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

A thesis submitted in partial fulfillment
of the requirments for the degree

of

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APPROVAL

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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;

$$R_T = \text{transpiration (g } H_2O) \text{ / dry matter production (g).} \quad [1]$$

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

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

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.

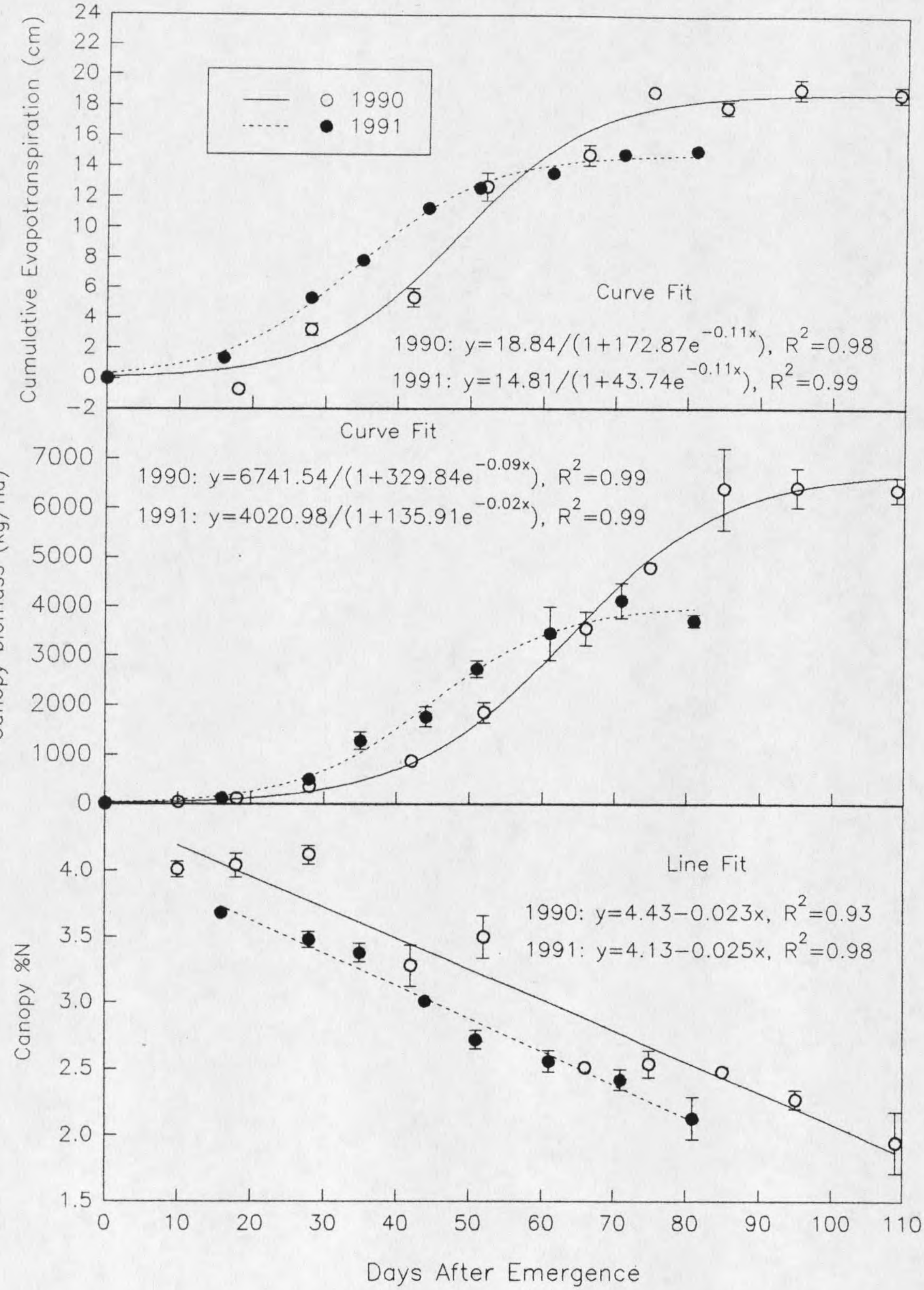

Fig. 1. Indianhead lentil ET, canopy biomass accumulation and canopy %N after emergence in 1990 and 1991. Values are means of 4 replicates ± standard error.