SPECTRAL REFLECTANCE OF CANOPIES OF RAINFED AND SUBSURFACE IRRIGATED ALFALFA

Dennis Wayne Hancock

University of Kentucky, hancock.dennis@gmail.com
ABSTRACT OF DISSERTATION

Dennis Wayne Hancock

The Graduate School
University of Kentucky
2006
SPECTRAL REFLECTANCE OF CANOPIES OF RAINFED AND SUBSURFACE IRRIGATED ALFALFA

ABSTRACT OF DISSERTATION

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Crop Science from the College of Agriculture, Food, and the Environment at the University of Kentucky

By
Dennis Wayne Hancock
Lexington, Kentucky

Director: Dr. Charles T. Dougherty,
Professor of Grassland Systems
Lexington, Kentucky

2006

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ABSTRACT OF DISSERTATION

SPECTRAL REFLECTANCE OF CANOPIES OF RAINFED AND SUBSURFACE IRRIGATED ALFALFA

The site-specific management of alfalfa has not been well-evaluated, despite the economic importance of this crop. The objectives of this work were to i) characterize the effects of soil moisture deficits on alfalfa and alfalfa yield components and ii) evaluate the use of canopy reflectance patterns in measuring treatment-induced differences in alfalfa yield. A randomized complete block design with five replicates of subsurface drip irrigation (SDI) and rainfed treatments of alfalfa was established at the University of Kentucky Animal Research Center in 2003. Potassium, as KCl, was broadcast on split-plots on 1 October 2004 at 0, 112, 336, and 448 kg K$_2$O ha$^{-1}$. In the drought year of 2005, five harvests (H1 - H5) were taken from each split-plot and from four locations within each SDI and rainfed plot. One day prior to each harvest, canopy reflectance was recorded in each plot. Alfalfa yield, yield components, and leaf area index (LAI) were determined. In 2005, dry matter yields in two harvests and for the seasonal total were increased (P<0.05) by SDI, but SDI did not affect crown density. Herbage yield was strongly associated with yield components but yields were most accurately estimated from LAI. Canopy reflectance within blue (450 nm), red (660 nm) and NIR bands were related to LAI, yield components, and yield of alfalfa and exhibited low variance (cv < 15%) within narrow (± 0.125 Mg ha$^{-1}$) yield ranges. Red-based Normalized Difference Vegetation Indices (NDVIs) and Wide Dynamic Range Vegetation Indices (WDRVIs) were better than blue-based VIs for the estimation of LAI, yield components, and yield. Decreasing the influence of NIR reflectance in VIs by use of a scalar (0.1, 0.05, or 0.01) expanded the range of WDRVI-alfalfa yield functions. These results indicate that VIs may be used to estimate LAI and dry matter yield of alfalfa within VI-specific boundaries.

KEYWORDS: Alfalfa; Subsurface Drip Irrigation; Leaf Area Index; Canopy Reflectance; Vegetation Index
SPECTRAL REFLECTANCE OF CANOPIES OF RAINFED AND SUBSURFACE IRRIGATED ALFALFA

By

Dennis Wayne Hancock

Dr. Charles Doughery
Director of Dissertation

Dr. Charles Doughery
Director of Graduate Studies

September 11, 2006
Date
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2006

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This work is devoted to my children, Ethan, Andy, and Logan, whom I hope are emboldened in their pursuit of dreams.
ACKNOWLEDGMENTS

The following dissertation is the sum of three years of research, wherein I have learned much. I gratefully acknowledge the contribution of my Dissertation Chair, Dr. Charles Dougherty, from whom I received much guidance, constructive criticism, and endless support. In addition, I appreciate the loan of equipment and advice from Drs. Egli, Mueller, Schwab, Shearer, and Stombaugh. I especially want to acknowledge the contribution of Dr. Shearer in aiding the development of the Multispectral Sensing and Subsurface Drip Irrigation Research Project at the Animal Research Center, from which I collected the bulk of the data in this dissertation. Further, I wish to thank Dr. David Williams and outside examiner, Dr. Larry Wells for their insights and guidance in the construction of this dissertation. I also wish to recognize the contributions of Mike Peters, Farm Manager at UK’s Animal Research Center at the Woodford County farm and the hard work of two student workers, Rob Eckman and David Marshall, during the summer of 2005.

In addition to the assistance above, I received tremendous support from my family. My wife, Stephanie, has been a great source of moral support during my pursuit of this dream. My sons, Ethan, Andy, and Logan have also provided much support and have served as a constant reminder of what the future holds. I also wish to extend my thanks for the support of my sisters and my wife’s family. However, one of the most important contributions to this effort was the love for the land and an appreciation for farming that my grandparents instilled in me.

Further, this work is the culmination of the lessons from many teachers, who are too numerous to name. But, it is important to me to acknowledge my high school Agriculture teacher, Dewayne Vinson, who steered my avid interest in Agriculture toward a vocation.

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CHAPTER 1: INTRODUCTION

1.1. BACKGROUND

Alfalfa (*Medicago sativa* L.) is one of the most important crops in the United States, ranking 3rd in both the area planted and estimated value (National Agricultural Statistics Service, 2006) (Table 1.1). Alfalfa has the highest yield potential and feed value of any perennial forage legume, which has earned it the title of “Queen of the Forages.” However, alfalfa requires intensive management and is expensive to establish, grow and maintain as it yields the highest productivity only on deep, fertile, and well-drained soils (Undersander et al., 2004). Its perennial nature requires a balance between the nutritive quality, productivity and stand longevity, as these parameters are dependent on harvest frequency (Sheaffer and Marten, 1990). Soil fertility, specifically the amount of plant available phosphorus (P) and potassium (K), are also critical to both yield and stand longevity (Berg et al., 2005). Annual applications are required when P or K are deficient, however, at some threshold level, the alfalfa stand is no longer capable of producing enough high-quality forage to warrant application of these nutrients.

1.2. GENERAL PROBLEM

Alfalfa producers have very few site-specific management (SSM) tools or methods. A significant volume of research has identified production issues that limit alfalfa yield, but only recently have researchers begun to evaluate how these limitations vary within fields.

Such SSM approaches could be especially advantageous to alfalfa producers in Kentucky. Much of the alfalfa production in Kentucky occurs on the fertile, phosphoritic limestone derived soils of the Bluegrass and Mississippi Plateau. In these soils, P is rarely limiting, but two primary limitations to yield remain: soil moisture and K availability. Variations in soil depth and the resulting variation in available soil moisture affect alfalfa productivity (e.g., Karlen et al.,
Table 1-1. Area, productivity, and value of the five top agricultural crops in the United States in 2005.†

<table>
<thead>
<tr>
<th>Crop</th>
<th>Area Planted‡</th>
<th>Total Productivity</th>
<th>Total Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>--- 1000 ha ---</td>
<td>---1000 Mg---</td>
<td>$, Billion</td>
</tr>
<tr>
<td>Corn</td>
<td>33,087</td>
<td>282,260</td>
<td>21.04</td>
</tr>
<tr>
<td>Soybeans</td>
<td>29,195</td>
<td>83,999</td>
<td>16.93</td>
</tr>
<tr>
<td>Alfalfa</td>
<td>9,061</td>
<td>68,738</td>
<td>7.32</td>
</tr>
<tr>
<td>Wheat</td>
<td>23,160</td>
<td>57,280</td>
<td>7.14</td>
</tr>
<tr>
<td>Cotton</td>
<td>5,765</td>
<td>5,201</td>
<td>5.57</td>
</tr>
</tbody>
</table>

† Adapted from National Agricultural Statistics Service, 2006.
‡ Crop data represent only grain (corn and wheat), oilseed (soybean), fiber (cotton), or hay (alfalfa) production.
1990; Tolk et al., 1998). Similarly, K deficiency affects both alfalfa yield and the life of established stands, especially when P levels are sufficient (Berg et al., 2005). This gives rise to the first hypothesis of this dissertation, which is that strategies that provide site-specific water supplementation or K fertilization within a field have the potential to improve the productivity of alfalfa.

To assess these management strategies, alfalfa producers need a tool that monitors yield variation within their fields. Relatively accurate sensors to monitor mass flow and crop moisture in harvesters have been commercially available since the mid-1990s (Reyns et al., 2002). In addition, sensors that measure crop canopy reflectance are being used to predict crop yield, yield potential, crop health, and nutritional status. An example is in the site-specific sensing of nitrogen (N) need in wheat and site-specific application of N, which improves N use efficiency and grain yield (Raun et al., 2002).

The indices of canopy reflectance could potentially be used as proxies for vegetative biomass, which often is highly correlated with grain yield (e.g. Stone et al., 1996; Ma et al., 2001; Shanahan et al., 2001). This leads to the second hypothesis of this dissertation, which is that indices of canopy reflectance provided by currently available, multispectral sensors can be used to predict spatial distribution patterns of alfalfa biomass and other canopy variables of significance to alfalfa producers.

