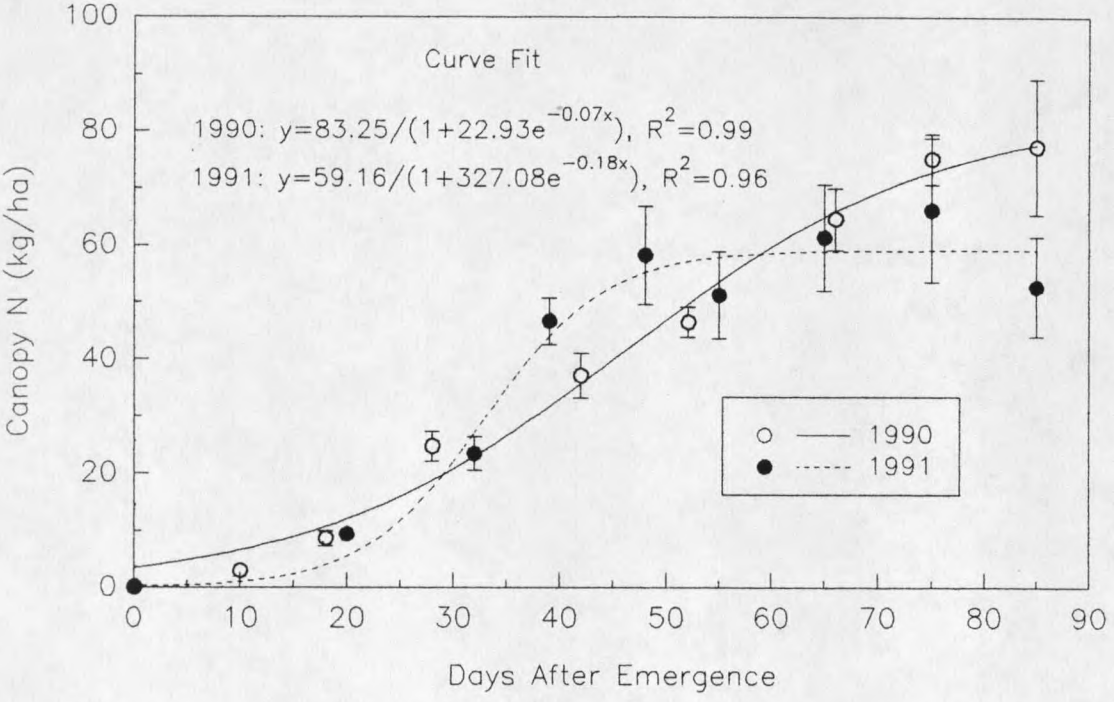

Fig. 14. Spring wheat canopy nitrogen accumulation after emergence in 1990 and 1991. Values are means of 4 replicates ± standard error.

Using canopy nitrogen results, N_2-fixation was estimated at each harvest by the difference method. However, only spring wheat was employed as a non-fixing comparison. Greater nitrogen accumulation in barley canopies generated a higher number of negative N_2-fixation estimates.

All N_2-fixation results are fit to the logistic equation. At harvest dates where estimates of N_2-fixation were negative, zero values were substituted. N_2-fixation over time curves for 1991 George black medic and Cahaba white vetch are not included: each species generated positive estimates of N_2-fixation at only two harvest dates.

In 1990, mean Austrian winterpea N_2-fixation reached a maximum value of 107.1 kg N/ha (Fig. 15). The 1991 Austrian winterpea curve fit approaches a limit of 32.5 kg N/ha.

Lower estimates of Indianhead lentil N_2-fixation in 1991 appear to be associated with a shorter growth period (Fig. 16). The 1990 logistic fit approaches a limit of 64.6 kg N/ha while the 1991 curve fit plateaus just short of 30 kg N/ha.

The 1990 logistic fit of yellow sweetclover N_2-fixation approaches a limit of 82.1 kg N/ha (Fig. 17). In 1991, mean yellow sweetclover N_2-fixation reached a maximum value of 45.6 kg N/ha.

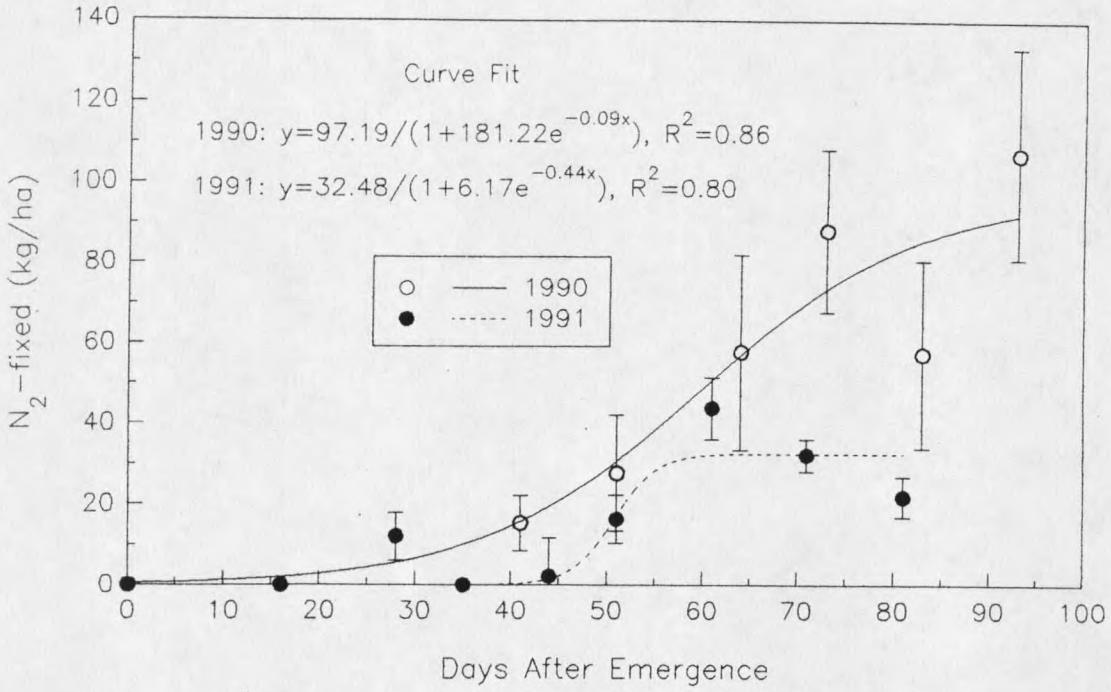

Fig. 15. Austrian winterpea N_2-fixation after emergence in 1990 and 1991. Values are means of four replicates ± standard error.

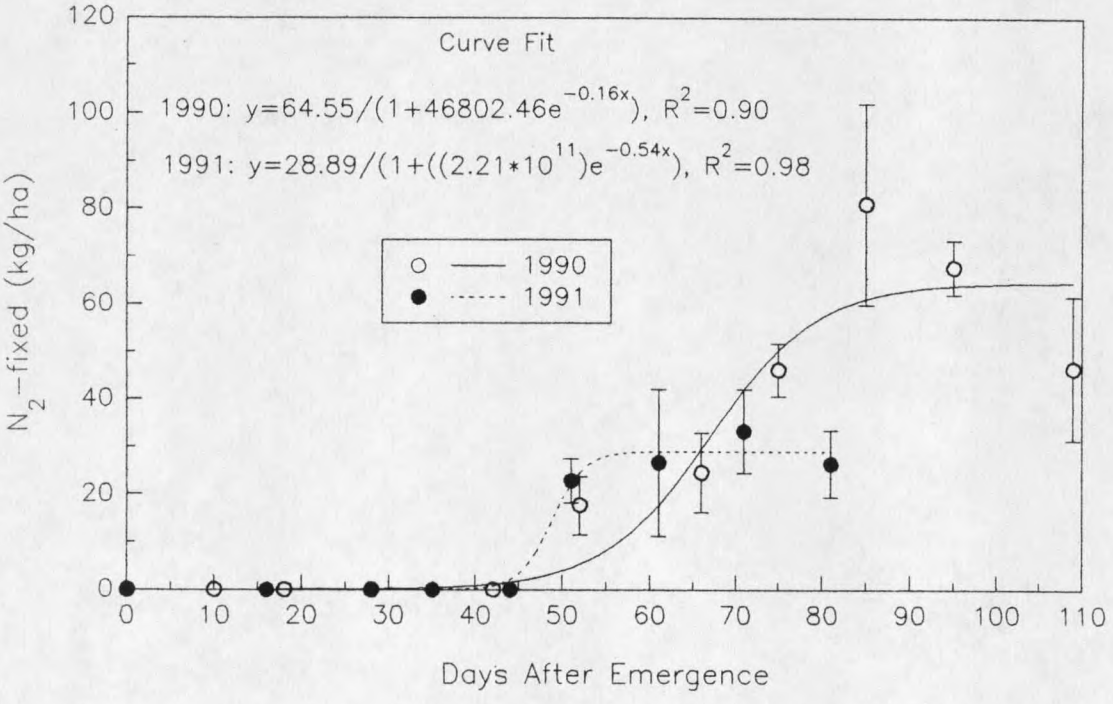

Fig. 16. Indianhead lentil N_2-fixation after emergence in 1990 and 1991. Values are means of four replicates ± standard error.

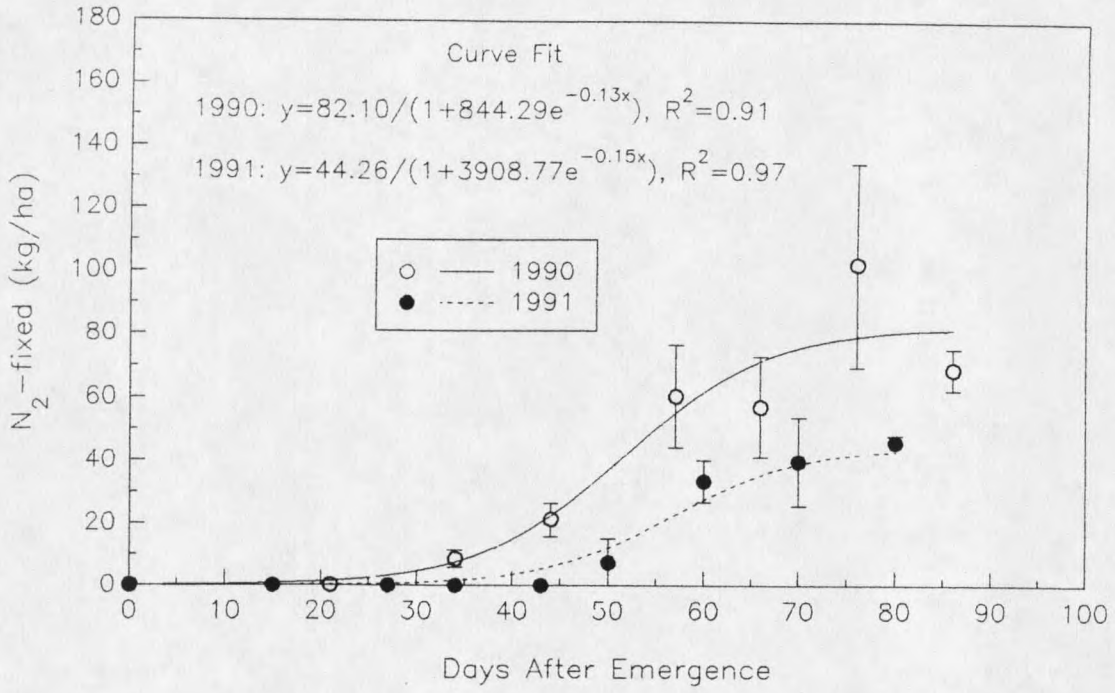

Fig. 17. Yellow sweetclover N_2-fixation after emergence in 1990 and 1991. Values are means of four replicates ± standard error.

In 1990, mean George black medic N_2-fixation reached a maximum value of 113.8 kg N/ha (Fig. 18). At this maximum, the logistic fit of black medic data has not started to plateau. In 1991, black medic N_2-fixation was estimated as 1.43 and 6.57 kg N/ha at 50 and 60 days after emergence, respectively.

The 1990 Cahaba white vetch logistic fit approaches a limit of 111.50 kg N/ha (Fig. 19). In 1991, Cahaba white vetch N_2-fixation was estimated as 9.8 and 17.9 kg N/ha at 50 and 60 days after emergence, respectively.

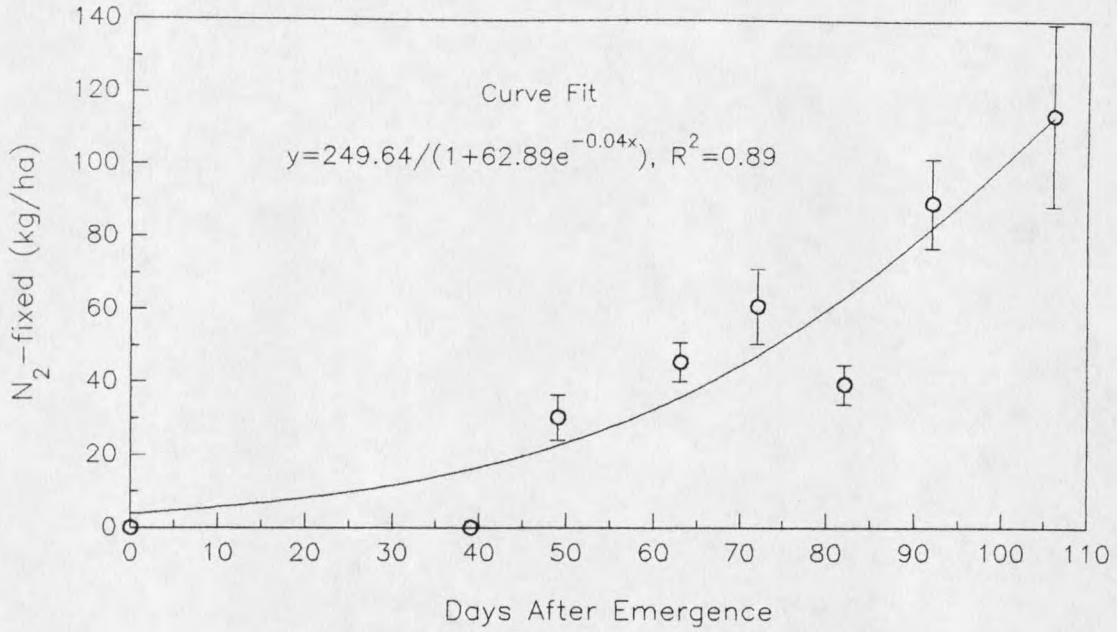

Fig. 18. George black medic N_2-fixation after emergence in 1990. Values are means of four replicates ± standard error.

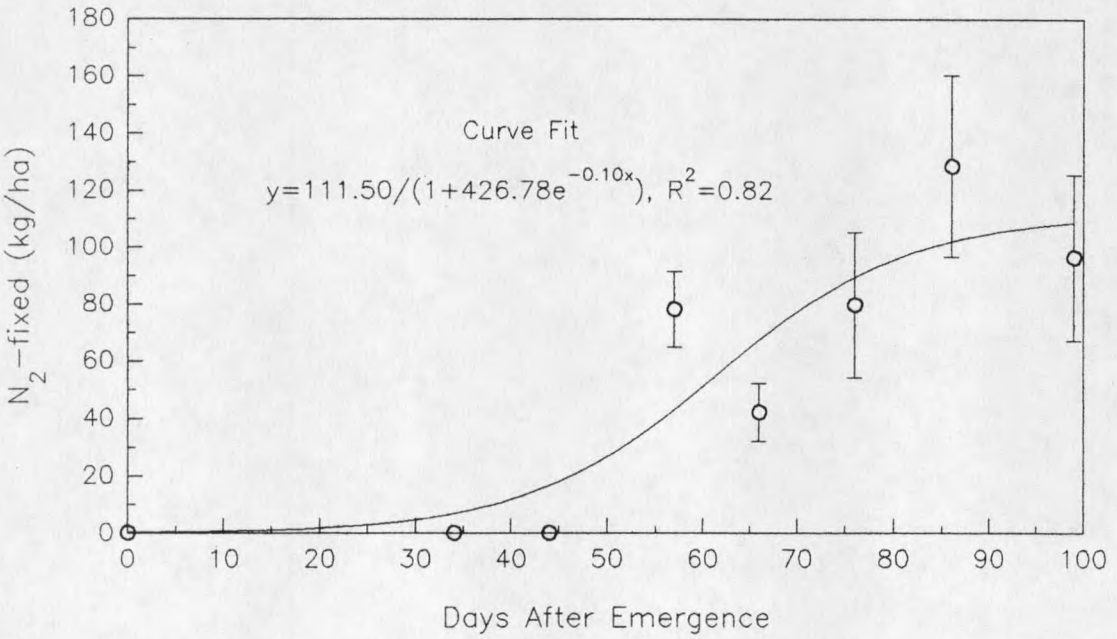

Fig. 19. Cahaba white vetch N_2-fixation after emergence in 1990. Values are means of four replicates ± standard error

Evapotranspiration Efficiencies in Terms of Canopy Biomass Accumulation, Canopy Nitrogen Accumulation, and N_2-Fixation

Measurements of yield (in terms of canopy biomass accumulation, canopy nitrogen accumulation, and N_2-fixation) and evapotranspiration were combined at each harvest date to produce evapotranspiration efficiencies expressed as yield in kg ha^{-1} per cm of H_20 evapotranspired. Legume names are abbreviated in Figures 20-25 as: Austrian winterpea=AWP, Indianhead lentil=IHL, yellow sweetclover=YSC, Cahaba white vetch=CWV, and George black medic=GBM.