1.3. SPECIFIC PROBLEMS

Addressing these hypotheses in the context of alfalfa production in Kentucky first requires a better understanding of how spatial variation in the dominant limiting factors of soil moisture stress and plant available K contribute to spatial variation in alfalfa productivity and longevity. A substantial body of work has addressed the overall effects of these factors on alfalfa yield and stand longevity (e.g., Lanyon and Smith, 1985; Sheaffer et al., 1988). However, the research on supplementing soil moisture for alfalfa production in the southeastern U.S. has been inconclusive. It is unclear whether or not some areas of the field would be more responsive to irrigation than others. Similarly, it is
unknown whether K fertilization rates should differ in those specific sites where soil moisture is supplemented (Sheaffer et al. 1986).

Secondly, few studies have specifically addressed the physiological responses that influence or alter spectral reflectance patterns of alfalfa canopies on a spatial basis. This is especially important because of the physiological plasticity of alfalfa in adapting to limiting resources (e.g., Lanyon and Smith, 1985; Sheaffer et al., 1988). Further, studies that have measured alfalfa canopy reflectance have used spectrophotometers rather than on-the-go optical sensors. More research is required to assess the potential for canopy reflectance measured with commercially available multispectral sensors, to assess variables relevant to alfalfa production (e.g., yield, yield components, and stand variables). From this foundation, a determination can be made as to whether or not site-specific approaches to soil moisture supplementation and K fertilization can be successfully employed in alfalfa production.

1.4. OBJECTIVES

Therefore, the objectives of this work are to:

i. Examine the feasibility of supplementing soil moisture to increase alfalfa yield without reducing stand longevity;

ii. Determine how variation in soil moisture deficits and K fertility affect alfalfa and alfalfa yield components, with specific regard to the physiological responses that may influence or alter spectral reflectance patterns;

iii. Characterize variations in alfalfa canopy reflectance, as measured by “field-ready” multispectral sensors, to identify specific wave bands that exhibit the strongest relationship with alfalfa yield, yield components, and canopy variables;

iv. Evaluate vegetation indices that use these wavelength bands for their strength and robustness in their relationships to the LAI, yield components, and yield of alfalfa.
1.5. ORGANIZATION OF DISSERTATION

The various elements of this research are quite diverse, but are central to any investigation of the relations between canopy reflectance and alfalfa characteristics. To present this research in the most succinct and clear way, the following chapters address the preceding objectives in order. Chapter 2 presents a literature review on the issues within each of these objectives. Chapters 3 - 6 individually present the findings of the work on each objective and are written as stand-alone publications. In chapter 7, a summary of the findings of the research within the three objectives is discussed in the context of the general problem. Finally, a concluding statement highlights the findings, discusses the overall potential, and outlines the implications for further research.
CHAPTER 2: LITERATURE REVIEW

To begin to develop site-specific management strategies for alfalfa, simultaneous consideration must be given to those issues that contribute to spatial variation in alfalfa productivity and persistence and should establish how that variation may be integrated into management tactics. This requires research at the intersection between the traditional agronomic themes of rectifying soil moisture and K deficiencies and the fundamental physical and biological properties of leaves and canopies. The premise is that a snapshot of this dynamic merger can be captured, queried for specific data, provide information pertaining to an issue of interest, and aid site-specific management decisions. Connecting these diverse themes requires the understanding of the contributions of each aspect to the overall picture. Therefore, this review of the literature is divided into four sections, each outlining what is known about specific aspects of this effort.

2.1. SITE-SPECIFIC IRRIGATION

Overview

It is clear that water-holding and supply capacities of the soil are the largest source of yield variation within a field (e.g., Carlson, 1990; Mulla et al., 1992; Dale and Daniels, 1995). Soil depth, or effective plant-rooting depth, has been found to be significantly related to yield (Karlen et al., 1990; Tolk et al., 1998). The use of such soil characteristics as a basis for a SSM strategy has been pursued because variables such as soil depth remain stable over time, assuming proper conservation management. Yet, yield and rooting depth relationships are weather dependent (Swan et al., 1987) with higher correlations between yield and rooting depth in drier years (Timlin et al., 1998). The dynamic interaction between a temporally-stable/spatially-variable parameter (e.g., soil water-holding capacity) with a temporally-variable/spatially-stable parameter (e.g., climate) increases the complexity of interpreting spatial variations in yield. If
the dominating temporally-variable parameter of soil moisture could be held stable, yield potential could be approached in sites where soil depth had previously limited yield.

In this first section of the literature review, the potential to site-specifically irrigate alfalfa is explored. A review of alfalfa irrigation successes and failures are explored, particularly as they relate to alfalfa production in Kentucky and the southeastern U.S. Attention is focused on a relatively low-cost, micro-irrigation technique that may enable producers to irrigate alfalfa in specific sites.

**Irrigating Alfalfa**

Over 99% of the irrigated alfalfa haylands are west of the Mississippi River (National Agricultural Statistics Service, 2004). The success of alfalfa production in these western states is largely due to the high evapotranspirative demand, to which alfalfa yield increases linearly when soil moisture is sufficient (Bauder et al., 1978; Undersander, 1987; Grimes et al., 1992; and Saeed and El-Nadi, 1997). Many studies have shown the benefits of irrigating alfalfa when soil moisture is limiting (e.g., Kisselbach et al., 1929; Lucey and Tesar, 1965; Carter and Sheaffer, 1983a; Undersander, 1987; Grimes et al., 1992; and Saeed and El-Nadi, 1997). Yet, providing supplemental irrigation to alfalfa is a controversial issue. One-third of all alfalfa acres in the U.S. were irrigated in 2002, which represented nearly 13% of the 22.4 million hectares (55.3 million acres) of irrigated crop land that year (National Agricultural Statistics Service, 2004). Further, alfalfa uses 90% more water during a growing season than does corn (Loomis and Wallinga, 1991). Given actual and forecasted water shortages, many in the western U.S. question the use of water for the production of a crop that is arguably a relatively inefficient user of water (Loomis and Wallinga, 1991; Natural Resources Defense Council, 2001). Others have begun to look for methods that increase the efficiency of this water use (Takele and Kallenback, 2001) (Table 2.1). Because of these issues, more efficient precision and micro-irrigation methods have gained recent interest.
Table 2-1. Observations of water use efficiency (WUE) for alfalfa.†

<table>
<thead>
<tr>
<th>Location</th>
<th>WUE</th>
<th>Irrigation Method‡</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>NM and NV</td>
<td>9 - 18</td>
<td>Surface</td>
<td>Sammis, 1981</td>
</tr>
<tr>
<td>N. Dakota</td>
<td>15.9</td>
<td>Surface</td>
<td>Bauder et al., 1978</td>
</tr>
<tr>
<td>Idaho</td>
<td>17.2</td>
<td>Surface</td>
<td>Wright, 1988</td>
</tr>
<tr>
<td>Texas</td>
<td>17.4</td>
<td>Surface</td>
<td>Bolger and Matches, 1990</td>
</tr>
<tr>
<td>Utah</td>
<td>14 - 22</td>
<td>Surface</td>
<td>Retta and Hanks, 1980</td>
</tr>
<tr>
<td>California</td>
<td>23.3</td>
<td>Surface</td>
<td>Grimes et al., 1992</td>
</tr>
<tr>
<td>Minnesota</td>
<td>30.1</td>
<td>Surface</td>
<td>Carter and Shaeffer, 1983a</td>
</tr>
<tr>
<td>S. Carolina</td>
<td>12.2</td>
<td>Surface</td>
<td>Rice et al., 1989</td>
</tr>
<tr>
<td>California</td>
<td>15.3</td>
<td>Surface</td>
<td>Hutmacher et al., 2001</td>
</tr>
<tr>
<td>California</td>
<td>18.8</td>
<td>SDI</td>
<td>Hutmacher et al., 2001</td>
</tr>
<tr>
<td>Coahuila, Mexico</td>
<td>10.7</td>
<td>Surface</td>
<td>Godoy-Avila et al., 2003</td>
</tr>
<tr>
<td>Coahuila, Mexico</td>
<td>20.1 - 24.7</td>
<td>SDI</td>
<td>Godoy-Avila et al., 2003</td>
</tr>
</tbody>
</table>

† Updated from Loomis and Wallinga, 1991.
‡ Irrigation method indicated as either surface (i.e., sprinkler or flood) or SDI (i.e., subsurface drip irrigation).
Irrigating Alfalfa in the Southeast

In contrast to the necessity of growing alfalfa on irrigated lands in the western U.S., supplementing rainfall to produce alfalfa in the Eastern U.S. has generally not been deemed necessary (Rice et al., 1989). Sporadic droughts, changes in risk aversion attitudes, and the potential to increase production on limited farmland has led to an increased interest in irrigating alfalfa in this region (Salim et al., 2005). However, studies on the feasibility of irrigating alfalfa in the southeastern USA produced mixed results with reports that irrigation substantially increased yield (Kilmer et al., 1960; Jones et al., 1974), did not affect yield (Morris et al., 1992), or increased disease and stand losses which resulted in yield decreases (Wahab and Chamblee, 1972; Rice et al., 1989). As a result, irrigating alfalfa in this region has been considered a marginally successful practice (Rice et al., 1989).