In 1990, no consistent pattern emerged among ET efficiencies based on canopy biomass accumulation (Fig. 20). One exception to these muddled results is the consistently high values exhibited by Austrian winterpea. At all dates where Austrian winterpea was harvested, its mean ET efficiency was never significantly less ($p<0.05$) than any other mean.

In 1991, both Austrian winterpea and Indianhead lentil exhibited high efficiencies of biomass accumulation (Fig. 21). Their ET efficiencies were statistically similar at all harvest dates but 7/1 and were never significantly less than any other legume means. Relative to the ET efficiencies of Austrian winterpea and Indianhead lentil, the ET efficiencies of yellow sweetclover, Cahaba white vetch and George black medic were statistically equivalent or significantly worse ($p<0.05$) from 7/1 to 8/23.

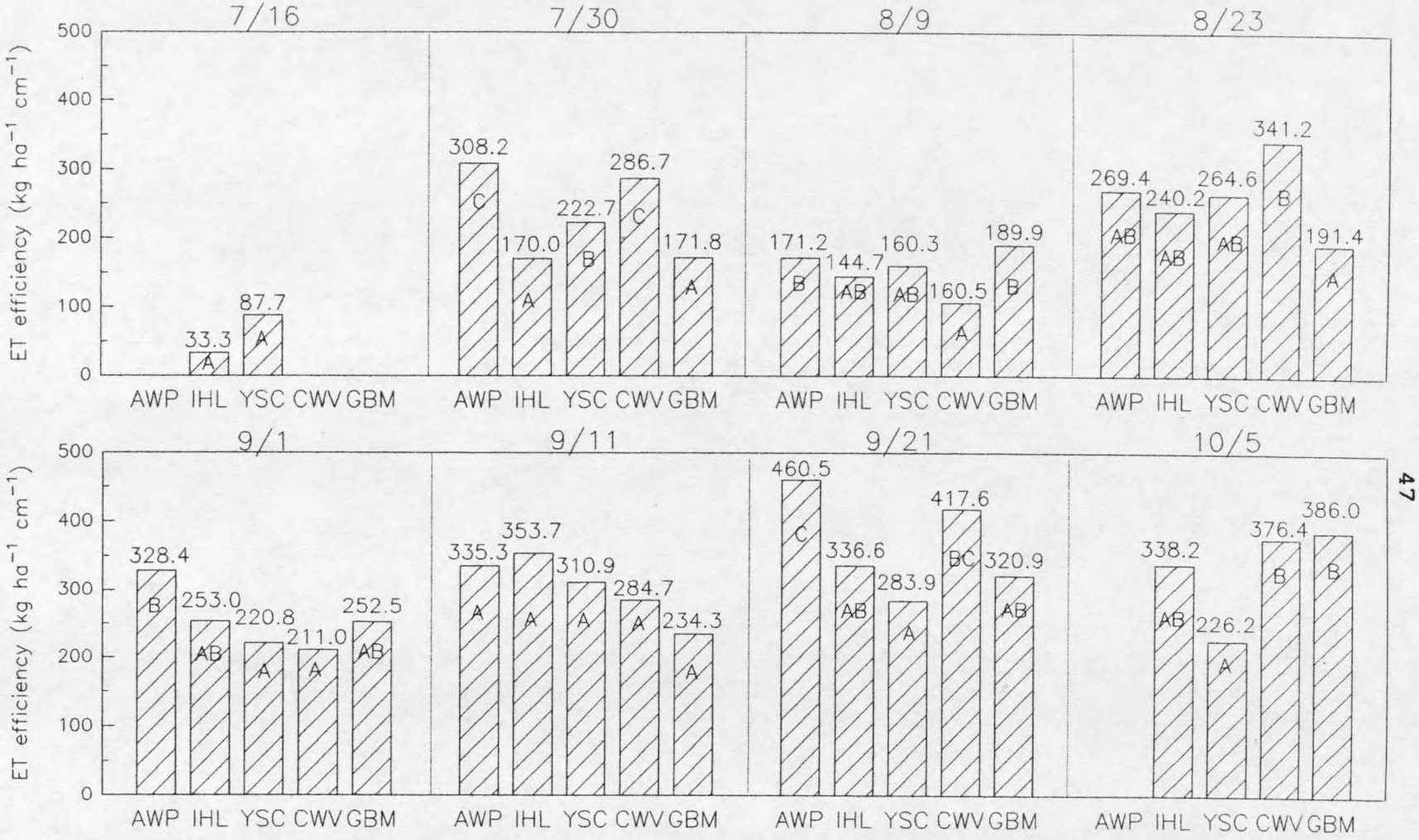

Fig. 20. Evapotranspiration efficiencies in terms of canopy biomass accumulation at 8 harvest dates in 1990. Values are means of 4 replicates. Means at each harvest date with different letters are significantly different ($p<0.05$) by ANOVA.

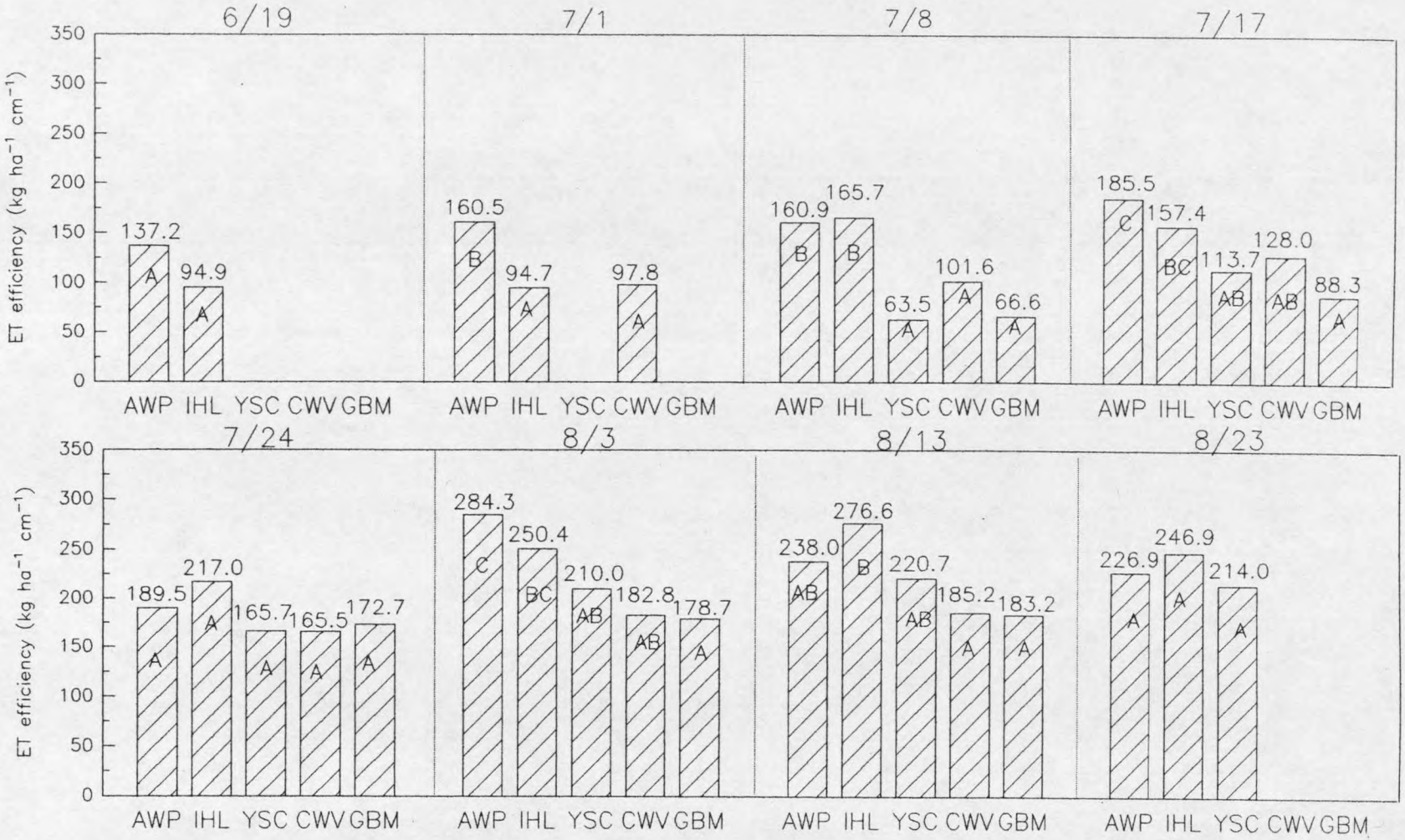

Fig. 21. Evapotranspiration efficiencies in terms of canopy biomass accumulation at 8 harvest dates in 1991. Values are means of 4 replicates. Means at each harvest date with different letters are significantly different ($p<0.05$) by ANOVA.

Little pattern emerged from 1990 ET efficiencies based on canopy nitrogen accumulation (Fig. 22). However, Austrian winterpea performed consistently well; its ET efficiencies were statistically superior ($p<0.05$) or similar to all other legume ET efficiencies at all but one harvest date, 8/23.

In 1991, both Austrian winterpea and Indianhead lentil exhibited consistently high ET efficiencies in terms of canopy nitrogen accumulation (Fig. 23). Relative to Austrian winterpea and Indianhead lentil performance, the ET efficiencies of yellow sweetclover, Cahaba white vetch, and George black medic were significantly lower ($p<0.05$) or similar from 7/1 to 8/13. After displaying low ET efficiencies at the first four harvest dates, yellow sweetclover performed well from 7/24 to 8/23. At the 8/23 harvest date, yellow sweetclover ET efficiency was superior ($p<0.05$) to Austrian winterpea performance and similar to Indianhead lentil ET efficiency.

No significant differences were found among 1990 ET efficiencies based on N_2-fixation at the 7/30, 8/9, 8/23, 9/1, and 9/11 harvest dates (Fig. 24). At the 9/21 harvest, the ET efficiencies of Austrian winterpea and Cahaba white vetch were superior ($p<0.05$) to the ET efficiencies of Indianhead lentil and yellow sweetclover while George black medic occupied an intermediate position. At the 10/5 harvest, George black medic ET efficiency was superior

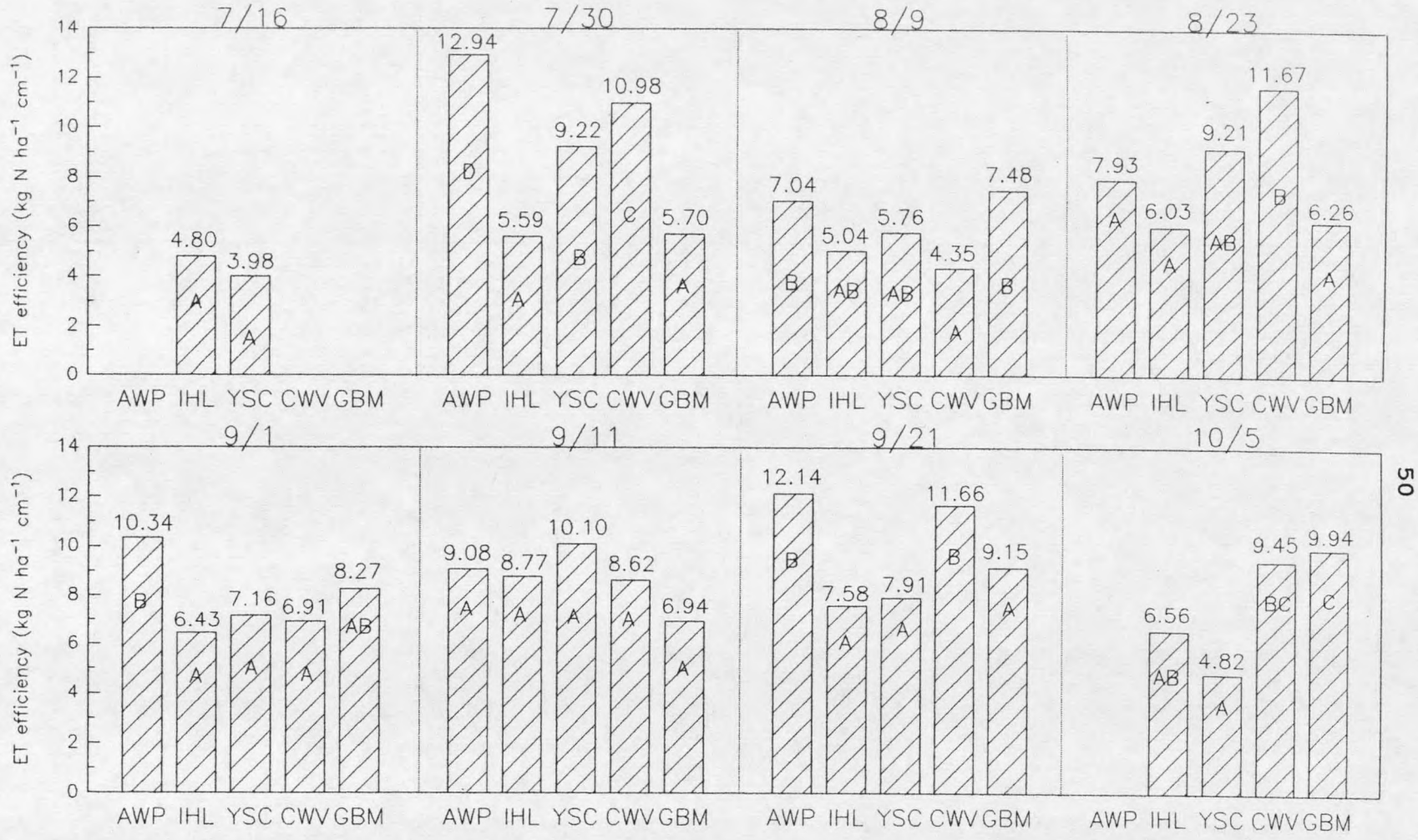

Fig. 22. Evapotranspiration efficiencies in terms of canopy nitrogen accumulation at 8 harvest dates in 1990. Values are means of 4 replicates. Means at each harvest date with different letters are significantly different ($p<0.05$) by ANOVA.

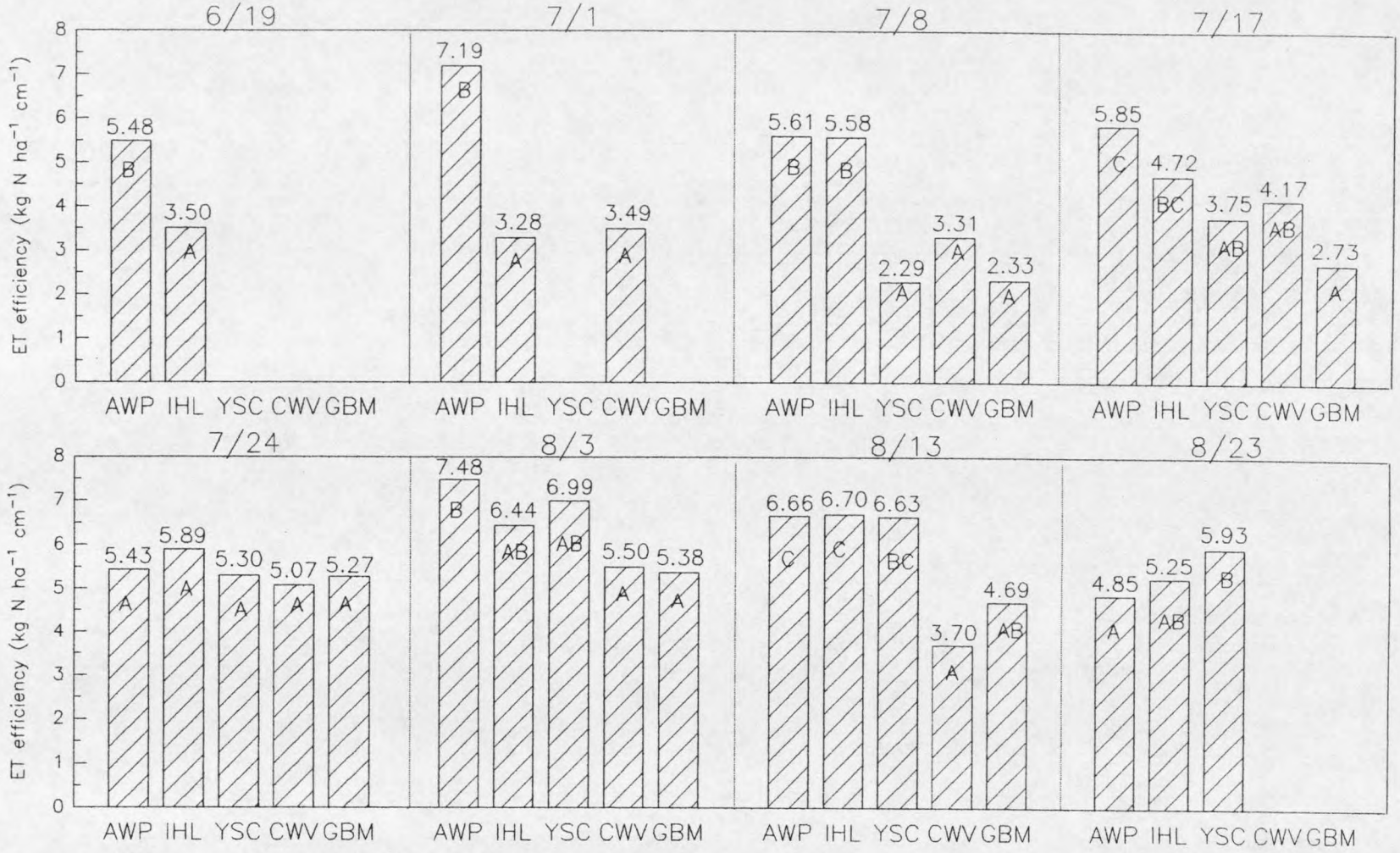

Fig. 23. Evapotranspiration efficiencies in terms of canopy nitrogen accumulation at 8 harvest dates in 1991. Values are means of 4 replicates. Means at each harvest date with different letters are significantly different ($p<0.05$) by ANOVA.

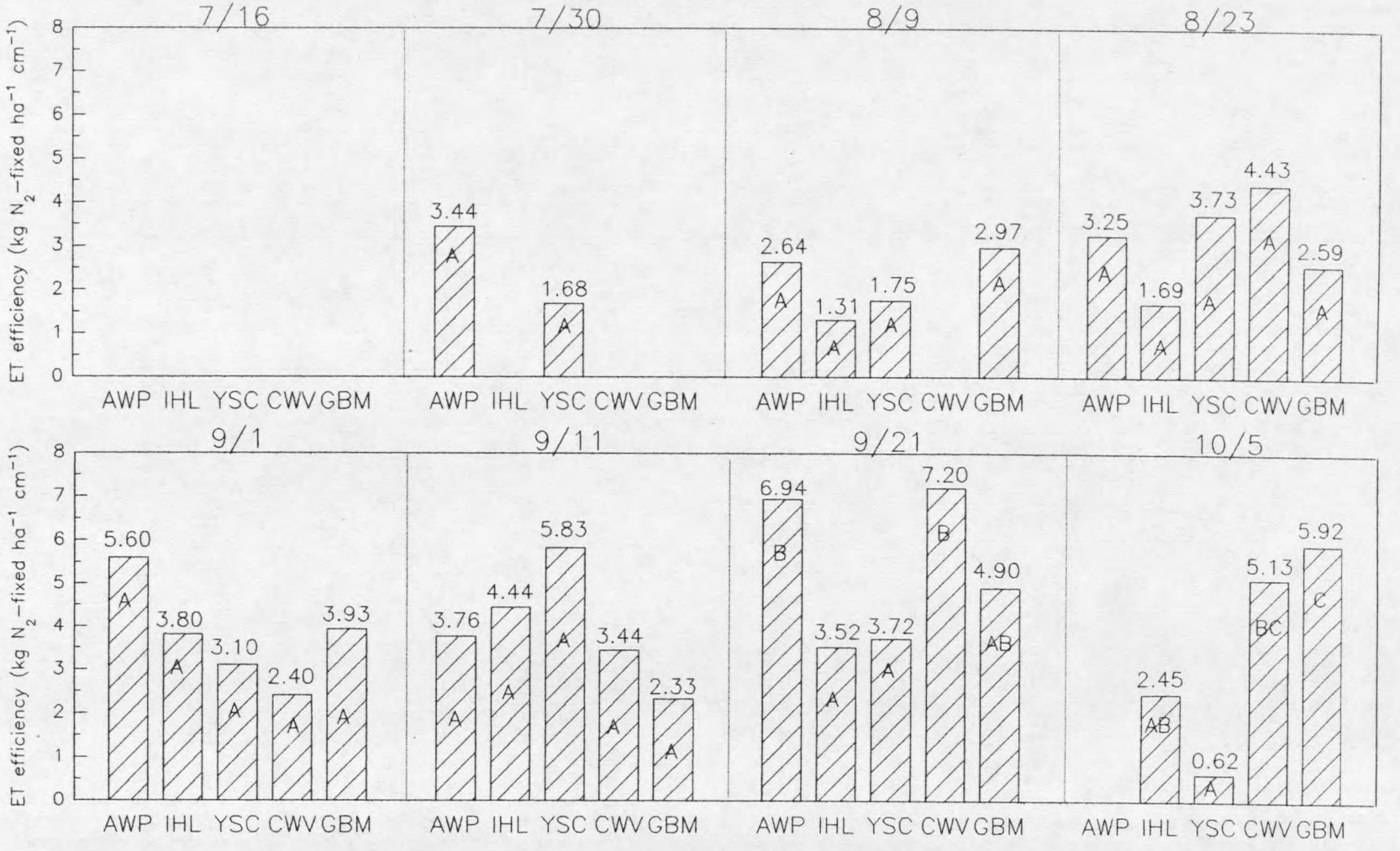

Fig. 24. Evapotranspiration efficiencies in terms of N_2-fixation at 8 harvest dates in 1990. Values are means of 4 replicates. Means at each harvest date with different letters are significantly different ($p<0.05$) by ANOVA.

($p<0.05$) to Indianhead lentil ET efficiency while Cahaba white vetch occupied an intermediate position.

In 1991, relatively few positive estimates of N_2-fixation were obtained (Fig. 25). From 6/19 to 7/17, only two ET efficiencies are plotted. At the 7/24 harvest, ET efficiencies of Austrian winterpea, Indianhead lentil, yellow sweetclover, and Cahaba white vetch were statistically similar. At the 8/3 harvest, Austrian winterpea and yellow sweetclover ET efficiencies were superior ($p<0.05$) to George black medic performance while Indianhead lentil and Cahaba white vetch occupied intermediate positions. At the 8/13 harvest, ET efficiencies of Austrian winterpea, Indianhead lentil, and yellow sweetclover were statistically similar. Lastly, at the 8/23 harvest, yellow sweetclover ET efficiency was superior ($p<0.05$) to Austrian winterpea ET efficiency while Indianhead lentil occupied an intermediate position.

To develop an integrated picture of ET efficiencies in terms of canopy biomass or nitrogen accumulation over the growing season, ET efficiencies were averaged over sample dates where all species were harvested. In 1990, all legumes were harvested at six sample dates. In 1991, that number fell to five sample dates. This method of analysis integrates ET efficiency over the growing season and cuts through the "noise" apparent in Figures 20 through 23.

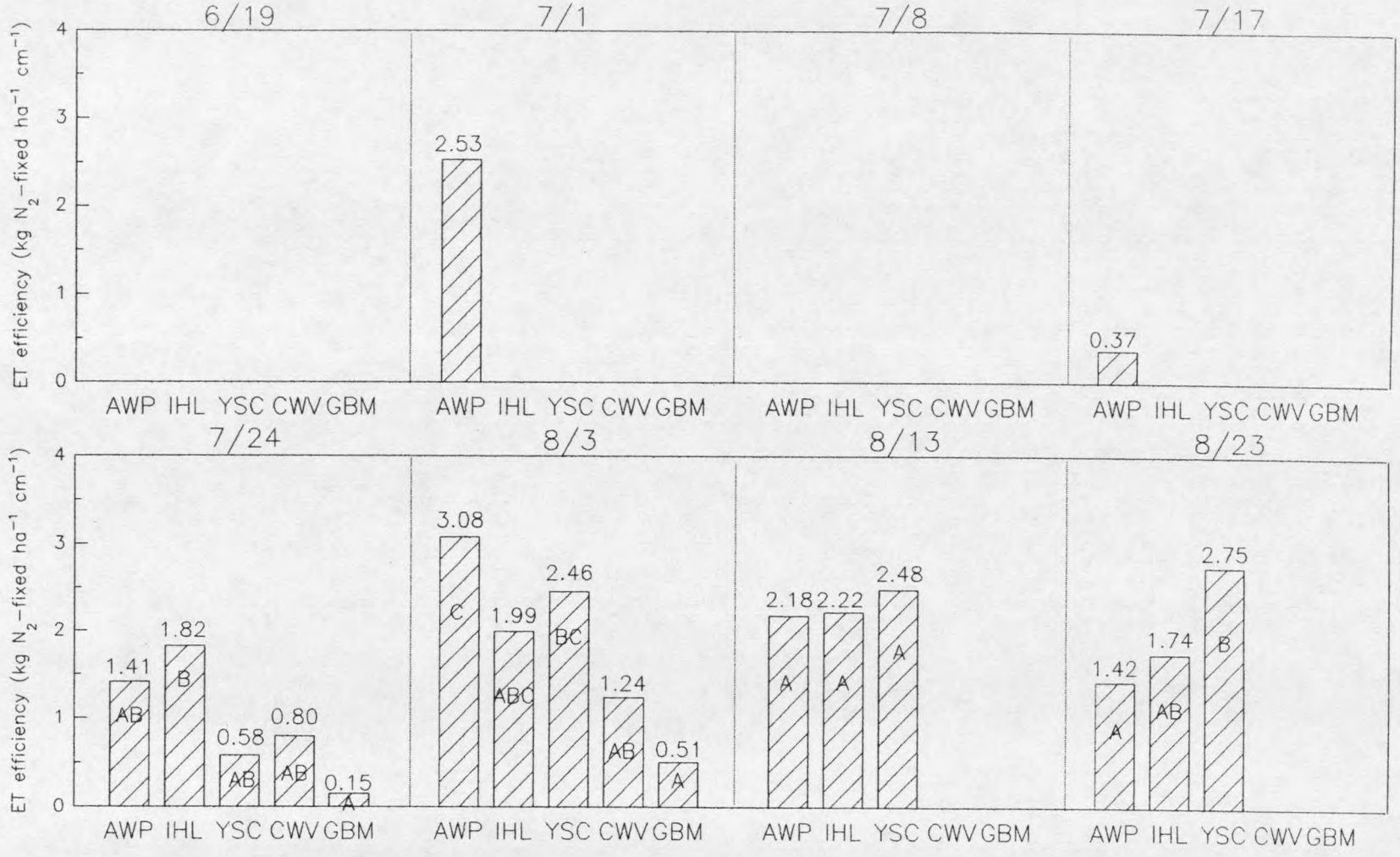

Fig. 25. Evapotranspiration efficiencies in terms of N_2-fixation at 8 harvest dates in 1991. Values are means of 4 replicates. Means at each harvest date with different letters are significantly different ($p<0.05$) by ANOVA.

In 1990, average Austrian winterpea ET efficiency in terms of canopy biomass accumulation was superior ($p<0.05$) to the ET efficiencies of all other legumes (Table 1). Average evapotranspiration efficiencies of yellow sweetclover, Cahaba white vetch, and Indianhead lentil were statistically similar.

Table 1. Evapotranspiration efficiencies in terms of canopy biomass accumulation averaged over sample dates where all legumes were harvested

Legume	ET efficiency (Kg ha^{-1} cm^{-1}) 1990	1991
Austrian winterpea	311.2c	210.2b
Indianhead lentil	249.5ab	213.7b
Yellow sweetclover	243.9ab	154.7a
Cahaba white vetch	274.6b	152.6a
George Black medic	226.8a	137.9a
LSD (p=0.05)	33.8	22.3

*means within columns followed by different letters are significantly different ($p<0.05$) by ANOVA

In 1991, Austrian winterpea and Indianhead lentil displayed the highest efficiencies of canopy biomass accumulation (Table 1). Yellow sweetclover, Cahaba white vetch, and George black medic had similar ET efficiencies and these efficiencies were significantly lower ($p<0.05$) than Austrian winterpea and Indianhead lentil values. Lastly, all 1991 ET efficiencies were lower than 1990 values.

In terms of canopy nitrogen accumulation, average 1990 Austrian winterpea ET efficiency was signficantly greater ($p<0.05$) than Indianhead lentil, yellow sweetclover, and George black medic means (Table 2). Cahaba white vetch ET efficiency was statistically similar to Austrian winterpea ET efficiency and superior ($p<0.05$) to Indianhead lentil and George black medic means.

Table 2. Evapotranspiration efficiencies in terms of canopy nitrogen accumulation averaged over sample dates where all legumes were harvested.

Legume	ET efficiency (Kg N ha^{-1} cm^{-1}) 1990	1991
Austrian winterpea	9.89d	6.14c
Indianhead lentil	6.57a	5.87c
Yellow sweetclover	8.23bc	4.99b
Cahaba white vetch	9.02cd	4.35ab
George Black medic	7.30ab	4.08a
LSD (p=0.05)	1.10	0.72

*means within columns followed by different letters are significantly different ($p<0.05$) by ANOVA

In 1991, average Austrian winterpea and Indianhead lentil ET efficiencies in terms of canopy nitrogen accumulation were similar and statistically superior ($p<0.05$) to all other legumes. Average ET efficiencies of yellow sweetclover and Cahaba white vetch were statistically similar. Lastly, all 1991 ET efficiencies were less than 1990 values.

Average ET efficiencies were also generated in terms of N_2-fixation. In this case, ET efficiencies were averaged over sample dates where all legume species generated positive estimates of N_2-fixation. N_2-fixation estimates of all legumes were positive at four harvest dates in 1990 and two harvest dates in 1991.

In 1990, average Cahaba white vetch and Austrian winterpea ET efficiencies in terms of N_2-fixation were superior ($p<0.05$) to Indianhead lentil ET efficiency (Table 3). Average yellow sweetclover, Austrian winterpea, and Cahaba white vetch ET efficiencies were statistically similar.

Table 3. Evapotranspiration efficiencies in terms of N_2-fixation averaged over sample dates where all legumes exhibited positive N_2-fixation estimates.

Legume	ET efficiency (kg N_2-fixed ha^{-1} cm^{-1}) 1990	1991
Austrian winterpea	4.78bc	2.21c
Indianhead lentil	3.01a	1.93bc
Yellow sweetclover	4.33abc	1.52bc
Cahaba white vetch	4.93c	1.02ab
George Black medic	3.44ab	0.33a
LSD (p=0.05)	1.44	1.10

*means within columns followed by different letters are significantly different ($p<0.05$) by ANOVA

In 1991, the average ET efficiency of George black medic N_2-fixation was significantly less ($p<0.05$) than

Indianhead lentil, yellow sweetclover, and Austrian winterpea ET efficiencies (Table 3). Average Austrian winterpea ET efficiency was significantly greater ($p<0.05$) than average Cahaba white vetch ET efficiency. Lastly, all 1991 ET efficiencies were lower than 1990 values.

Linear Regressions: Canopy Biomass Accumulation vs. ET, Canopy Nitrogen Accumulation vs. ET, and N_2-Fixation vs. ET

Linear and curvilinear regressions reveal yield vs. ET relationships that can be used to examine differences in legume performance. Canopy biomass accumulation vs. ET and canopy nitrogen accumulation vs. ET regressions are fit to a linear equation of the form $y=a+bx$. N_2-fixation vs. ET regressions are fit to a curvilinear equation of the form $y=a+bx+cx^2$. Where negative estimates of N_2-fixation were obtained, zero values have been substituted.

Relative to 1990 results, all Austrian winterpea regressions reveal poor performance in 1991 (Fig. 26). Increasing ET was associated with less canopy biomass accumulation, canopy nitrogen accumulation, and N_2-fixation in 1991. When 1990 and 1991 results are combined, lower R^2 values are obtained; 0.76 in the canopy biomass accumulation vs. ET regression, 0.73 in the canopy N accumulation vs. ET regression, and 0.60 in the N_2-fixation vs. ET regression.