It remains unclear why stand losses were so prevalent under irrigation in the southeastern U.S. It is known that alfalfa plants under moisture stress store carbohydrates in the taproot at a much higher rate than do irrigated plants (Cohen et al., 1972). High night time temperatures have also been associated with a depletion of carbohydrate reserves and increased stand losses (Robison and Massenga, 1968). This led Rice et al. (1989) to speculate that carbohydrate reserves were depleted at a higher rate in irrigated alfalfa plants than in moisture stressed plants.

The situation may be more complex. Rice et al. (1989) noted that an increased disease pressure from both *Sclerotium rolfsii* Sacc. and *Colletrotrichum trifolii* Bain & Essary accompanied the irrigation treatment. Rice et al. (1989) did not specify the severity of the disease pressure and did not address plant available K levels or other soil characteristics. Morris et al. (1992) ruled out any interaction between irrigation treatment and differences in soil acidity. However, Sheaffer et al. (1986) showed that K fertilization, irrigation and harvest treatment interacted to affect alfalfa yield and stand response in Minnesota. Stand losses were greater in alfalfa harvested three times per season when irrigated, but these losses were offset somewhat if K was sufficient.
(Sheaffer et al., 1986). This reinforces earlier work that indicates that adequate plant available soil K maintains yields and stands and reduces disease susceptibility (Huber and Arny, 1985; Collins et al., 1986; Undersander et al. 2004; and Berg et al., 2005). It remains unclear, however, if the disadvantages to irrigating alfalfa in this region are endemic to the region or an artifact of surface-applied irrigation methods. More research is needed to determine if subsoil moisture exerts the same negative effect on stand longevity in the southeastern U.S. as surface moisture has exhibited.

**Subsurface Drip Irrigation**

Water conservation efforts have been the primary impetus for the development of alternative methods of irrigation, and interest in more efficient systems has increased internationally (Camp, 1998). Micro-irrigation systems, such as trickle or drip tubes and tapes, have gained popularity for fruit, vegetable, and nursery crop production. In contrast to sprinkler systems, these systems reduce evaporative losses at the soil surface by irrigating below the soil surface or in the rooting zone. Of the micro-irrigation systems, subsurface drip irrigation (SDI) has been the most popular with researchers and producers of grain, oilseed, and forage crops (Camp, 1998).

The American Society of Agricultural and Biological Engineers (ASABE) has defined SDI as the “application of water below the soil surface through emitters, with discharge rates generally in the same range as drip irrigation” (ASAE Standards, 1996). This unique ability to slowly apply water below the soil surface has significant advantages, particularly for alfalfa producers (Mead et al., 1992; Lamm, 2002; Lamm et al., 2002) (Table 2.2). Research findings, such as increased water use efficiency (WUE); the ability to use low-quality or waste water from other farm enterprises; improved weed control; decreased variable and fixed costs for smaller fields; the ability to continue irrigation before, during, and after harvest; the reduction in disease pressure; and the enhanced growth and yields of alfalfa produced are advantages that are especially relevant to
Table 2-2. Advantages of subsurface drip irrigation (SDI) relative to sprinkler and flood irrigation systems.†

<table>
<thead>
<tr>
<th>Advantage</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Soil and Water Issues</strong></td>
<td></td>
</tr>
<tr>
<td>More efficient water use‡</td>
<td>Improved WUE</td>
</tr>
<tr>
<td>Reduced/eliminated runoff/leaching</td>
<td>Application at the infiltration rate</td>
</tr>
<tr>
<td>Improved in-field application uniformity</td>
<td>Adaptive design aids uniformity</td>
</tr>
<tr>
<td>Possible to use degraded/waste water‡</td>
<td>Reduces human/animal contact with such waters</td>
</tr>
<tr>
<td>Reduced foliar burn‡</td>
<td>Less effect of low-quality water</td>
</tr>
<tr>
<td><strong>Cropping and Cultural Practices</strong></td>
<td></td>
</tr>
<tr>
<td>Enhanced growth and yield‡</td>
<td>Some evidence for yield improvement over surface application treatments</td>
</tr>
<tr>
<td>Improved plant health‡</td>
<td>Drier canopies led to less disease pressure</td>
</tr>
<tr>
<td>Improved fertilizer management</td>
<td>Opportunity for fertigation and greater nutrient use efficiency</td>
</tr>
<tr>
<td>Improved weed control‡</td>
<td>Lack of surface moisture reduces weed germination</td>
</tr>
<tr>
<td>Improved farm operation efficiency</td>
<td>Eliminates removal of irrigation prior to harvest or between crops</td>
</tr>
<tr>
<td>Continued irrigation while harvesting‡</td>
<td>Irrigation can continue prior to, during, and immediately after harvest</td>
</tr>
<tr>
<td><strong>System Infrastructure</strong></td>
<td></td>
</tr>
<tr>
<td>Automation</td>
<td>Easily automated for efficient control</td>
</tr>
<tr>
<td>Decreased energy costs</td>
<td>Operates at pressures much less than sprinkler irrigation</td>
</tr>
<tr>
<td>System integrity</td>
<td>Fewer mechanized parts and reduced corrosion</td>
</tr>
<tr>
<td>Design flexibility</td>
<td>Matching field shape/size, compensation for variations in slope</td>
</tr>
<tr>
<td>System longevity</td>
<td>Estimated system life of ca. 20 yrs.</td>
</tr>
</tbody>
</table>

† Summarized from Lamm, 2002.
‡ Issues of heightened relevance to alfalfa producers.
alfalfa production (Mead et al., 1992; Camp, 1998; Ayars et al., 1999; Alam et al., 2000; Alam et al., 2002a; 2002b; Lamm, 2002; and Godoy-Avilla et al., 2003).

However, SDI has significant disadvantages, particularly for alfalfa producers (Lamm, 2002) (Table 2-3). Leaks or obstructions are difficult to identify and may lead to non-uniform applications resulting in crop loss. More importantly, the cost of a SDI system is directly proportional to the area being irrigated, whereas the cost ha$^{-1}$ of center pivot or flood irrigation systems decreases as area increases (Lamm et al., 2002).

As such, the cost of irrigation systems has been cited as a major limitation to the use of irrigation for alfalfa production in the southeastern U.S. (Rice et al., 1989; Morris et al., 1992). Hancock et al. (2004) adapted a decision aid developed by Lamm et al. (2002) for comparing the economics of center pivot and SDI systems on row crops to compare these systems for use in alfalfa production (Fig. 2-1). Hancock et al. (2004) found that SDI was more profitable than center pivot systems in small fields, but the converse was true for fields larger than 15.6 ha (38.5 acres). That model compared only the cost of the installed systems and the conservative constraint that yield and water use efficiency (WUE) from the two systems would be equivalent (Hancock et al., 2004). However, several studies comparing SDI to surface application methods have shown that SDI produced higher yields and increased WUE (Mead et al., 1992; Alam et al., 2000; Alam et al., 2002a; 2002b; and Godoy-Avilla et al., 2003; Table 2.4). This analysis supports the contention that SDI will site-specifically supplement alfalfa production. The minimum irrigated area required to make site-specific SDI application economically feasible remains to be determined.