Similar regression lines are found among Indianhead lentil canopy biomass accumulation vs. ET, canopy nitrogen

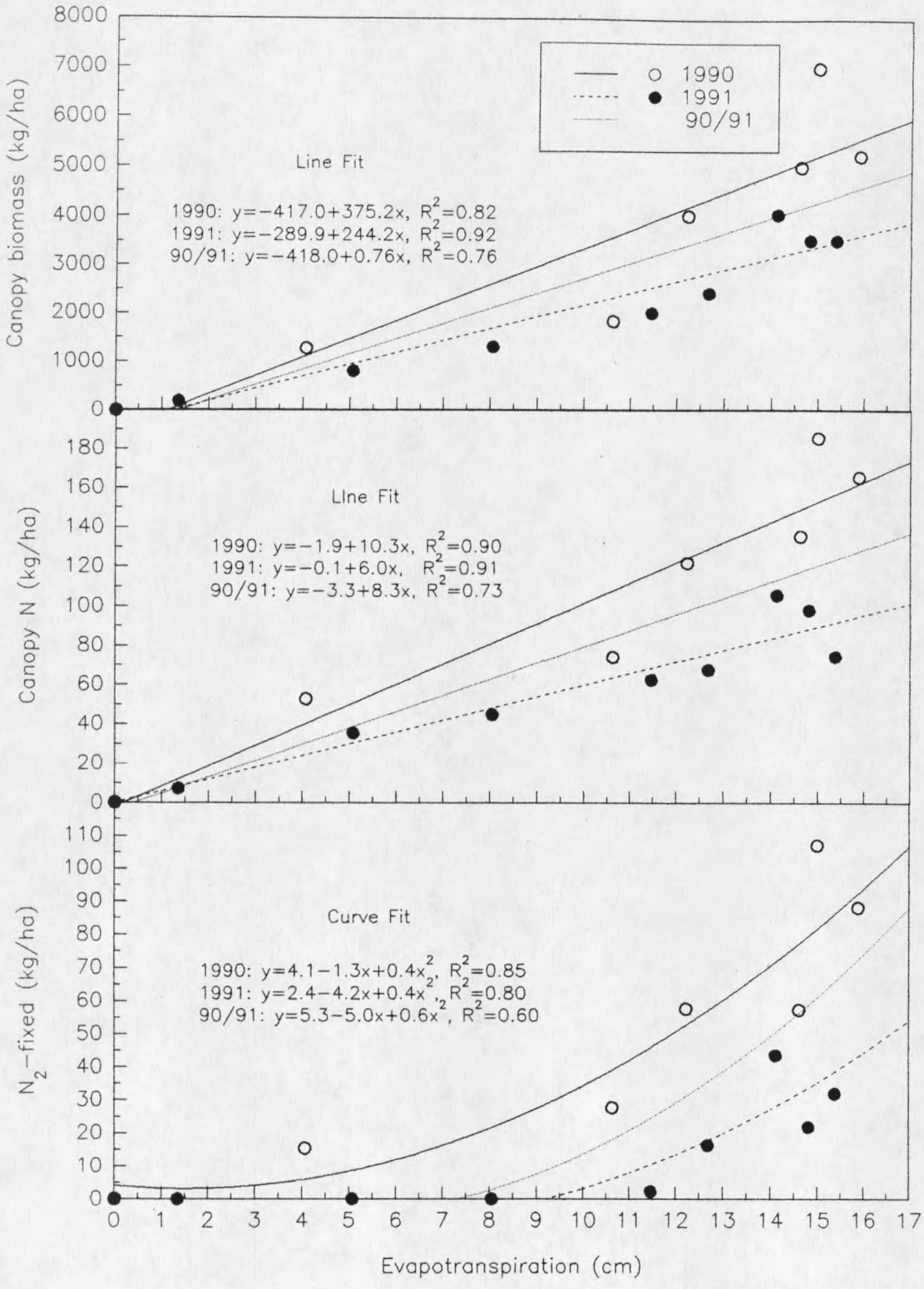

Fig. 26. Austrian winterpea canopy biomass accumulation vs. ET, canopy nitrogen accumulation vs. ET, and N_2-fixation vs. ET regressions.

and N_2-fixation vs. ET regressions from individual years (Fig. 27). Combining 1990 and 1991 data sets does not reduce R^2 values.

All 1991 yellow sweetclover regression lines are displaced slightly below 1990 regression lines (Fig. 28). However, combination of data sets produces similar R^2 values.

A large difference is observed among Cahaba white vetch canopy biomass and nitrogen regressions from individual years (Fig. 29). Combination of data sets in these regressions produces low R^2 values: 0.77 in the 1990/1991 canopy biomass accumulation vs. ET regression and 0.76 in the 1990/1991 canopy nitrogen accumulation vs. ET regression. Because Cahaba white vetch produced only two positive estimates of N_2-fixation in 1991, a 1991 N_2-fixation vs. ET regression is not included in Figure 29.

Canopy biomass accumulation vs. ET and canopy nitrogen accumulation vs. ET regressions reveal poor performance of George black medic in 1991 (Fig. 30). However, pooling 1990 and 1991 results does not produce large declines in R^2 values. A 1991 N_2-fixation vs. ET regression line is not included in Figure 30 because George black medic produced only two positive estimates of N_2-fixation in 1991.

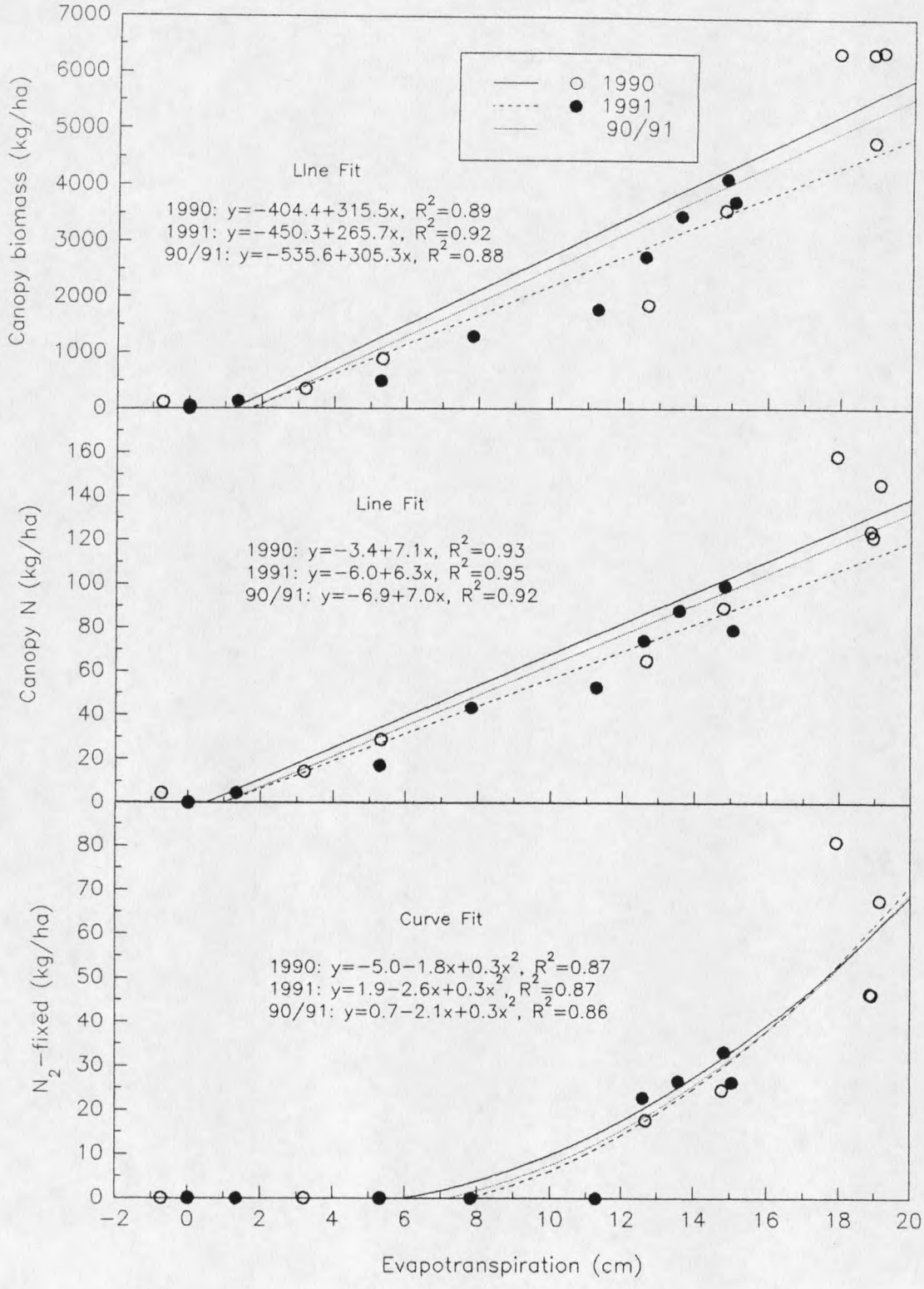

Fig. 27. Indianhead lentil canopy biomass accumulation vs. ET, canopy nitrogen accumulation vs. ET, and N_2-fixation vs. ET regressions.

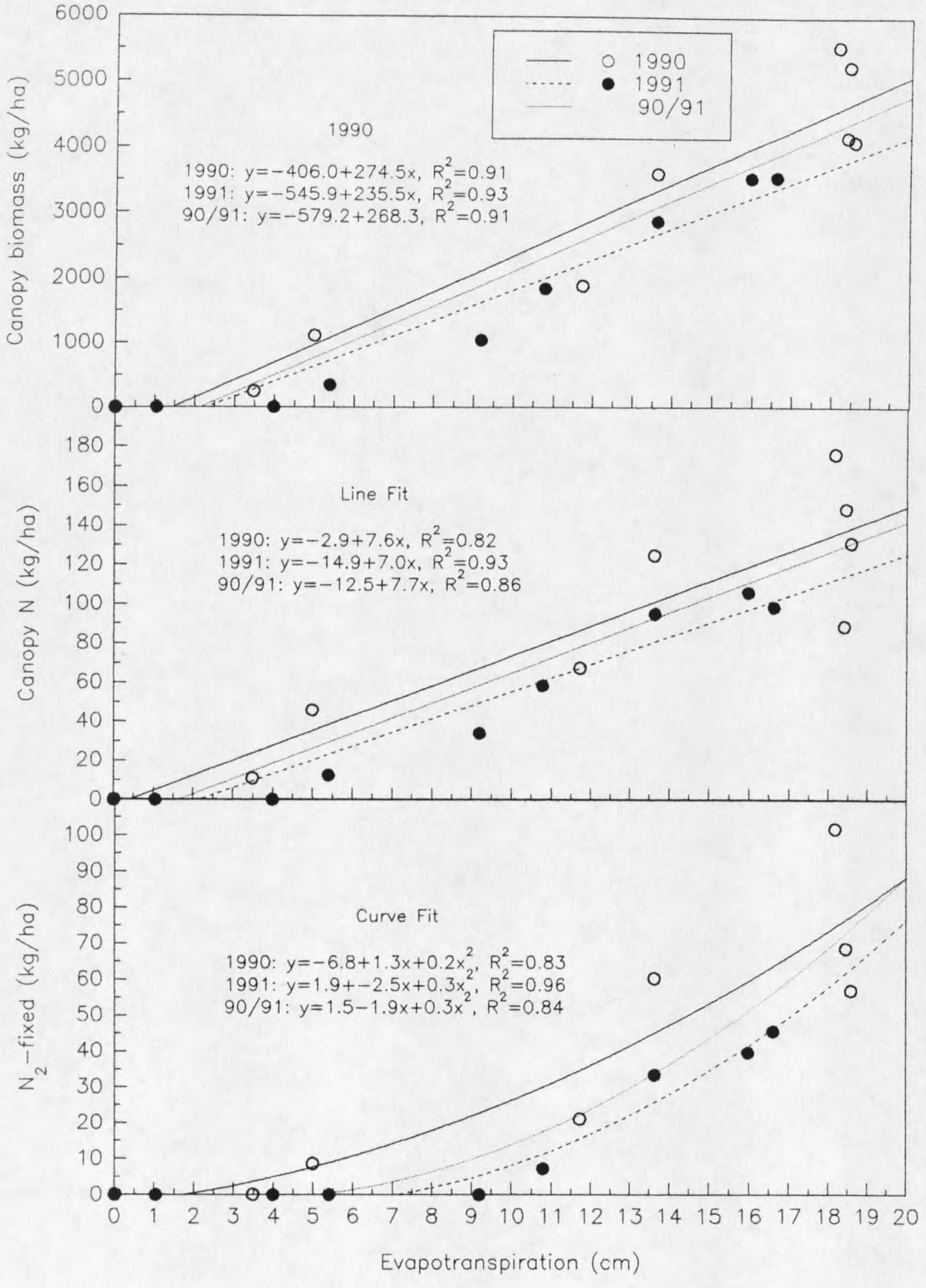

Fig. 28. Yellow sweetclover canopy biomass accumulation vs. ET, canopy nitrogen accumulation vs. ET, and N_2-fixation vs. ET regressions.

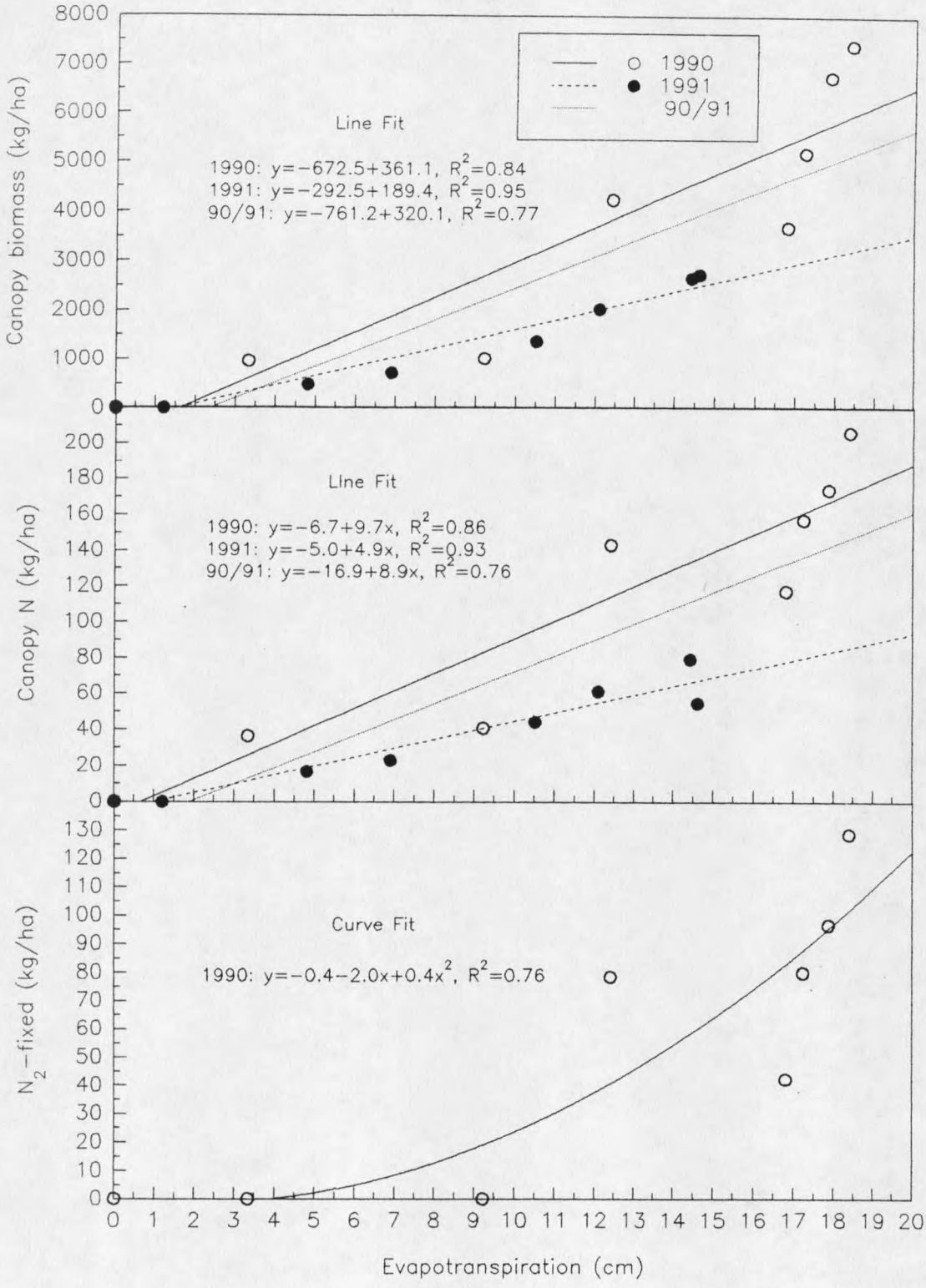

Fig. 29. Cahaba white vetch canopy biomass accumulation vs. ET, canopy nitrogen accumulation vs. ET, and N_2-fixation vs. ET regressions.

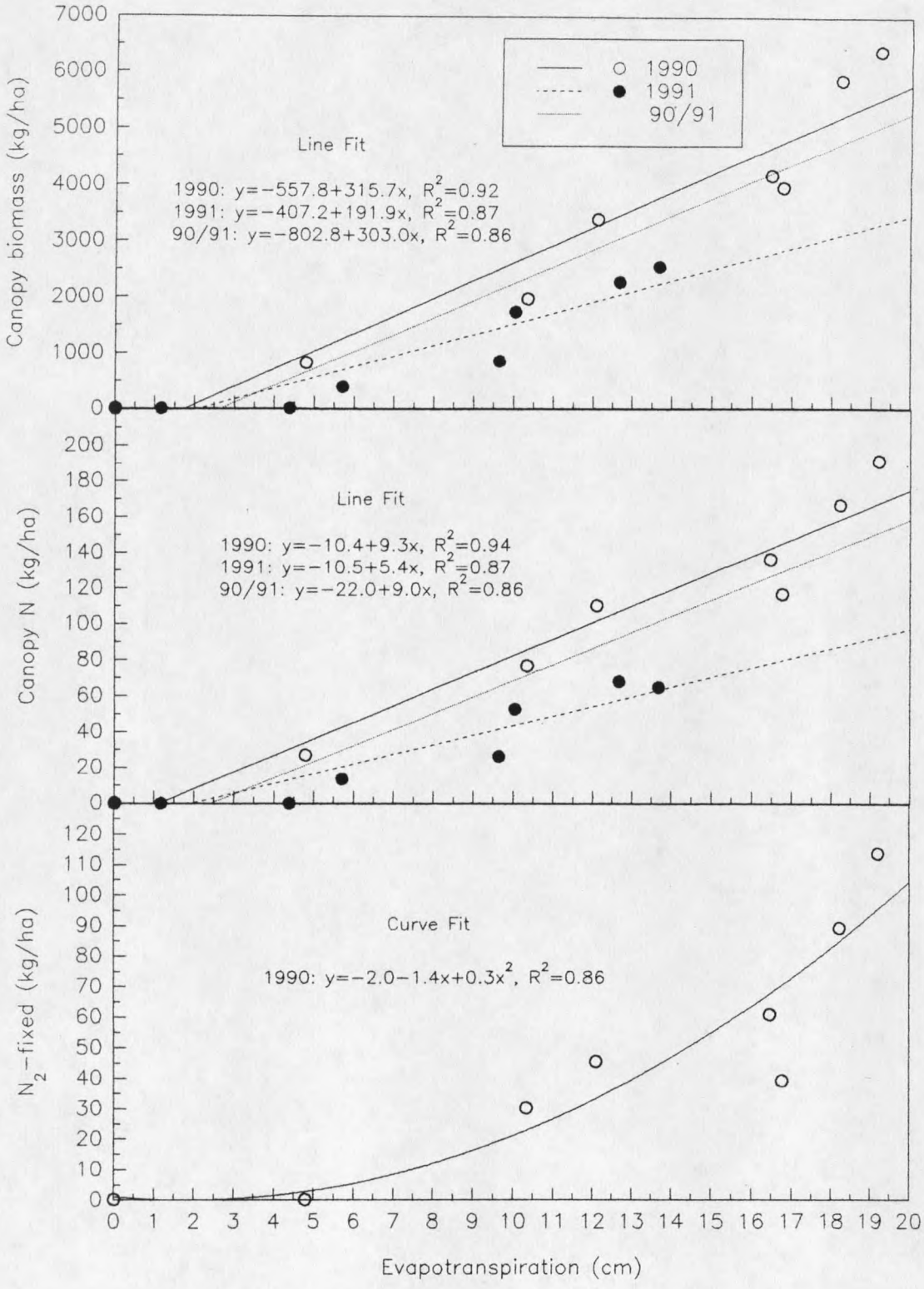

Fig. 30. George black medic canopy biomass accumulation vs. ET, canopy nitrogen accumulation vs. ET, and N_2-fixation vs. ET regressions.

Pair-wise Comparisons of Regression Lines

Canopy biomass accumulation vs. ET regression lines from 1990, 1991, and pooled 1990/1991 results are compared in Figures 31-33.

All pair-wise comparisons among 1990 and 1990/1991 regression lines are coincident at the p=0.5% level (Figs. 31 and 33). Among 1991 regression lines, the following pair-wise comparisons of species are not coincident ($p<0.05$); Indianhead lentil/yellow sweetclover, Indianhead lentil/Cahaba white vetch, Indianhead lentil/George black medic, Austrian winterpea/yellow sweetclover, Austrian winterpea/Cahaba white vetch, and Austrian winterpea/George black medic (Fig. 32).

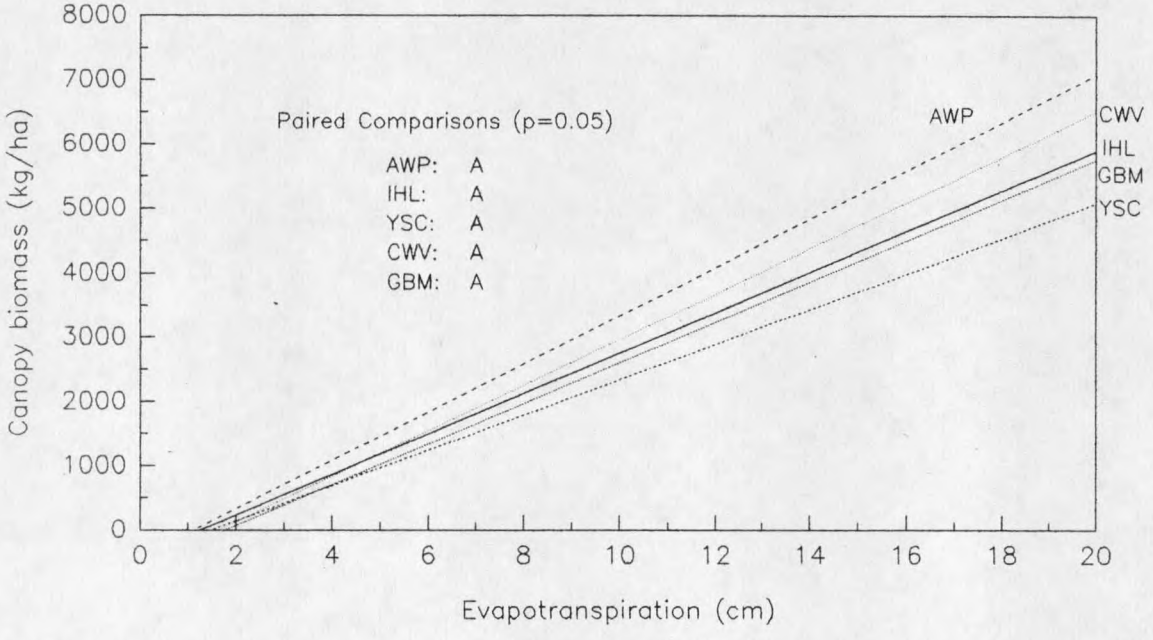

Fig. 31. Legume canopy biomass accumulation vs. ET in 1990. Regressions followed by the same letters are coincident at the p=0.05 level.

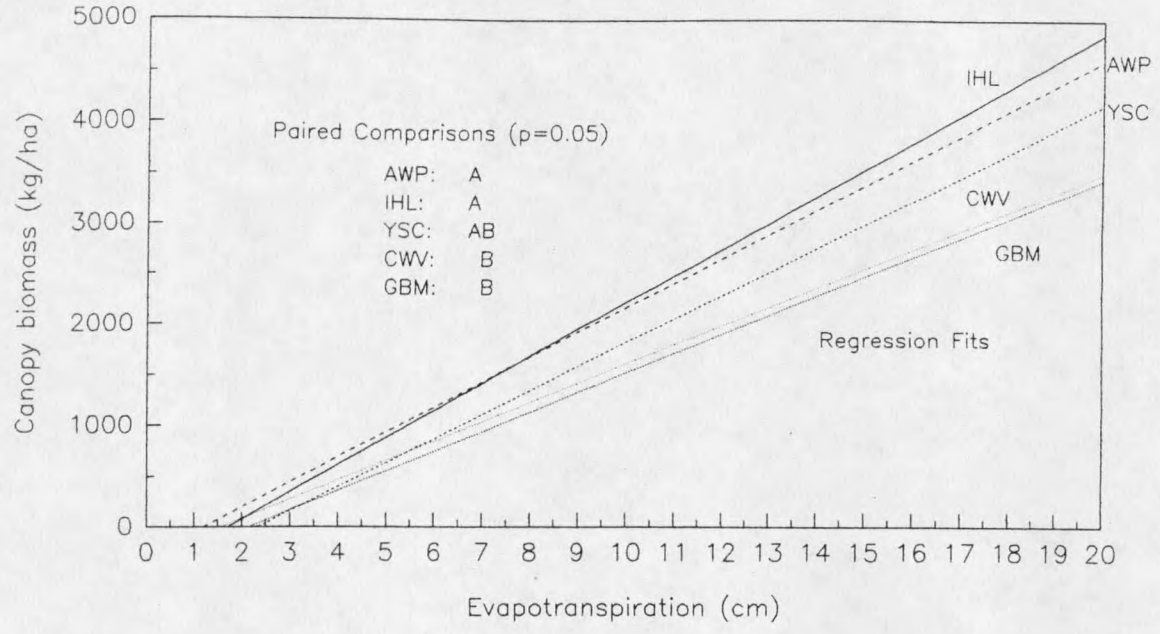

Fig. 32. Legume canopy biomass accumulation vs. ET in 1991. Regressions followed by the same letters are coincident at the p=0.05 level.

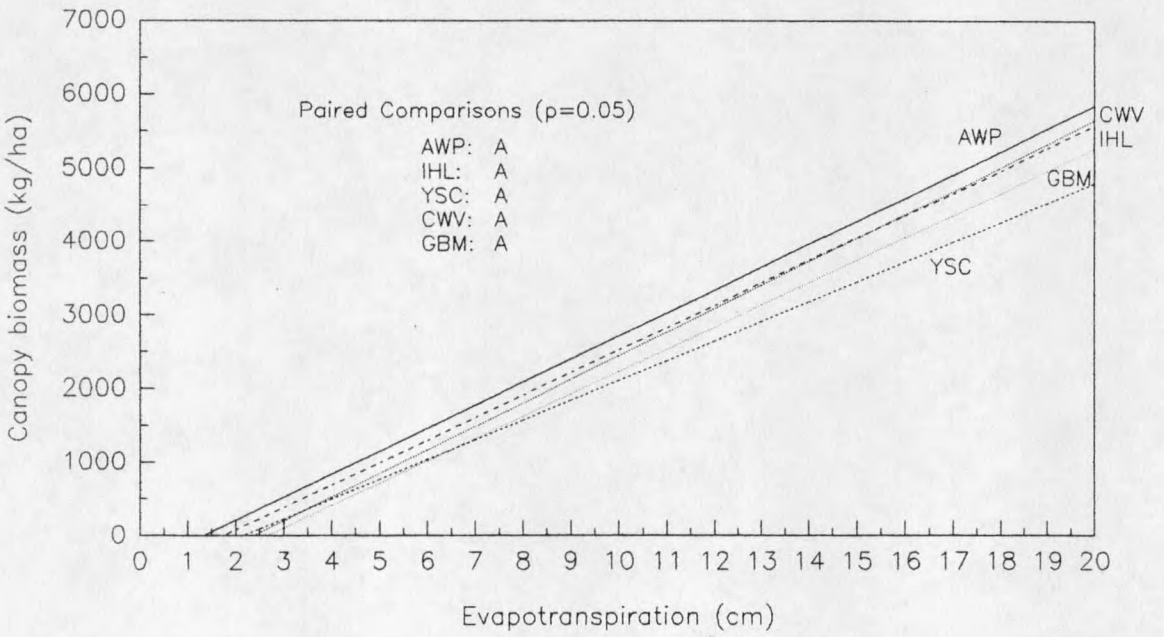

Fig. 33. Legume 1990/1991 canopy biomass accumulation vs. ET. Regressions followed by the same letters are coincident at the p=0.05 level.

Legume canopy N accumulation vs. ET regression lines are compared in Figures 34-36. 1990 pair-wise comparisons of Austrian winterpea/Indianhead lentil, Cahaba white vetch/Indianhead lentil, and George black medic/Indianhead lentil regression lines are not coincident ($p<0.05$) (Fig. 34). Among 1991 regression lines, the following pairs of legume species are not coincident ($p<0.05$); Indianhead lentil/Cahaba white vetch, Indianhead lentil/George black medic, Austrian winterpea/Cahaba white vetch, and Austrian winterpea/George black medic (Fig. 35). All 1990/1991 pair-wise comparisons of regression lines are coincident at the p=0.5% level (Fig. 36).

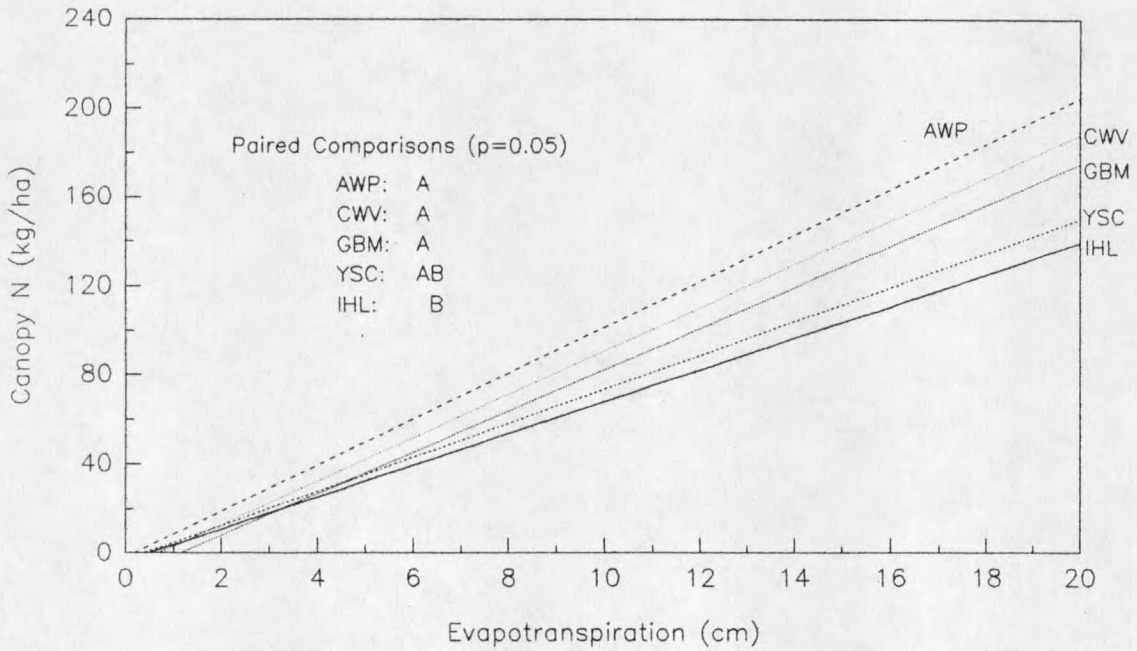

Fig. 34. Legume canopy nitrogen accumulation vs. ET in 1990. Regressions followed by the same letters are coincident at the p=0.05 level.

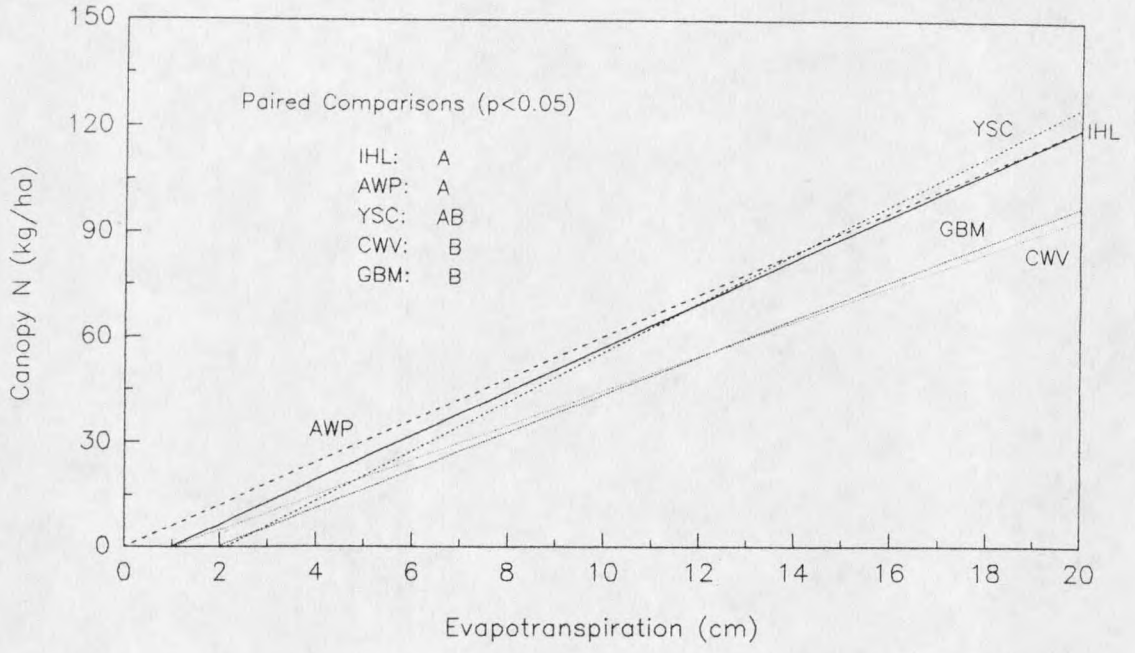

Fig. 35. Legume canopy nitrogen accumulation vs. ET in 1991. Regressions followed by the same letters are coincident at the p=0.05 level.