Another disadvantage is that SDI is not useful for irrigating alfalfa during establishment (Lamm, 2002). This is because SDI has a subsurface wetting pattern that provides little upward movement, particularly in coarse textured soils. Trout et al. (2005) evaluated distribution about a SDI tape in combinations of a number of sandy to silt loam soil types and soil moisture levels (Fig. 2-2). Expressing the lateral distance of the wetting front from the tapeline as a ratio to the vertical distance of the wetting front from the tapeline (horizontal:vertical),
Table 2-3. Disadvantages of subsurface drip irrigation (SDI) relative to sprinkler and flood irrigation systems.†

<table>
<thead>
<tr>
<th>Disadvantage</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Soil and Water Issues</strong></td>
<td></td>
</tr>
<tr>
<td>Smaller wetting pattern‡</td>
<td>Wetted area may be too small, limiting system capacity</td>
</tr>
<tr>
<td>Monitoring/evaluating irrigation events</td>
<td>Applications are largely unseen, uniformity is difficult to evaluate.</td>
</tr>
<tr>
<td>Soil infiltration/application rates</td>
<td>Emitter discharge rates can exceed infiltration and redistribution rates of some soils.</td>
</tr>
<tr>
<td>Soil surface moisture is limited‡</td>
<td>SDI for germinating and sustaining seedlings is difficult and inefficient</td>
</tr>
<tr>
<td><strong>Cropping and Cultural Practices</strong></td>
<td></td>
</tr>
<tr>
<td>Less tillage options</td>
<td>Tillage depth is limited</td>
</tr>
<tr>
<td>Restricted root development</td>
<td>Root zones are smaller and often limited to wetted area</td>
</tr>
<tr>
<td>Row spacing/crop rotation‡</td>
<td>Tape spacing is fixed and may not adequately accommodate variations in plant spacing</td>
</tr>
<tr>
<td><strong>System Infrastructure</strong></td>
<td></td>
</tr>
<tr>
<td>Costs‡</td>
<td>High initial investment cost, no salvage value</td>
</tr>
<tr>
<td>Filtration needs</td>
<td>Water filtration is critical to prevent plugged emitters and to maintain uniformity</td>
</tr>
<tr>
<td>Maintenance issues‡</td>
<td>Leaks/obstructions are difficult to identify and fix</td>
</tr>
<tr>
<td>Operational issues</td>
<td>Monitoring system dynamics is more complex than sprinkler or flood irrigation systems</td>
</tr>
<tr>
<td>Design complexity</td>
<td>SDI systems are adaptive to the site and require more expertise and training.</td>
</tr>
<tr>
<td>Abandonment issues</td>
<td>Concerns about recovery of plastic when abandoned or replaced</td>
</tr>
</tbody>
</table>

† Summarized from Lamm, 2002.
‡ Issues of heightened relevance to alfalfa producers.
Fig. 2-1. The modeled relationship between whole field area and the advantage of SDI compared to center pivot demonstrates that a SDI system would be more cost-effective than center pivot sprinkler systems when fields are smaller than 15.6 ha. (Adapted from Lamm et al., 2002).

\[ y = 95.6 - 14.0x + 0.70x^2 - 0.013x^3 \]
Table 2-4. Research findings on alfalfa yield response to subsurface drip irrigation at various depths and emitter spacings.

<table>
<thead>
<tr>
<th>Source (Location and Soil Type)</th>
<th>Depth</th>
<th>Emitter Spacing†</th>
<th>Year</th>
<th>Yield</th>
<th>Relative Yield‡</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alam et al., 2000; 2002a; 2002b§</td>
<td>0.46</td>
<td>0.76 x 0.61</td>
<td>1999</td>
<td>10.0</td>
<td>86</td>
</tr>
<tr>
<td>(Kansas, sandy loam)</td>
<td>0.30</td>
<td>1.0 x 0.61</td>
<td>1999</td>
<td>11.3</td>
<td>98</td>
</tr>
<tr>
<td></td>
<td>0.46</td>
<td>1.0 x 0.61</td>
<td>1999</td>
<td>11.6</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>0.30</td>
<td>1.5 x 0.61</td>
<td>1999</td>
<td>10.6</td>
<td>92</td>
</tr>
<tr>
<td>Sprinkler Irrigated Control</td>
<td>0.46</td>
<td>1.5 x 0.61</td>
<td>1999</td>
<td>10.3</td>
<td>89</td>
</tr>
<tr>
<td></td>
<td>0.30</td>
<td>1.0 x 0.61</td>
<td>2000</td>
<td>20.2</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>0.46</td>
<td>0.76 x 0.61</td>
<td>2000</td>
<td>19.0</td>
<td>94</td>
</tr>
<tr>
<td></td>
<td>0.30</td>
<td>1.0 x 0.61</td>
<td>2000</td>
<td>19.4</td>
<td>96</td>
</tr>
<tr>
<td></td>
<td>0.46</td>
<td>1.5 x 0.61</td>
<td>2000</td>
<td>16.1</td>
<td>80</td>
</tr>
<tr>
<td>Sprinkler Irrigated Control</td>
<td>0.46</td>
<td>1.5 x 0.61</td>
<td>2000</td>
<td>17.9</td>
<td>88</td>
</tr>
<tr>
<td>Hutmacher et al., 1992, Ayars et al. 1999</td>
<td>0.41</td>
<td>1.02 x 1.02</td>
<td>1991</td>
<td>-</td>
<td>100</td>
</tr>
<tr>
<td>(California, silty clay)</td>
<td>0.41</td>
<td>2.04 x 1.02</td>
<td>1991</td>
<td>-</td>
<td>83</td>
</tr>
<tr>
<td></td>
<td>0.41</td>
<td>1.02 x 1.02</td>
<td>1992</td>
<td>-</td>
<td>67</td>
</tr>
<tr>
<td></td>
<td>0.41</td>
<td>2.04 x 1.02</td>
<td>1992</td>
<td>-</td>
<td>98</td>
</tr>
<tr>
<td>Furrow Irrigated Control</td>
<td>0.41</td>
<td>1.02 x 1.02</td>
<td>1992</td>
<td>-</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>0.41</td>
<td>2.04 x 1.02</td>
<td>1992</td>
<td>-</td>
<td>84</td>
</tr>
<tr>
<td>Furrow Irrigated Control</td>
<td>0.67</td>
<td>1.02 x 1.02</td>
<td>1995</td>
<td>22.2</td>
<td>100</td>
</tr>
<tr>
<td>Hutmacher et al., 2001 (California, silty clay)</td>
<td>0.67</td>
<td>2.04 x 1.02</td>
<td>1995</td>
<td>18.2</td>
<td>82</td>
</tr>
<tr>
<td></td>
<td>0.67</td>
<td>1.02 x 1.02</td>
<td>1996</td>
<td>19.7</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>0.67</td>
<td>2.04 x 1.02</td>
<td>1996</td>
<td>16.4</td>
<td>83</td>
</tr>
<tr>
<td>Furrow Irrigated Control</td>
<td>0.50</td>
<td>1.0 x 0.20</td>
<td>2001</td>
<td>16.8 a</td>
<td>100</td>
</tr>
<tr>
<td>Godoy-Avila et al., 2003 (Coahuila, Mexico, clayey sand)</td>
<td>0.50</td>
<td>0.76 x 0.61</td>
<td>2001</td>
<td>12.9 b</td>
<td>77</td>
</tr>
</tbody>
</table>

† Emitter spacing denotes the spacing between lateral lines x the spacing of emitters on the tapeline.
‡ In some sources, only the percentage of maximum yield (relative yield) was published. For comparison, relative yields were calculated for all yield values.
§ Data from Alam et al. (2000; 2002a; 2002b) are from a demonstration plot where treatments were not replicated.
Fig. 2-2. A theoretical cross-section exhibiting the wetting fronts of three horizontal:vertical distribution patterns (1:1, 0.88:1, and 0.75:1) relative to a horizon perpendicular to the centered SDI tapeline (Adapted from Trout et al., 2005).
Trout et al. (2005) demonstrated that the shape of the wetted area is affected by interactions between soil type, soil moisture status, and application rate. In dry and slightly moist silt loam soils, low application rates are critical to maintaining high horizontal:vertical values (i.e., maximum horizontal distribution) (Trout et al., 2005). At these low rates, a moisture gradient is created in the soil, and water is drawn away from the tapeline. The differences in matric and gravitational potentials establish this gradient and lead to water flow in both a downward and horizontal direction. If the tapelines are closely spaced and a low application rate is maintained, the wetting fronts from adjoining tapelines will converge. As the application rate increases, the soil becomes saturated and gravitational head pressure dominates the resulting water flow. As a result, water primarily moves downward and leads to leaching loss (Trout et al., 2005). If water is applied at a rate that exceeds the infiltration rate of the soil, upward movement may be achieved with a SDI system (Lamm, 2002). However, this upward movement is not sufficient to wet the soil surface adequately for uniform germination (Alam et al. 2000; 2002a; 2002b).

Several studies have compared alfalfa yield from SDI and surface irrigation methods at various SDI tapeline spacings and depths (Table 2.4) (Hutmacher et al., 1992; Ayars et al. 1999; Hutmacher et al., 2001; Alam et al., 2000; 2002a; 2002b; Godoy-Avila et al., 2003). With the lack of clear reporting of the results and confounding effects of different distances between emitters on the tapelines, the optimum spacing between tapelines has not been established. In general, spacing tapelines 1.0 - 2.0 m apart can result in yield improvements over surface irrigated controls if emitters are spaced <0.6 m. However, the unreplicated demonstration plot of Alam et al. (2000; 2002a; 2002b) indicates that the optimum spacing may depend on the depth to which the tapelines are placed. Research indicates that tapelines should be closer (1.0 - 1.5 m) and shallower (0.3 - 0.5 m) when application rates increase. Recommendations by a leading manufacturer of SDI tape are for spacing tapelines on 1.0-m centers and at depths of 0.30 - 0.63-m for alfalfa (T-Systems International, Inc. 2005). However, further research is needed to assess if this recommendation is the true
optimum spacing for SDI of alfalfa. Because SDI tape spacing is fixed, proper planning is needed to ensure that the horizontal:vertical distribution of the system adequately accommodates the various plant populations and row spacings of the crops in the rotation (Lamm, 2002). This may need to be done site-specifically, as the optimum water application rate and tapeline spacing is dependent on the hydraulic properties of the soil (Alam et al., 2002a; 2002b; Trout et al., 2005).