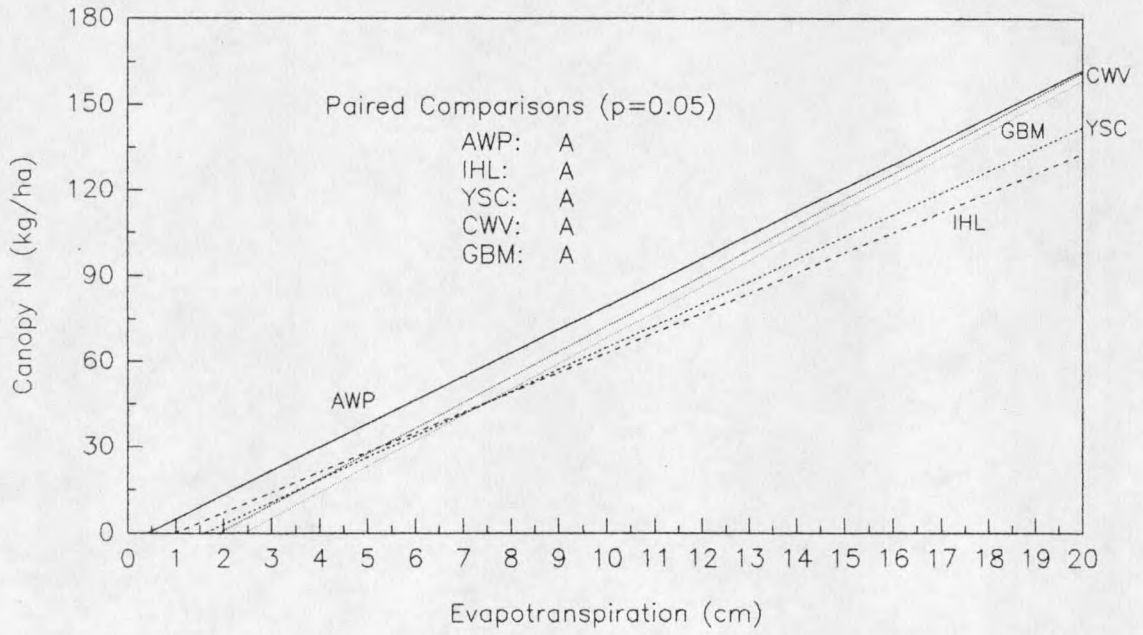

Fig. 36. Legume 1990/1991 canopy nitrogen accumulation vs. ET. Regressions followed by the same letters are coincident at the p=0.05 level.

Legume N_2-fixation vs. ET regressions are compared in Figures 37-39. Among 1990 regression lines, only the Austrian winterpea/Indianhead lentil pair-wise comparison is not coincident ($p<0.05$) (Fig. 37). All 1991 pair-wise comparisons of regression lines are coincident at the p=0.5% level (Fig. 38). Among 1990/1991 regressions lines, only the Austrian winterpea/Indianhead lentil pair-wise comparison is not coincident ($p<0.05$) (Fig. 39).

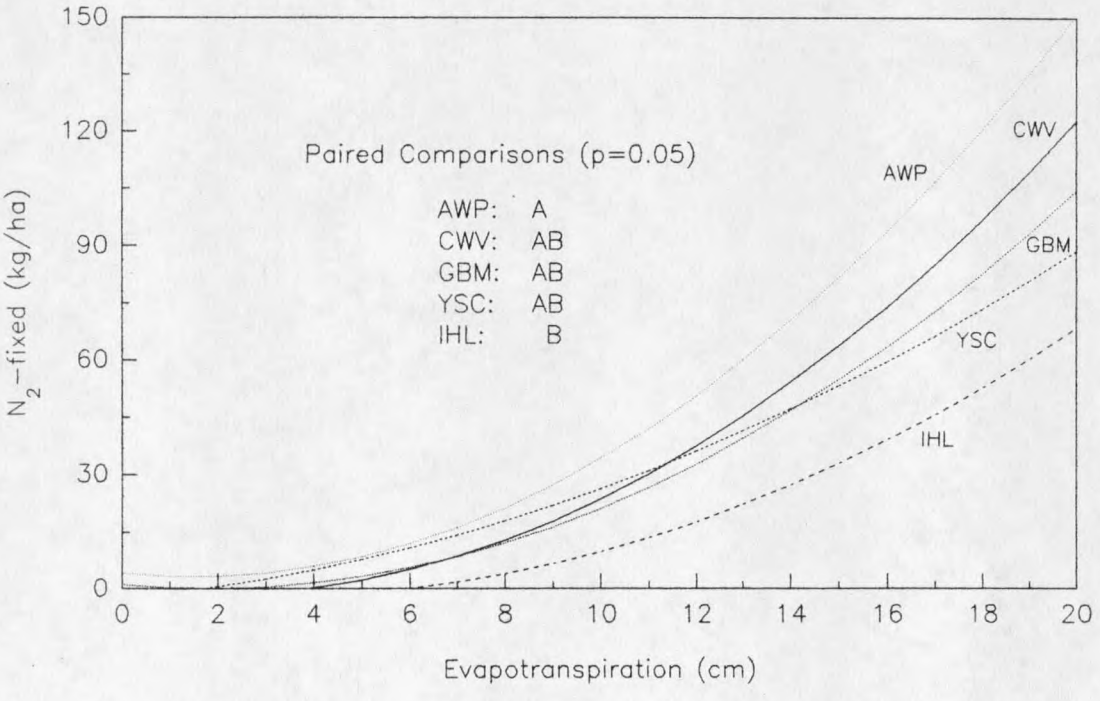

Fig. 37. Legume N_2-fixation vs. ET in 1990. Regressions followed by the same letters are coincident at the p=0.05 level.

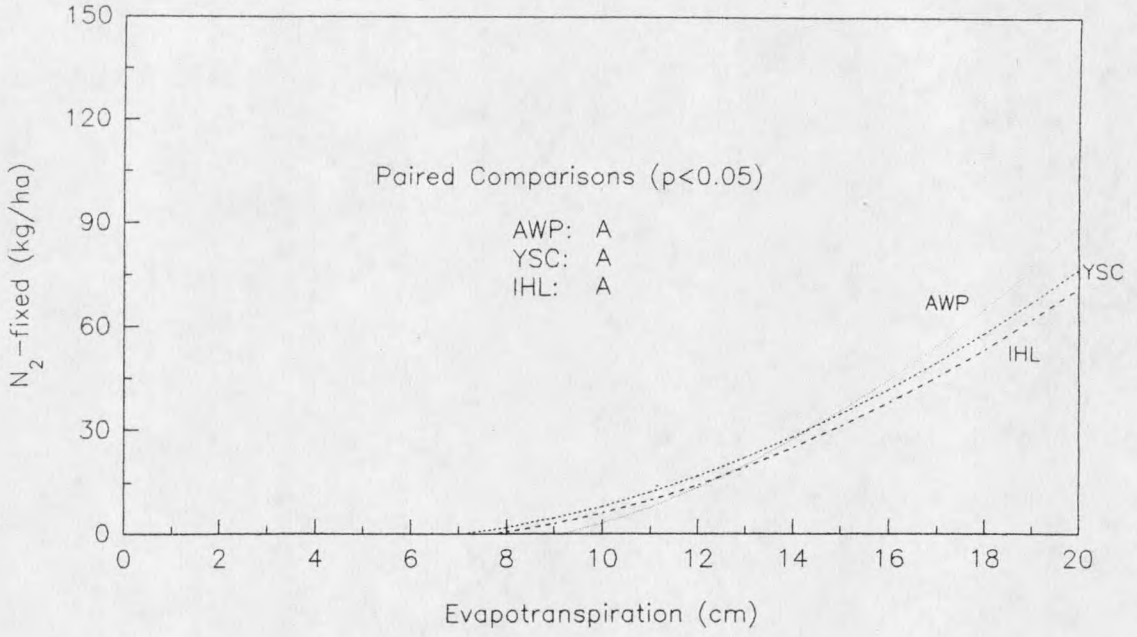

Fig. 38. Legume N_2-fixation vs. ET in 1991. Regressions followed by the same letters are coincident at the p=0.05 level.

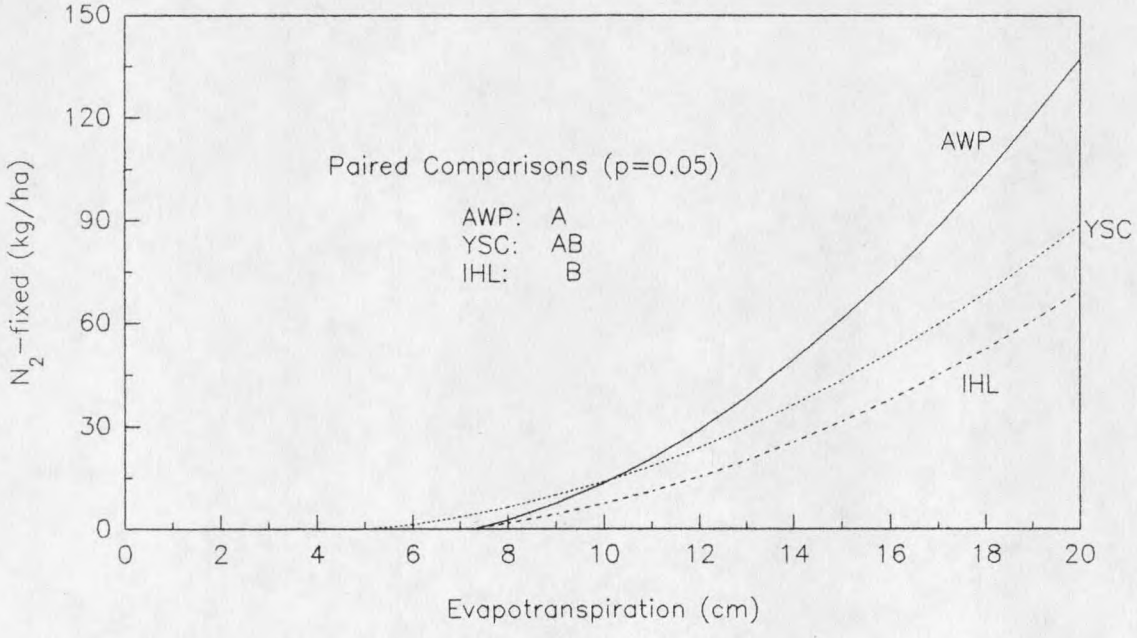

Fig. 39. Legume 1990/1991 N_2-fixation vs. ET. Regressions followed by the same letters are coincident at the p=0.05 level.

Soil Properties

Analyses of soil NO_3-N, Olson P, and percent organic matter are reported in Tables 4 through 13.

Emergence NO_3-N means in 1990 were generally similar (Table 4). Over the 0-15 cm increment, mean soil nitrate for spring wheat plots was significantly higher ($p<0.05$) than mean NO_3-N for Austrian winterpea, Indianhead lentil, and yellow sweetclover plots. Over the 15-61 cm increment, no significant differences were observed. Over the 61-107 cm increment, soil NO_3-N for barley was significantly greater ($p<0.05$) than all other means.

Table 4. Emergence NO_3-N at three soil depths in 1990. Values are means of four replicates.

1990 crop	NO_3-N in ppm 0-15 cm	15-61 cm	61-107 cm
Austrian winterpea	4.60a	4.93a	4.50a
Indianhead lentil	4.08a	6.40a	10.18a
Yellow sweetclover	3.58a	4.35a	5.43a
Cahaba white vetch	5.93ab	4.58a	4.33a
George black medic	4.88ab	3.53a	5.38a
Barley	3.16a	7.38a	19.67b
Spring wheat	7.83b	5.96a	10.18a
LSD (0.05)	2.94	3.95	6.66
CV (SE/MEAN)%	20.19	20.19	26.92

*means within columns followed by different letters are significantly different ($p<0.05$) by ANOVA

Emergence NO_3-N means in 1991 were also generally similar (Table 5). Over the 15-61 cm and 61-107 cm depth intervals, no statistically significant differences were detected. Over the 0-15 cm increment, soil nitrate was statistically similar among all legume plots while NO_3-N for spring wheat plots was significantly less ($p<0.05$) than black medic, Cahaba white vetch, and yellow sweetclover means. Over the same increment, soil nitrate for barley plots was significantly less ($p<0.05$) than yellow sweetclover and Cahaba white vetch means.

Table 5. Emergence NO_3-N at three soil depths in 1991. Values are means of four replicates.

1991 crop	NO_3-N in ppm 0-15 cm	15-61 cm	61-107 cm
Austrian winterpea	2.58abc	1.78a	2.85a
Indianhead lentil	2.75abc	1.63a	2.48a
Yellow sweetclover	3.35c	1.88a	3.20a
Cahaba white vetch	3.05c	1.58a	2.35a
George black medic	2.98bc	2.13a	3.93a
Barley	2.03ab	1.93a	2.73a
Spring wheat	1.88a	1.75a	2.68a
LSD (0.05)	0.98	0.75	1.79
CV (SE/MEAN)%	12.36	13.90	20.90

*means within columns followed by different letters are significantly different ($p<0.05$) by ANOVA

In Tables 6 and 7, legume emergence NO_3-N, maturity NO_3-N, and NO_3-N use are summed over the 107 cm depth

increment and expressed in terms of kg/ha. NO_3-N use is defined as losses of NO_3 from the study site via plant uptake, leaching, and denitrification.

In 1990, mean emergence NO_3-N for Austrian winterpea, yellow sweetclover, Cahaba white vetch, and George black medic plots was statistically similar while mean NO_3-N use for Indianhead lentil plots was significantly greater ($p<0.05$) than NO_3-N use for Austrian winterpea and Cahaba white vetch plots (Table 6). NO_3-N use for Indianhead lentil, yellow sweetclover, and George black medic plots was statistically similar.

Table 6. Legume emergence NO_3-N, maturity NO_3-N, and total NO_3-N use to the 107 cm soil depth increment in 1990. Values are means of four replicates.

1990 Crop	NO_3-N in kg/ha emergence	maturity	use
Austrian winterpea	73.68a	58.08c	15.60a
Indianhead lentil	120.60b	16.27ab	104.30c
Yellow sweetclover	73.75a	6.08a	67.67bc
Cahaba white vetch	73.15a	23.70b	49.45ab
George black medic	70.85a	7.40ab	63.45bc
LSD (0.05)	37.76	16.58	45.77
CV (SE/MEAN)%	14.87	24.12	24.71

*means within columns followed by different letters are significantly different ($p<0.05$) by ANOVA

In 1991, both emergence NO_3-N and NO_3-N use over the 0-107 cm soil increment were statistically similar among all legume plots (Table 7).

Table 7. Legume emergence NO_3-N, maturity NO_3-N, and total NO_3-N use to the 107 cm soil depth increment in 1991. Values are means of four replicates.

1991 Crop	NO_3-N in kg/ha emergence	maturity	use
Austrian winterpea	36.90a	20.70a	16.20a
Indianhead lentil	33.77a	18.58a	15.20a
Yellow sweetclover	41.65a	20.58a	21.08a
Cahaba white vetch	33.25a	23.67a	9.58a
George black medic	47.35a	35.83b	11.52a
LSD (0.05)	18.57	16.58	23.79
CV (SE/MEAN)%	15.62	24.12	52.47

*means within columns followed by different letters are significantly different ($p<0.05$)

When averaged across all legume species, both nitrate fertility and use to the 107 cm depth increment were significantly greater ($p<0.05$) in 1990 (Table 8).

At emergence, soil phosphorus to the 15 cm depth for Austrian winterpea, Indianhead lentil, Cahaba white vetch, spring wheat and barley plots was statistically similar (Table 9). At maturity, all means but spring wheat were similar.

Table. 8. Average legume emergence NO_3-N and NO_3-N use to the 107 cm soil depth increment in 1990 and 1991.

Year	Average Legume NO_3-N in kg/ha emergence	use
1990	82.40a	60.10a
1991	38.58b	14.71b
LSD (0.05)	11.96	14.57

*means within columns followed by different letters are significantly different ($p<0.05$) by ANOVA

Table 9. Emergence and maturity Olsen P over the 0-15 cm soil increment in 1990. Values are means of four replicates.

1990 Crop	phosphorus in ppm emergence	maturity
Austrian winterpea	17.40c	9.43ab
Indianhead lentil	14.37abc	8.65a
Yellow sweetclover	9.70a	9.15a
Cahaba white vetch	17.50c	9.63ab
George black medic	10.35ab	8.85a
Barley	16.05bc	9.43ab
Spring wheat	17.50c	11.32b
LSD (0.05)	5.73	2.06
CV (SE/MEAN)%	13.07	7.27

*means within columns followed by different letters are significantly different ($p<0.05$) by ANOVA

In 1991, emergence phosphorus levels for Indianhead lentil, yellow sweetclover, Cahaba white vetch, George black medic, barley, and spring wheat plots were statistically

similar (Table 10). Post-harvest phosphorus levels for Indianhead lentil, spring wheat, yellow sweetclover, George black medic, and barley plots were also similar. Among legumes, post-harvest soil phosphorus for black medic was significantly greater ($p<0.05$) than Austrian winterpea and Cahaba white vetch means.

Table 10. Emergence and maturity Olsen P over the 0-15 cm soil increment in 1991. Values are means of four replicates.

1991 Crop	phosphorus in ppm emergence	maturity
Austrian winterpea	15.80a	16.38a
Indianhead lentil	24.97ab	21.83ab
Yellow sweetclover	17.98ab	18.85ab
Cahaba white vetch	27.03b	15.98a
George black medic	19.90ab	24.22b
Barley	20.85ab	21.13ab
Spring wheat	24.45ab	20.58ab
LSD (0.05)	11.17	7.53
CV (SE/MEAN)%	17.43	12.77

*means within columns followed by different letters are significantly different ($p<0.05$) by ANOVA

When averaged across all legume plots, phosphorus fertility at emergence was significantly greater ($p<0.05$) in 1991 than in 1990 (Table 11). Where phosphorus uptake is defined as the difference between phosphorus levels at emergence and maturity, average phosphorus uptake in 1990 was statistically similar to average P uptake in 1991.

Table. 11. Average legume emergence P and P uptake over the 0-15 cm soil increment in 1990 and 1991.

Year	Average Legume P in kg/ha emergence	uptake
1990	31.09a	10.68a
1991	47.39b	3.79a
LSD (0.05)	7.38	7.08

*means within columns followed by different letters are significantly different ($p<0.05$) by ANOVA

At emergence in 1990, soil organic matter content for Austrian winterpea, Indianhead lentil, yellow sweetclover, barley, and spring wheat plots was statistically similar (Table 12). At maturity, no significant differences in

Table 12. Emergence and maturity organic matter content over the 0-15 cm soil increment in 1990. Values are means of four replicates.

1990 Crop	Percent Organic Matter emergence	maturity
Austrian winterpea	1.43abc	1.40a
Indianhead lentil	1.35ab	1.53a
Yellow sweetclover	1.35ab	1.48a
Cahaba white vetch	1.53c	1.41a
George black medic	1.33a	1.50a
Barley	1.48bc	1.43a
Spring wheat	1.39ab	1.38a
LSD (0.05)	0.13	0.15
CV (SE/MEAN)%	3.00	3.52

*means within columns followed by different letters are significantly different ($p<0.05$) by ANOVA

percent organic matter were found. In 1991, no significant differences were found among both emergence and maturity percent organic matter means (Table 13).

Table 13. Emergence and maturity organic matter content over the 0-15 cm soil increment in 1991. Values are means of four replicates.

1991 Crop	Percent Organic Matter emergence	maturity
Austrian winterpea	1.31a	1.29a
Indianhead lentil	1.38a	1.32a
Yellow sweetclover	1.41a	1.35a
Cahaba white vetch	1.31a	1.28a
George black medic	1.39a	1.31a
Barley	1.40a	1.34a
Spring wheat	1.37a	1.29a
LSD (0.05)	0.13	0.10
CV (SE/MEAN)%	3.00	2.65

*means within columns followed by different letters are significantly different ($p<0.05$)

Legume Flowering and Pod Set Dates in 1991

George black medic began flowering around 7/18/91 (44 days after emergence) while Indianhead lentil, Cahaba white vetch, and Austrian winterpea began flowering around 7/26/91 (53 days after emergence). Seed pods on all legume species had matured by 8/23/91 (81 days after emergence).

Estimating Green Manure ET by Measurements of Plant Height

One minor focus of this study was to assess the potential of using plant height measurements to estimate legume green manure evapotranspiration. Demonstration of a strong relationship between legume ET and plant height might provide dryland growers with a simple management tool that would allow them to estimate legume water use without resorting to *in situ* assessment of soil water status. In this light, the relationship between ET and plant height was examined by linear regression. Results from 1990, 1991, and pooled years are fit to an equation of the form $y=a+bx$.

In 1990 and 1991, a strong relationship was found between Austrian winterpea evapotranspiration and plant height; R^2 values of 1990 and 1991 ET vs. plant height regressions are 0.97 and 0.97, respectively (Fig. 40). When 1990 and 1991 results are pooled, the R^2 value of the association between ET and plant height drops to 0.85.

The 1990, 1991, and 1990/1991 Indianhead lentil ET vs. plant height regressions all exhibit high R^2 values; 0.95, 0.99, and 0.96, respectively (Fig. 41).

High R^2 values are found in 1990 and 1991 yellow sweetclover ET vs. plant height regressions, 0.95 and 0.96, respectively (Fig. 42). A slightly lower R^2 value, 0.89, is found when 1990 and 1991 results are combined.

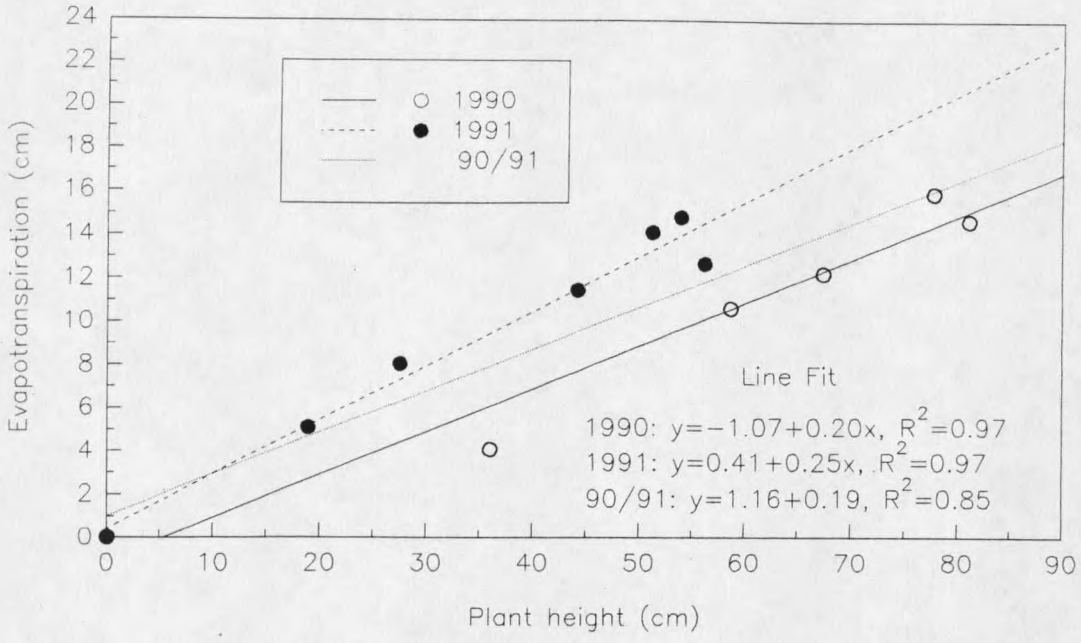

Fig. 40. Austrian winterpea 1990, 1991, and 1990/1991 ET vs. plant height regressions.

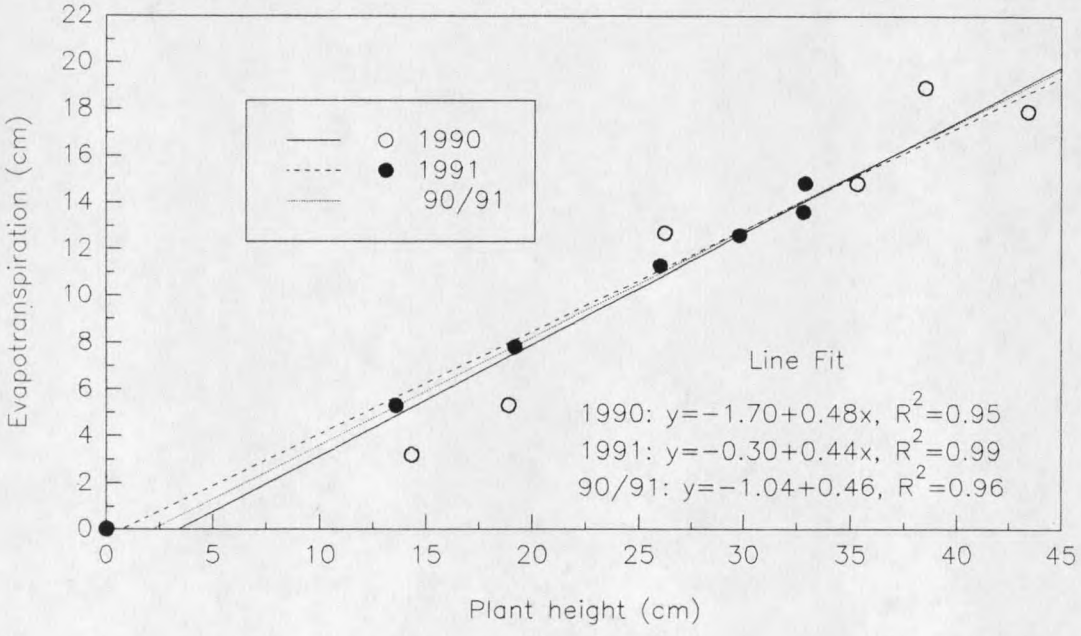

Fig. 41. Indianhead lentil 1990, 1991, and 1990/1991 ET vs. plant height regressions.

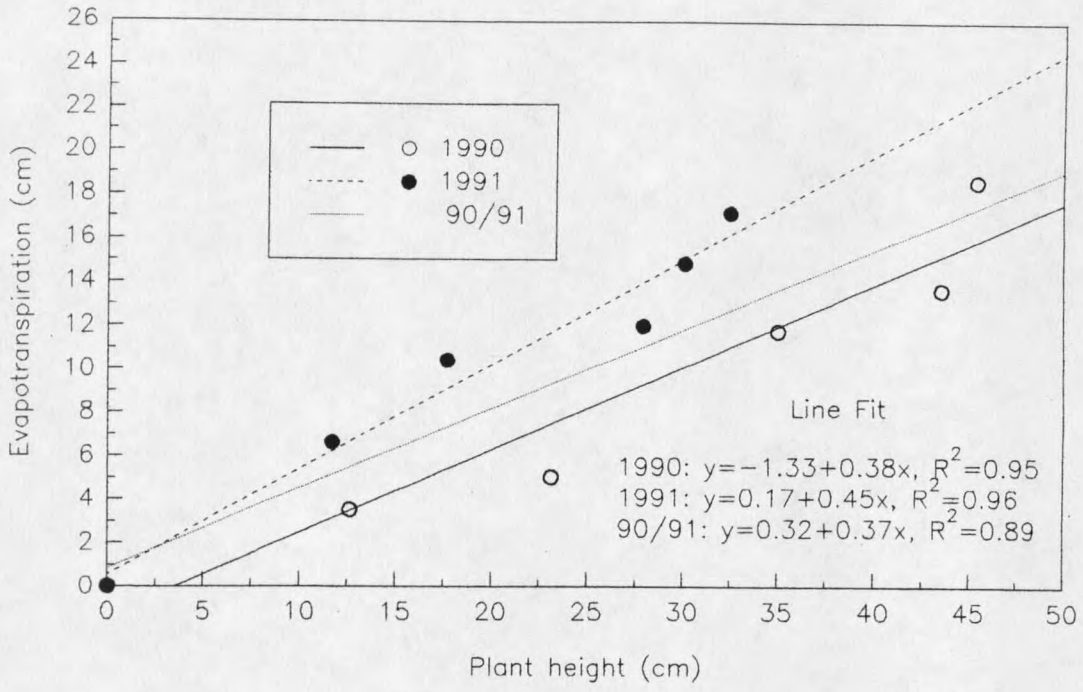

Fig. 42. Yellow sweetclover 1990, 1991, and 1990/1991 ET vs. plant height regressions.

High R^2 values of 0.95 and 0.91 are found in 1990 and 1991 Cahaba white vetch ET vs. plant height regressions, respectively (Fig. 43). Combination of 1990 and 1991 results produces a slightly weaker association with an R^2 value of 0.86.

R^2 values of 1990 and 1991 George black medic ET vs. plant height regression lines are 0.90 and 0.98, respectively (Fig. 44). A strong association between ET and plant height is also found in the 1990/1991 regression with an R^2 of 0.92.

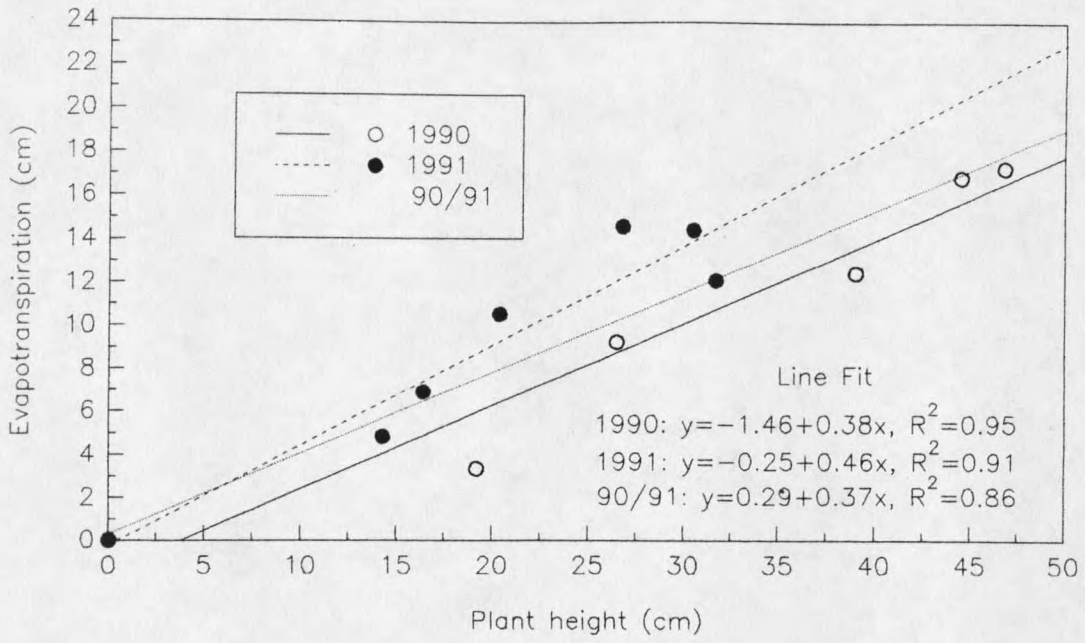

Fig. 43. Cahaba white vetch 1990, 1991, and 1990/1991 ET vs. plant height regressions.

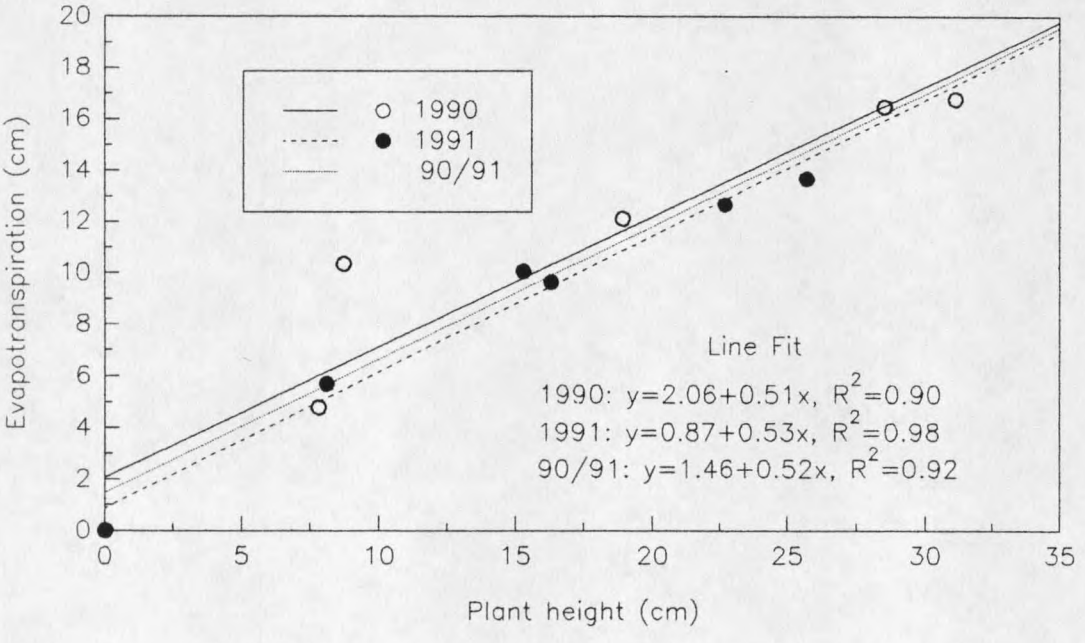

Fig. 44. George black medic 1990, 1991, and 1990/1991 ET vs. plant height regressions.