**Summary**

This review has shown that there are several key issues regarding the management of soil moisture stress in alfalfa that remain unresolved, especially for producers in Kentucky and the southeastern U.S. Particularly as one considers the possibility of applying irrigation to specific sites within an alfalfa field, SDI appears to be the best option for these producers to site-specifically increase yields. Yet, a number of issues regarding the irrigation of alfalfa using SDI must first be addressed. First, it is unclear if alfalfa will show a significant yield response to SDI in Kentucky. Second, it is not known if SDI will negatively affect stand longevity in this area in a manner similar to that which has been observed in surface irrigated alfalfa. To be a legitimate option for site-specific management in alfalfa, SDI should increase yield and minimize stand losses. Further, very few investigations elaborate on differences in the installation and management of SDI for alfalfa, particularly for producers in areas where alfalfa is not conventionally irrigated. An evaluation of the use of SDI on alfalfa should be robust enough to provide results that can address these questions.

### 2.2. RESPONSE OF ALFALFA TO MOISTURE AND POTASSIUM DEFICITS

**Overview**

Understanding the response of alfalfa to moisture stress and K deficit is important to a discussion on the hypotheses of this dissertation. For example, the physiological and morphological response of alfalfa to these stresses may change the relative importance of a specific yield component on overall yield. In
this section, observations on the responses of alfalfa to moisture and K deficits from the literature are presented. The review of these effects concludes with an elaboration on an approach that dissects alfalfa yield into components. This yield component approach will establish a framework for discussing how moisture and K deficit-induced changes affect harvested yield. Specific attention is given to those physical changes in alfalfa induced by responses to moisture and K deficits that could affect remotely sensing alfalfa yield, yield components, and stand variables. The specific influences that these physiological and morphological changes have on the spectral reflectance of the crop canopy are presented in section 2.3.

**The Response of Alfalfa to Soil Moisture Stress**

Plant available soil moisture varies both temporally and spatially and sporadic droughts often limit alfalfa yield. Strategies to mediate the effect of drought have been classically divided into methods of escape, avoidance, and tolerance (Levitt, 1972; Turner, 1986). Yet, these are not mutually exclusive (Ludlow, 1989) and often elements of each of these strategies can be observed, especially in alfalfa. Alfalfa largely avoids drought by virtue of a well-developed root system. Though alfalfa roots frequently can be found to extend to depths of 6 m or more (Undersander et al., 2004), Caradus (1981) observed that half of the root mass is typically confined to the top 15 cm of soil depth. When subjected to drought stress, alfalfa partitions greater portions of photoassimilate to the roots (Hall et al., 1988) and more efficiently removes soil moisture in the rooting zone (Lanyon and Smith, 1985). The success of this strategy is not unique to alfalfa. Much of the gains in grain yield have been linked with tolerance to moisture stress through deeper and more efficient exploration and use of water in the soil profile (Fisher and Turner, 1978; Campos et al., 2004). For alfalfa, however, this partitioning to the roots is not only for further root development but primarily to store assimilate for later remobilization (Sheaffer and Barnes, 1982; Hall et al., 1988). For example, drought stressed alfalfa has been observed to show increased regrowth compared to well-watered controls when the moisture stress
is relieved (Sheaffer and Barnes, 1982; Hall et al., 1988). This ability likely results from an increased ability to mobilize root reserves, as Rodrigues et al. (1995) observed in white lupin (*Lupinus albus* L.).

In addition to maximizing water uptake, alfalfa minimizes water loss by reducing stomatal apertures and inhibiting growth (Carter and Sheaffer, 1983a; 1983b; Sheaffer et al., 1988; Hattendorf et al., 1990). Though the induction of stomatal closure can result from changes in CO₂ and water vapor concentrations in and around a plant leaf, signaling from moisture stressed roots also reduce stomatal aperture (Gowing et al., 1990). ABA and other hormones released into the xylem of roots stimulate stomatal closure and gene transcription cascades responsible for acclimation to moisture stress (reviewed by Chaves et al., 2003).

Soil moisture stress causes the rate of several yield-critical plant processes to be reduced. Closed stomata reduce evaporative cooling, increases leaf and canopy temperature, and decreases photosynthetic activity (Carter and Sheaffer, 1983b; Undersander, 1987; Hattendorf et al., 1990). Stomatal closure also causes a CO₂ deficit and an O₂ surplus-induced increase in photorespiration. Antolin and Sanchez-Diaz (1993) demonstrated that RuBP carboxylase activity and electron transport rates declined in moderate and severely drought-stressed alfalfa plants, substantially decreasing carbon fixation. Through experimental manipulation, this decrease in photosynthesis was shown to be independent of stomatal closure. Carter and Sheaffer (1983c) found the rate of N₂ fixation was nearly reduced to zero as plant water potential approached -3.0 MPa. As in all plants, alfalfa attempts to maintain water transport by manipulating water potential gradients. These osmotic adjustments increasingly cannot sustain cell turgidity and, thus, cell expansion slows and then stops as moisture deficits escalate. Even mild moisture stress results in smaller cells and the more rigid cell walls (Wilson et al., 1980; Carter and Sheaffer, 1983c). This impedance to cell expansion is manifested in alfalfa as reduced stem diameters, stem and internode length, leaf size, and leaf area index (LAI) (Brown and Tanner, 1983; Sheaffer et al., 1988; Petit et al., 1992).
Drought stress can affect stand longevity and stand parameters, as well. Takele and Kallenbach (2001) observed an inverse relationship between alfalfa stand persistence and the duration of drought-induced dormancy. However, moisture deficits have been shown to increase the freezing tolerance of alfalfa (Sheaffer et al., 1988). Water stress also results in fewer stems and internodes and reduced stem mass (Vough and Marten, 1971; Sheaffer et al., 1988; Petit et al., 1992). However, in comparing well-watered to moderately moisture stressed alfalfa, Carter and Sheaffer (1983a) observed that moisture stress was associated with greater leaf:stem ratios (0.96 vs. 1.24, respectively).

It is apparent from this review that alfalfa is plastic in response to moisture stress. Several of these factors, however, have the potential to influence different yield components of alfalfa. These include, but may not be limited to, the following:

- Reduction in cell size,
- Variations in cell wall architecture and increased lignification,
- Reduced stem diameters and shoot mass,
- Reduced shoot length,
- Fewer shoots,
- Reduced leaf size and LAI,
- Increases in leaf:stem ratios, and
- Changes in stand persistence.

Because variation in soil moisture affects these factors, field investigations should address how these influence the individual components of alfalfa yield. Further, these yield components may influence the quality and quantity of light reflected from alfalfa canopies. In Section 2.3. Factors Affecting Canopy Reflectance of Alfalfa, more detailed consideration is given to how these and other factors may be expected to affect patterns alfalfa canopy reflectance.

**The Response of Alfalfa to Potassium Deficit**

Potassium (K) is an essential element to plants, functioning in several physiological processes such as enzyme activity, carbohydrate production and transport, stomatal activity, and as a solute in osmotic adjustments that maintain
electrochemical gradients and plant water potential (Lanyon and Smith, 1985). In their guide for alfalfa management, Undersander et al. (2004) stated that K is one of the most limiting nutrients for alfalfa production and is critical for maintaining yields, reducing susceptibility to disease, increasing winter hardiness, and fostering stand persistence. As with plant soil water availability, plant available soil K is spatially variable and has been associated with variations in alfalfa yield (Leep et al., 2000).

The responses of alfalfa to K deficits are somewhat similar to the responses to moisture stress. The intimate relationship between K and water relations is evident in the work of Sheaffer et al. (1986), who concluded that “K fertilization reduces water deficit effects on alfalfa yield” as well as “improves yield under adequate moisture levels.” In one study, it was demonstrated that K had a major role in root development, stomatal conductance, manipulation of plant water potential, photosynthesis, N$_2$-fixation, stem and leaf growth, and stand persistence (Lanyon and Smith, 1985).

Alfalfa partitions significant portions of photoassimilate to the roots, particularly during moisture stress conditions (Hall et al., 1988). This process, however, depends on K nutrition. For example, one study in Canada demonstrated that K deficits reduced root starch and buffer-soluble protein concentrations (Li et al., 1997). These observations could be partially explained by dry matter dilution effects from increased root development in response to K deficiencies. Rominger et al. (1975) provided some evidence of this as they observed that unfertilized alfalfa had a root:shoot ratio of 0.28 that declined to 0.22 when fertilizer was applied. However, it is unclear how changes in shoot and root mass affected these ratios and the dilution of storage compounds. Li et al. (1997) also found that K deficits slowed the utilization of total non-structural carbohydrate (TNC) reserves following shoot removal. In alfalfa, both the low concentration of organic C and N reserves in the root and a slowed remobilization of these reserves have been widely recognized to adversely affect tolerance to shoot removal (Kalengamaliro et al., 1997 and Li et al., 1996), rate of leaf and stem regrowth (Kimbrough et al., 1971; Skinner et al., 1999; Grewal and
Williams, 2002; and Dhount et al., 2006), leaf:stem ratio (Grewal and Williams, 2002), and persistence (e.g., Graber et al., 1927; Wang et al., 1953; Skinner et al., 1999; and Dhount et al., 2006). Insufficient K to maintain the enzymatic and transport systems that support these plant responses may exacerbate the effects of insufficient organic C and N reserves (Lanyon and Smith, 1985).

Many studies have evaluated the role of K in the maintenance of water relations in plants and sustaining turgid cell growth (Taiz and Zeiger, 2002). Specifically, plant K status can impact guard cell turgidity, which determines stomatal aperture. Numerous studies have elucidated the importance of K, along with sucrose and their counterions, malate and Cl⁻, to stomatal aperture control (e.g., Fisher and Hsairo, 1968, Fisher, 1971; Talbott and Zeiger, 1996). Cell turgidity drives cell expansion and plant growth (see review by Cosgrove, 2000) and K is one of the primary ions whose concentration is manipulated to maintain turgid conditions (Taiz and Zeiger, 2002).

The specific weight of the cell (and ultimately the leaves and stems) is an important yield component that is directly influenced by photosynthesis and the accumulation of assimilate. Several studies have found negative effects of K deficits on photosynthesis and respiration in alfalfa (Peoples and Koch, 1979; Collins and Duke, 1981; Huber, 1983). In one of these studies, K deficits sharply decreased photosynthesis and increased dark respiration in alfalfa (Peoples and Koch, 1979). Resistance to CO₂ movement increased through the stomata but decreased in the mesophyll as K level increased. Electron transport in photosystem I and II were not affected by K levels in the substrate, but RuBP carboxylase activity sharply declined when K was low (Peoples and Koch, 1979). Further analysis demonstrated that K did not interact with RuBP carboxylase in the enzymatic assimilation of carbon, but rather stimulated synthesis of additional RuBP carboxylase (Peoples and Koch, 1979). Collins and Duke (1981) found that higher rates of carbon assimilation in alfalfa when K was sufficient resulted from a linear increase in chlorophyll concentration.

More recent studies have shown that K is critical to the prevention of the evolution from reactive oxygen species (ROS) (e.g., O₂⁻, H₂O₂, and OH⁻) and
their membrane disruption effects on photosynthesis (Cakmak, 2005). Plants exposed to drought, chilling, and high heat stress suffer oxidative damage from ROS, the primary causes of cellular function impairment and growth depression under these conditions (Apel and Hirt, 2002). Cakmak (2005) presented several examples of the ability of K to alleviate the effects of ROS-mediated abiotic stress factors, such as moisture stress. Recent evidence suggests that ROS production increases during both photosynthetic electron transport and NADPH-oxidizing enzyme reactions in K-deficient plants (Cakmak, 2005). The ROS damage cellular and organelle membranes and are associated with chlorophyll degradation (Cakmak, 2005) and K-deficient plants have been shown to rapidly become chlorotic and necrotic when exposed to intense light (Cakmak, 2005).

Potassium deficiency has also been associated with poor nodule formation and N$_2$-fixation in alfalfa plants (Collins and Duke, 1981; Barta, 1982; Duke and Collins, 1985; Collins et al., 1986; and Grewal and Williams, 2002). Duke and Collins (1985) concluded that K deficits most likely indirectly affected N$_2$-fixation rates through the reduced photosynthetic efficiency of K deficient plants.

It is clear from this review that K deficiency affects many processes in alfalfa. However, the physiological responses to K deficit are not as thoroughly investigated, as compared to the effects of moisture stress. The mechanisms for many of the effects of K deficiency remain ambiguous. The specific effect of K on alfalfa yield is difficult to experimentally discern from its interactions with other factors, such as plant water potential, photosynthetic activity, assimilate transport and storage, and nitrogen fixation and storage. Evidence in the literature has suggested that variations in the response of alfalfa to K deficiency may result in the following:

- Reduction in cell size,
- Reduced shoot mass,
- Fewer shoots,
- Reduced leaf and shoot regrowth rate,
- Reduced LAI,
- Increases in leaf:stem ratios, and
- Decreased stand persistence.
However, research has not yet specifically addressed how K deficiency affects cell wall architecture and lignification, stem length, and stem diameters. These should be considered because they have the potential to influence individual components of alfalfa yield. Additionally, these plant attributes have the potential to individually influence the quality and quantity of light reflected from alfalfa canopies, and are considered in Section 2.3. Factors Affecting Canopy Reflectance of Alfalfa.

Analyzing Effects on Alfalfa Yield Components

Volenec et al. (1987) described alfalfa yield (Y) as the product of plant density, shoots plant\(^{-1}\), and mass shoot\(^{-1}\) in Eq. [2.1].

\[
Y = \left( \frac{\text{Plants}}{\text{Area}} \times \frac{\text{Shoots}}{\text{Plant}} \times \frac{\text{Mass}}{\text{Shoot}} \right)
\]  

Some have expressed reservations about using plant density in the yield component models because alfalfa yield rarely correlates well with plant density unless stands have thinned beyond economic thresholds for renovation (Undersander et al., 1998). These researchers have proposed the simplified variable of shoot density (shoots area\(^{-1}\)) be used, as it is often related to alfalfa yield and has been shown to be predictive of future yields and stand density (Undersander et al., 1998). Recent work by Berg et al. (2005) evaluated the influence of mass shoot\(^{-1}\) and the simplified shoot density variable on yield. They found that mass shoot\(^{-1}\) was often significantly (P<0.0001) related and explained much more of the variation in yield (avg. R\(^2\): 0.63 vs. 0.18, respectively) than shoot density.

Though this dissection of yield is a reasonable first step, further divisions are needed for the evaluation in this dissertation. Specifically, these components must be further divided into elements to allow for a better understanding of how individual responses to moisture stress and K deficit affect yield. I have proposed Eq. [2.2] as an elaboration of the Volenec et al. (1987) yield component equation that accommodates more of the responses in alfalfa to these stresses.
This model can thus evaluate the effects on yield that result from changes in leaf area, leaf mass, leaf number, and stem mass, as well as their combinations as total leaf mass, total stem mass, leaf:stem ratios, shoot mass. From these elements, the majority of the morphological factors that are affected by soil moisture and K deficits are accommodated. The model retains the shoot density variable as used by Berg et al. (2005), and which Undersander et al. (1998) related to stand density thresholds. Though shoot length decreases in response to moisture stress and K deficit, it is not represented in my model. However, the positive effect of shoot length on yield is caused by its effect on shoot mass. As previously discussed, variations in cell wall architecture and increased lignification is a common response of alfalfa to moisture stress. This response only indirectly affects yield and is excluded from the model.

One limitation to this model, as is the case in all similar yield component approaches, is the inherent multicollinearity between the predictor variables. For example, the -3/2 self-thinning law stipulates that shoot mass is not independent of shoot density (Yoda et al., 1963; Matthew et al., 1995; Sackville Hamilton et al., 1995). This limitation to the model warrants caution but does not preclude its use as a conceptual framework for stepwise insertions of individual elements for determination of the strength of their contribution.

It should be noted that the specific leaf weights of alfalfa leaves (mass per unit leaf area) are known to fluctuate in a diurnal pattern with photosynthesis and respiration patterns (i.e., increasing in the afternoon and declining at night; Robinson et al., 1992). The leaf:stem ratio also increases in the afternoon as starch storage in the chloroplast peaks, then decreases at night as the starch is mobilized and translocated (Lechtenberg et al., 1971). These diurnal changes are a potential source of error that should be considered in sampling protocols.
Summary

Drought stress and a deficiency of plant available K result in very similar responses in alfalfa productivity. In fact, K fertilization has been shown to improve yield under adequate soil moisture levels and to reduce the some of effects of water deficit stresses on alfalfa yield. Still, these factors affect several alfalfa yield components and stand persistence. Effects on cell size, cell wall architecture and lignification, stem diameters, stem mass, shoot length, leaf area, leaf mass, leaf:stem ratios, shoot number, and stand thickness may also individually or collectively, affect alfalfa canopy reflectance. Alterations in canopy reflectance resulting from these factors may affect the accuracy of remote sensing techniques for estimating alfalfa yield and stands.