Chapter 5

DISCUSSION

Using Plant Height Measurements to Estimate ET

Legume evapotranspiration vs. plant height regressions reveal strong associations between ET and plant height over individual seasons: R^2 values of single-year regressions range from 0.90 to 0.99. When 1990 and 1991 results are pooled, R^2 values generally decline, suggesting that variation in edaphic and climatic conditions influences evapotranspiration. However, 1990/1991 ET vs. plant height associations are still fairly strong: R^2 values of pooled regressions range from 0.85 to 0.96. In this light, pooled regressions may provide reasonable models of ET vs. plant height relationships that could be used to estimate legume water use.

Poor Legume Performance in 1991

Relative to 1990 results, all legumes performed poorly in 1991. All 1991 logistic fits of canopy biomass accumulation over time, canopy nitrogen accumulation over time, and N_2-fixation over time approach lower limits than 1990 curves (Figs. 1-5, 8-12, 15-19). All 1991 average ET efficiencies (in terms of canopy biomass accumulation, canopy nitrogen accumulation, and N_2-fixation) were lower than 1990 values (Tables 1-3). Relative to 1990

regressions of canopy biomass accumulation vs ET and canopy N accumulation vs. ET , additional evapotranspiration was associated with smaller yield increases in 1991 (Figs. 26-30). Additionally, relative to 1991 performance, increased ET was associated with more N_2-fixation by Austrian winterpea and yellow sweetclover in 1990 (Figs. 26 and 28). Lastly, combination of 1990 and 1991 results in canopy biomass accumulation vs. ET, canopy nitrogen accumulation vs. ET, and N_2-fixation vs. ET regressions generally produced lower R^2 values than found in single-year regressions (Figs. 26-30)

Large differences between 1990 and 1991 findings may be the result of varying transpirational demand as predicted by de Wit's equation [4] (1958). However, the evaporation and transpiration components of ET were not isolated in this study and, thus, de Wit's equation cannot be used to normalize results. Nonetheless, it does appear that transpirational demand was slightly greater in 1991. 1990 E_e, pan evaporation over the growing season, was 68 mm d^{-1}. In 1991, E_e was slightly greater, 74 mm d^{-1}. This variation in transpirational demand suggests the potential usefulness of separating transpiration from evaporation in future studies of legume water use efficiency.

In 1991, biomass production by Austrian winterpea, Indianhead lentil, Cahaba white vetch, and George black medic began to plateau at the end of July, 50 to 60 days

after emergence (Figs. 1-4). This phenomenon is contrasted by 1990 legume perfomance where biomass increases continued for a much longer interval after emergence; up to 106 days in the case of George black medic (Figs. 1-5). The shorter duration of legume growth in 1991 might reveal vulnerability of these species to transient drought: total precipitation over the month of July in 1991 was only 1.17 cm. In 1990, total July precipitation was 3.28 cm. In response to a dry July, perhaps Austrian winterpea, Indianhead lentil, Cahaba white vetch, and Indianhead lentil moved from vegetative states to reproductive modes. This possibility is supported by the observation that declining biomass increases at the end of July coincided with the onset of flowering. The apparent indeterminancy of Austrian winterpea, Indianhead lentil, Cahaba white vetch, and George black medic flowering may prevent these green manures from excessively reducing soil water content in a drought year.

While total yellow sweetclover biomass accumulation declined from 1990 to 1991, this decline was smaller than reductions in yield displayed by the four other legumes (Figs. 1-5). This phenomenom may be a manifestation of yellow sweetclover's biennial habit. As a biennial, yellow sweetclover could not move to a reproductive mode in response to drought.

Unlike the five legumes studied, spring wheat and barley performed similarly in 1990 and 1991 (Figs. 6, 7, 13,

and 16). Perhaps spring wheat and barley are more tolerant of transient drought.

Poor legume performance in 1991 may have been the result of lower soil-N fertility. When averaged across all legume plots, both emergence nitrate fertility and nitrate use to the 107 cm depth increment were significantly greater ($p<0.05$) in 1990 (Table 13). Other researchers have found that inorganic-N can make significant contributions to legume growth. In a gravel-culture study, Allos and Bartholomew (1959) found positive yield responses associated with additions of inorganic nitrogen to soybean, alfalfa, sweetclover, Ladino clover (*Trifolium repens* L.), and birdsfoot trefoil (*Lotus corniculatus* L.). Harper (1974) found that optimum yields of soybean (*Glycine max* L. Merr.) required both soil and symbiotic sources of nitrogen. However, Semu and Hume (1979) reported that soybean yield responses to N-fertilizer were limited to sites where soybeans had never been cropped. At sites where soybeans had been frequently cropped, they found that N_2-fixation could support maximum yields. Semu and Hume's findings suggest that the efficiency of N_2-fixation increases as edaphic *Rhizobium* populations increase through repeated legume cropping. Though nodulation was observed in all legume plots in both 1990 and 1991, *Rhizobium* populations may have been below optimal levels. Lastly, perhaps July drought caused legumes to slough nodules.

Ranking Legume Performance

The ideal measures of relative legume performance are those that assess the relationship between legume N_2-fixation and water use. Along this line of reasoning, this study has included calculation of legume ET efficiencies in terms of N_2-fixation and development of curvilinear regressions of N_2-fixation vs. ET. These measures describe net additions of nitrogen to agroecosystems and the efficiency with which legumes make those additions.

Normally, one would claim that measures of legume performance employing N_2-fixation as a yield factor are more robust than measures of relative legume performance that employ other yield factors, i.e. canopy biomass accumulation or canopy nitrogen. When canopy biomass accumulation and canopy nitrogen accumulation are employed as yield factors, differences in ET efficiencies and yield vs. ET relationships may stem from varying abilities of legumes to incorporate soil nitrogen.

However, difficulties were encountered in this study when estimates of N_2-fixation were incorporated into measures of water use efficiency. While ET efficiencies in terms of canopy biomass accumulation and canopy nitrogen accumulation were averaged over six harvest dates in 1990 (Table 1), ET efficiencies in terms of N_2-fixation were averaged over only four harvest dates as there were only four 1990 harvest dates where all legume species generated

positive estimates of N_2-fixation (Table 3). In 1991, ET efficiencies in terms of N_2-fixation were averaged over only two harvest dates (Table 3). In this fashion, negative estimates of N_2-fixation reduced the robustness of measures of relative legume performance where N_2-fixation was used as a yield factor.

Negative estimates of N_2-fixation created similar problems in N_2-fixation vs ET regressions. George black medic and Cahaba white vetch produced only two positive estimates of N_2-fixation apiece in 1991; thus N_2-fixation vs. ET curves were not generated for these two species. In other regressions, zero values were substituted for negative estimates.

Negative estimates of N_2-fixation are a physical impossibility and can be interpreted in two ways: 1. at sample dates where negative estimates were obtained, legumes were not fixing N_2 2. spring wheat was not an appropriate non-fixing species for estimating legume N_2-fixation, i.e. N_2-fixation was occurring at sample dates where estimates were negative but spring wheat did not allow detection of this activity; possibly because spring wheat grew faster than legumes early in the growing season. Future estimates of green manure N_2-fixation may require use of legume isolines that are non-fixers. This approach has been employed to estimate N_2-fixation by soybean and alfalfa (Henson and Heichel, 1984).

In view of the problems encountered with estimates of N_2-fixation, measures that employ canopy biomass accumulation or canopy nitrogen accumulation as yield terms assume greater importance in attempts to rank the ET efficiencies and yield versus ET relationships of the five legume species studied. However, as mentioned earlier, use of these measures is problematic: differences in biomass production or nitrogen accumulation could be the result of varying abilities of legumes to incorporate soil nitrogen. With this caveat in mind, a discussion of NO_3-N use in legume plots is appropriate.

In 1991, NO_3-N use was statistically similar among all legume plots (Table 15). Assumuing that NO_3 leaching and denitrification were similar in all plots, it appears that differences in canopy biomass production and canopy nitrogen accumulation were not the result of varying NO_3 uptake.

In 1990, NO_3-N use in yellow sweetclover, Cahaba white vetch, and George black medic plots was statistically similar (Table 14). Once again, one could assume that differences in canopy biomass accumulation and canopy nitrogen accumulation among these three species were not the result of varying NO_3 uptake. Additionally, high NO_3-N use was found in 1990 Indianhead lentil plots while low NO_3-N use was found in Austrian winterpea plots. In 1990, Indianhead lentil ET efficiencies were generally poor while Austrian winterpea performed well. In this case,

differences in ET efficiency do not appear to be associated with differences in NO_3 uptake (assuming, once again, that NO_3 leaching and denitrification were similar in Austrian winterpea and Indianhead lentil plots).

Since soil tests reveal no important differences in NO_3-N use between legume plots, it appears that measures of ET efficiency and yield vs. ET regressions that employ canopy biomass accumulation or canopy nitrogen accumulation as yield terms represent accurate assessments of the efficiency with which legumes assimilate symbiotic nitrogen. In this light, these measures will be combined with measures based on N_2-fixation to rank the five legume species examined.

In 1990, only Austrian winterpea exhibited consistently high performance. Average 1990 Austrian winterpea ET efficiencies (in terms of canopy biomass accumulation, canopy nitrogen accumulation, and N_2-fixation) were equivalent or superior ($p<0.05$) to efficiencies of all other species (Tables 1-3). In 1990 pair-wise comparisons of regressions, Austrian winterpea regression lines (canopy biomass accumulation vs. ET, canopy nitrogen accumulation vs. ET, and N_2-fixation vs. ET) were coincident with or displaced above ($p<0.05$) all other regression lines (Figs. 31, 34, and 37).

Regression analyses from 1990 reveal that yellow sweetclover, Cahaba white vetch, George black medic, and

Indianhead lentil performed similarly as a group. All pair-wise comparisons among their canopy biomass accumulation vs. ET and N_2-fixation vs. ET regression lines were coincident (Figs. 31 and 37). Among canopy nitrogen accumulation vs. ET regressions, all pair-wise comparisons of Cahaba white vetch, George black medic, and yellow sweetclover regression lines were coincident (Fig. 34).

Average 1990 ET efficiencies also reveal that Indianhead lentil, yellow sweetclover, Cahaba white vetch, and George black medic performed similarly. In terms of canopy biomass accumulation, average ET efficiencies of the following triplets were statistically similar: Indianhead lentil/yellow sweetclover/Cahaba white vetch and Indianhead lentil/yellow sweetclover/George black medic (Table 1). In terms of canopy nitrogen accumulation, average ET efficiencies of the following pairs were statistically similar: Indianhead lentil/George black medic, yellow sweetclover/George black medic, and yellow sweetclover/Cahaba white vetch (Table 2). Lastly, in terms of N_2-fixation, average ET efficiencies of the following legume associations were statistically similar: Indianhead lentil/yellow sweetclover/George black medic and yellow sweetclover/Cahaba white vetch (Table 3).

In 1991, both Austrian winterpea and Indianhead lentil displayed similar performance. All Indianhead lentil regression lines (canopy biomass accumulation vs. ET, canopy

N accumulation vs. ET, and N_2-fixed vs. ET) were coincident with Austrian winterpea regression lines (Figs. 32, 35, and 38). Additionally, all average ET efficiencies (in terms of canopy biomass accumulation, canopy nitrogen accumulation, and N_2-fixation) of Austrian winterpea and Indianhead lentil were statistically similar (Tables 1-3).

Both Austrian winterpea and Indianhead lentil also exhibited consistently strong performance in 1991. Austrian winterpea and Indianhead lentil canopy biomass vs. ET regression lines were displaced above ($p<0.05$) Cahaba white vetch and George black medic regression lines (Fig. 32). Similarly, 1991 Austrian winterpea and Indianhead lentil canopy N accumulation vs. ET regression lines were displaced above ($p<0.05$) Cahaba white vetch and George black medic regression lines (Fig. 35). In terms of canopy biomass accumulation and nitrogen accumulation, average ET efficiencies of Austrian winterpea and Indianhead lentil were statistically superior ($p<0.05$) to average ET efficiencies of all other species (Tables 1 and 2). Lastly, in terms of N_2-fixation, the average ET efficiency of Austrian winterpea was statistically superior ($p<0.05$) to the average ET efficiencies of Cahaba white vetch and George black medic while the average ET efficiency of Indianhead lentil was statistically similar to the average ET efficiencies of yellow sweetclover and Cahaba white vetch

and superior ($p<0.05$) to the average ET efficiency of George black medic (Table 3).

Regression analyses from 1991 reveal that yellow sweetclover, Cahaba white vetch, and George black medic performed similarly as a group in 1991. All pair-wise comparisons among their canopy biomass accumulation vs. ET and canopy nitrogen accumulation vs. ET regression lines were coincident (Figs. 32 and 35).

Average ET efficiencies also reveal that yellow sweetclover, Cahaba white vetch, and George black medic performed similarly in 1991. In terms of canopy biomass accumulation, the average ET efficiencies of yellow sweetclover, Cahaba white vetch, and George black medic were statistically similar (Table 1). In terms of canopy nitrogen accumulation, the average ET efficiencies of yellow sweetclover and Cahaba white vetch were statistically similar while the average ET efficiencies of Cahaba white vetch and George black medic were similar (Table 2). Lastly, in terms of N_2-fixation, the average ET efficiencies of yellow sweetclover and Cahaba white were statistically similar while the average ET efficiencies of Cahaba white vetch and George black medic were statistically similar (Table 3).

When 1990 and 1991 results were combined in regressions of canopy biomass accumulation vs. ET, canopy nitrogen accumulation vs. ET, and N_2-fixation vs. ET, few differences

were found between species. Among 1990/1991 canopy biomass vs. ET and canopy nitrogen accumulation vs. ET regressions, all pair-wise comparisons of regression lines were coincident (Figs. 33 and 36). Among 1990/1991 N_2-fixation vs. ET regressions, the Austrian winterpea regression line was displaced above ($p<0.05$) the Indianhead lentil regression line (Fig. 38).

With respect to relative rankings of the legumes studied, the following summmary statements can be made. When 1990 and 1991 results were combined in regression analyses, no consistent differences between species were found. However, in light of the variation observed between 1990 and 1991 results, it is not surprising that their combination eliminated the differences found in individual years. Thus, combined results cannot be viewed with great weight and relative rankings should be confined to individual years. Indianhead lentil, yellow sweetclover, Cahaba white vetch, and George black medic performed similarly in 1990 while Austrian winterpea exhibited slightly better performance. In 1991, yellow sweetclover, Cahaba white vetch, and George black medic performed similarly while Austrian winterpea and Indianhead lentil exhibited slightly better performance.

Chapter 6

SUMMARY AND CONCLUSIONS

The objective of this study was to isolate differences in water use efficiency among five potential legume green manures, Austrian winterpea, Indianhead lentil, yellow sweetclover, Cahaba white vetch, and George black medic. Evapotranspiration and yield (in terms of canopy biomass accumulation, canopy nitrogen accumulation, and N_2-fixation) were measured over the 1990 and 1991 growing seasons at Bozeman, MT. These results were used to generate evapotranspiration efficiency values and yield vs. ET regressions. A secondary focus of this study was to examine the feasibility of using plant height measurements to estimate green manure ET.

Among the five legume green manures examined, Austrian winterpea exhibited consistently high performance over both growing seasons. In 1991, Indianhead lentil also performed well. Yellow sweetclover, Cahaba white vetch, and George black medic performed similarly over both growing seasons.

While this study detected differences in water use efficiency among the five legumes examined, these differences were relatively small. These results may be disheartening in that no glaringly superior legume species emerges. However, in another light, these findings suggest that dryland growers could choose from a range of different

legume species and still expect reasonable performance. In this fashion they could choose the legume that best suited their needs, e.g. in terms of seed availability, seed price, pest-resistance, etc.

Indirectly, this study suggests sensitivity of legumes to particular edaphic and climatic factors. Relatively poor performance of all legumes in 1991 coincided with higher transpirational demand, drought over the month of July, and lower NO_3-N soil fertility. Determining the relative impact of these factors was beyond the scope of this study. However, future implementation of cereal-legume rotations may require more careful examination of legume responses to transient drought and soil-N fertility.

Lastly, this study has demonstrated that measurements of plant height may provide dryland farmers with an easy method for estimating legume evapotranspiration. With further refinement, this method should allow farmers to terminate green manures at prescribed levels of water use.

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