2.3. FACTORS AFFECTING CANOPY REFLECTANCE OF ALFALFA

Overview

Remote sensing can be defined as the measurement or acquisition of information on an object or phenomenon without physical or disruptive contact (American Society for Photogrammetry and Remote Sensing, 2006). Many applications for remote sensing are found in modern agricultural systems (Pinter et al., 2003). Colwell (1956) demonstrated the value of infrared aerial photography to detect disease in small grains nearly 40 years ago, and since then, sensing the reflectance properties of a standing crop or other vegetation has developed into a valuable source of management information (Pinter et al., 2003). Remote sensing uses platforms ranging from aircraft/satellite imagery to handheld devices, and, most recently, ground-based booms (National Research Council, 1997; Pinter et al., 2003).

Numerous physical and biochemical factors affect the reflectance properties of a plant leaf and crop canopies. In this section, the factors known to affect leaf and canopy reflectance are explored. Particular emphasis has been placed on those issues that relate to the physiological and morphological
response of alfalfa to soil moisture and K deficits, as it relates to effects on the accuracy of remote sensing techniques for estimating alfalfa yield and stands. Multispectral sensors currently on the market are described and the implications of their designs on the measurement of canopy reflectance are also discussed.

**Factors Affecting Leaf Reflectance**

Virtually all green leaves reflect light in similar patterns within the visible, near-infrared (NIR), and shortwave-infrared regions of the electromagnetic spectrum (Fig. 2-3) (e.g., Gates et al., 1965; Gausman and Allen, 1973; Hoffer, 1978). Due to strong absorption by photosynthetic and accessory plant pigments in green plant leaves, reflectance of light in the visible region (400 to 700 nm) is low (Gates et al., 1965; Hoffer, 1978). The two main leaf pigments, chlorophyll a and b, absorb nearly 95% of light in the blue (430-450 nm) and red (640-670 nm) regions (Monteith and Unsworth, 1990; Chappelle et al., 1992; Adams et al., 1999). By comparison, absorption in the green (550 nm) band is relatively low (75-80%) leading to a higher reflection in this region (Monteith and Unsworth, 1990). It is this relatively higher reflection of light around the 550 nm bandwidth that gives plant leaves their green color (Gates et al., 1965; Monteith and Unsworth, 1990; Adams et al., 1999).

However, reflectance is usually high in the NIR region (700-1300 nm), where leaf structure is the dominant factor affecting optical properties. Cell wall components, cell size, and cell architecture result in the reflection of up to 60% of the NIR light, resulting in a reflectance plateau in this spectral region (Slaton et al., 2001). Reflectance and the shape of this plateau are dependent on the distribution of palisade and spongy mesophyll cells and the size and shape of their intercellular spaces (Gausman, 1974; Gausman, 1977; Vogelmann and Martin, 1993; Slaton et al., 2001). The long, cylindrical palisade mesophyll cells channel light deep into the leaf interior, whereas the spherical spongy mesophyll cells scatter radiation (Vogelmann and Martin, 1993). In general, spongy mesophyll tissues may also have more interfaces between intercellular air spaces and the cell wall (Terashima and Saeki, 1983). Variation in water and air
Fig. 2-3. Typical spectral reflectance characteristics of a green leaf (after Hoffer, 1978).
within these spaces results in differences in light refraction, scattering, and absorption (Terashima and Saeki, 1983). Cell heterogeneity and increasing cell layers have also been shown to increase the NIR reflectance of the leaf as it matures (Slaton et al., 2001) and this allows estimation of in situ and in vivo forage quality (e.g., Starks et al., 2004).

Spectral reflectance of leaves is also relatively high in the shortwave-infrared (1300 to 2500 nm) region. However, absorption by leaf water at the 1450, 1950, and 2500 nm wavelength bands causes the pattern in this region to be altered as the leaf dehydrates (Carter, 1993). Because of the confounding effects of tissue moisture, researchers have ruled out the use of this wavelength interval in the diagnosis of water stress in the field (Bowman, 1989; Carter, 1991) in favor of longer-wave NIR (thermal) bands (Sheaffer et al., 1988). As a result, shortwave-infrared reflectance is not measured by field-ready multispectral sensors.

Chlorosis is an indicator of plant stress, because low chlorophyll values are often the result of poor plant nutrition and/or disease. Chlorosis and senescence typically result in lower chlorophyll concentrations and the exposure of accessory leaf pigments such as carotenoids and xanthophylls. This causes the green reflectance peak (550 nm) to broaden towards longer (yellow) wavelengths and causes the tissues to appear chlorotic (Adams et al., 1999). Simultaneously, NIR reflectance decreases, albeit proportionately less than the increase in the visible region (Monteith and Unsworth, 1990). This disproportionate change affects the “red-edge wavelength.”

The “red-edge” is the region (690 to 740 nm) where the reflectance increases steeply from low in the visible to a high reflectance of the NIR bands. However, the rate of this transition is not uniform (Filella and Peñuelas, 1994). The “red-edge wavelength” is defined as that wavelength within the red-edge region where the rate of this transition is highest (i.e., corresponds to the maximum slope). The point of maximum slope is shifted towards shorter wavelengths as chlorophyll concentration decreases (Horler et al., 1983, Buschmann and Nagel, 1993; Pinar and Curran, 1996). Thus, chlorosis within the
leaf shifts the green reflectance peak to higher wavelengths and the red-edge wavelength to lower bands.

As is discussed more fully in Section 2.4, the striking difference between reflectance in the visible and NIR regions underpins many approaches for monitoring and managing crop productivity (Pinter et al., 2003). Because of the ability of reflectance from these two regions to provide independent information, commercially available multispectral sensors usually obtain reflectance from one band within both the visible and NIR region (Monteith and Unsworth, 1990). However, the weakness of this approach is that the use of only two bands does not allow for characterizing shifts in the green reflectance peak or the red-edge wavelength.

Soil moisture and K deficits affect alfalfa leaf reflectance. For the most part, these are only indirect effects on leaf reflectance (Carter, 1991; Fridgen and Varco, 2004). As visible and NIR regions are typically measured, absorption of light by water in the shortwave-infrared is not observed. However, as described in Section 2.2, soil moisture deficits affect cell size, mesophyll arrangement, and cell wall structure, all of which have the potential to increase NIR reflectance. However, little research has evaluated the effect of moisture deficit on individual leaves. Carter (1993) found that small (<4%) but significant increases in leaf reflectance in select visible wavelength bands (506-519 nm and 571-708 nm) occurred in the leaves of eight species when subjected to severe moisture stress. As expected, shortwave-infrared reflectance was substantially increased (>15%), however, reflectance in NIR wavelengths was not significantly altered (Carter, 1993).

Low chlorophyll concentrations (Collins and Duke, 1981) and ROS-mediated chlorophyll degradation (Cakmak, 2005) associated with K deficiency are known to cause the white spots and chlorosis symptomatic of K-deficient alfalfa leaves. As with moisture deficits, little research has evaluated the effect of K deficit on individual leaves. Fridgen and Varco (2004) found a pronounced broadening of the green reflectance peak and a shift in the red-edge wavelength between N stressed fully mature cotton leaves. Older leaves lower in the canopy
often show K deficiency because of remobilization of K to actively growing tissue and may have different reflectivity (Beringer and Northdurft, 1985), but may contribute little to whole canopy reflectance.

It remains unclear what effect moisture and K deficits have on the spectral reflectance of an alfalfa leaf. Slight effects of water deficits have been observed on reflectance of severely K-stress leaves. Deficit K levels, when N levels were sufficient had little effect on the reflectance properties of individual leaves high in the canopy. We may conclude that the effects of moisture and K deficits on individual leaves will contribute relatively little to the overall variation in canopy reflectance (Pinter et al., 2003; Fridgen and Varco, 2004). It is more likely the effects of soil moisture and K deficits will be exhibited in changes in canopy architecture, such as LAI or the effect of turgor on leaf arrangement.

**Factors Affecting Canopy Reflectance**

The spectral reflectance signatures of crop canopies in the field are more complex and often very different from that of a single green leaf isolated within a well-illuminated chamber (Pinter et al., 2003). On an elementary level, canopy reflectance \( R \) is estimated from the quantity of light that is intercepted by the crop canopy \( Q_i \) and the proportional reflectance of that light by the canopy \( \rho_c \) (Monteith and Unsworth, 1990; Eq. [2.3]).

\[
R = Q_i \rho_c
\]  

At a given latitude and altitude, time of day and cloud cover have the greatest influence over total incident light \( Q_T \) and its angle of incidence (Monteith and Unsworth, 1990). The effects of these variables have been elucidated in numerous studies (e.g., Monteith and Unsworth, 1990; Green et al., 1998; Guan and Nutter, 2001; Kim et al., 2001). The fractions of \( Q_i \) that are absorbed, transmitted, and reflected by a canopy depend on the angle of incidence (Monteith and Unsworth, 1990). For example, Tageeva and Brandt (1961) found that the reflected fraction remained nearly constant when the angle
of incidence was between 0 and 50° but declined sharply as the angle approached 90°. Yet, the angle of incidence does not equally affect the reflectance of light at all wavelengths. Lord et al. (1988) showed that changes in sun angle had a greater effect on reflectance of red light than on NIR regions from the canopies of five crop species that were examined. This would explain the effects observed by Ranson et al. (1986) of sun angle on a vegetation index that used a linear combination of red and NIR reflectance.

Guan and Nutter (2001) found that reflectance of alfalfa canopies significantly declined before 1100 h and after 1500 h during July and August. They concluded that alfalfa canopy reflectance should be measured ± 2 h of solar noon. Limiting measurements to this time also minimizes reflectance off of dew, which can alter the angle of incidence by refraction, and change the quality of light reflected (Pinter, 1986; Guan and Nutter, 2001). Water vapor in the atmosphere, particularly in the form of cloud cover, reduces light transmission to the canopy and increases diffusion of the reflected light (Monteith and Unsworth, 1990). Thus, cloud cover alters the quantity of light reflected at various bands and affects its correlation with canopy variables (e.g., Jackson et al., 1980; Green et al., 1998).

The angle that light strikes a leaf or leaves within a canopy is dependent on the position of the sun as well as some canopy properties (Monteith and Unsworth, 1990). For example, Gross et al. (1988) found that sun angle greatly affected R from grass canopies, but did not affect R of canopies of dicots, and they concluded that this was likely the result of leaf displays that increased angles of incidence above 50° in the grass canopies. Some dicot species, including alfalfa, exhibit various heliotropic leaf movements (i.e., solar tracking by the leaves in a canopy; Fig. 2-4). In many cases the canopies of these species track the sun by positioning their upper leaf surfaces at a 0° angle of incidence to sunlight (Travis and Reed, 1983; Reed and Travis, 1987). Such movements are defined as diaheliotropic (DHT). Reed and Travis (1987) demonstrated that alfalfa cultivars representative of nondormant, semidormant, and dormant germplasms showed DHT leaf movement. During periods of high vapor pressure
Fig. 2-4. Heliotropic leaf movements (i.e., solar tracking by the leaves in a canopy) of alfalfa have been shown to be both (A) diaheliotropic (DHT) where leaves maintain a 0° angle of incidence and (B) paraheliotropic (PHT) where leaves maintain a 90° angle of incidence to the light.
deficits (VPD), however, each also exhibited paraheliotropic (PHT) leaf movements where leaflet surfaces are oriented at a 90° angle of incidence to sunlight (Reed and Travis, 1987). This may also partially explain why Guan and Nutter (2001) observed differences in R between during and before/after mid-day. Nonetheless, measurement of reflectance at the same time each day, as suggested by Guan and Nutter (2001), may minimize errors associated with DHT and PHT changes in leaf angle.

Because heliotropic leaf movements alter the angle of incidence, their effect on light reflectance specifically relates to how light is intercepted by each layer of the crop canopy. The work of Travis and Reed (1983; Reed and Travis, 1987) and subsequent work by Moran et al. (1989) used leaf samples at or near the uppermost canopy layer. What is unclear from this work is whether or not DHT and PHT movements occur similarly or variably with canopy depth. This illustrates how R is affected by more than just \( Q_i \). If the ambient radiation environment is assumed equivalent for all canopy reflectance measurements, then issues related to canopy development and architecture are the major sources of variation as these factors affect R via changes in \( \rho_c \).

Monteith and Unsworth (1990) derived from Beer’s law the relationship between factors that affect \( \rho_c \) (Eq. [2.4]).

\[
[2.4] \quad \rho_c = \rho_c^* - \left( \rho_c^* - \rho_s \right) e^{-2(LAI)A}
\]

where canopy reflectance (\( \rho_c \)) is determined by the limiting (i.e., asymptotic maximum) coefficient of reflection for the canopy (\( \rho_c^* \)), the coefficient of reflection by the soil (\( \rho_s \)), the LAI, and the canopy attenuation coefficient (\( A \)) (which is analogous to Beer’s extinction coefficient, \( \varepsilon \)).

Canopies vary in each of these variables, and this relationship explains why some canopies reflect light differently than other canopies. Both \( \rho_c^* \) and \( \rho_s \) also differ with the wavelength being evaluated. The coefficient of reflection by

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1 Monteith and Unsworth (1990) use the character of K in their equation. To avoid confusion with reference to potassium (K), the character A is used as an alternate.
the soil ($\rho_s$) is usually different for red and NIR wavelengths and soil disproportionately reflects red and NIR bands and the degree to which this dissimilarity varies with soil color/moisture (e.g., Ångström, 1925; Weidong et al., 2002).

The aforementioned heliotropic movements have been shown to greatly alter $Q_i$, but DHT and PHT also affect $\rho_c$ through $A$ (Monteith and Unsworth, 1990). As a first approximation, $A$ can be regarded as a quantification of the average leaf arrangement, and in the case of a leaf that is oriented at a $0^\circ$ angle of incidence, $A$ is approximately equal to 1 (Monteith and Unsworth, 1990). However, as leaf orientation deviates from this angle, $A$ is reduced. Therefore, DHT leaf movements maximize $A$ at $\sim$1, while PHT movements reduce $A$ (Monteith and Unsworth, 1990). This is evidenced by the observations of Moran et al. (1989) who correlated alfalfa leaf cuppedness (a measure of PHT response) with changes in $R$. One of the limitations to Equation 2.4 is that predictor variables may not be independent.

Monteith and Unsworth (1990) also demonstrated that canopy transmission ($\tau$) is related to both LAI and $A$ in Eq. [2.5].

$$\tau = e^{-A(LAI)}$$

[2.5]

They noted that new leaves progressively shade old leaves, ultimately leading to the senescence of older leaves at an upper limit of LAI ($\text{LAI}'$). They inserted the theoretical minimum $\tau$ of 0.05 (i.e., light interception = 95%) and rearranged Eq. [2.5] as Eq. [2.6] to illustrate how LAI becomes dependent on $A$ at $\text{LAI}'$.

$$\text{LAI}' = -\ln(0.05) / A = 3 / A$$

[2.6]

Equation 2.6 is consistent with field observations of LAI in crop canopies with predominantly horizontal leaves, including alfalfa, where a LAI rarely exceeds 3-4 (Kimbrough et al., 1971; Monteith and Unsworth, 1990; Qi et al., 1995; Walter-Shea et al., 1997; Guan and Nutter, 2002b). LAIs near this maximum level are
associated with the saturation of many vegetation indices based on canopy reflectance.

Nevertheless, Eq. [2.4] illustrates several other important points about canopy development and architecture. One of the most striking illustrations is in how very sensitive $\rho_c$ is to changes in LAI. Monteith and Unsworth (1990) show that when LAI is high, $\rho_c$ is limited by $\rho_c^*$. In contrast, when LAI is low, $\rho_c$ can be seen to be more influenced by $\rho_s$. Major et al. (1986), Huete (1988), Baret et al. (1989), Mitchell et al. (1990), and Younan et al. (2004) have cited much influence on R by non-target reflectance (i.e., $\rho_s$) when LAI was low.

It is at this “leaf-area” level where the physiological responses of alfalfa to variations in soil moisture and K fertility become most relevant to R assessments. As established in Section 2.2, soil moisture and K deficits affect alfalfa by slowing the rate of leaf development, reducing overall leaf size and LAI, increasing leaf:stem ratios, and reducing shoot and stand density. As leaf area is associated with high yields and long-lived stands and because leaf area is affected by soil moisture and K deficits, assessing the development of leaf area holds great promise in better understanding site-specific needs of alfalfa for moisture and K.

Indices calculated from adjusted combinations of R in red and NIR wavelengths that account for variation in $\rho_s$, particularly as it relates to soil or crop residue in the viewing area, have been devised and evaluated for predicting biomass and canopy development in other crops (Huete, 1988; Baret et al., 1989; Raun et al., 2005), but have not been evaluated in alfalfa. For instance, prediction of LAI may be possible with adjusted indices at low LAIs or unadjusted indices at high LAIs. Yet, it is unclear how LAI at harvest or at any other growth stage relates to yield at harvest. Similarly, spikes in the reflectance of NIR relative to red at particular sites may indicate non-target/non-green reflectance, but it is unknown how that correlates to thin stands or impacts final alfalfa yield. Early successes have been found in evaluating R for associations with alfalfa yield variation (see Mitchell et al. 1990; Guan and Nutter, 2002a; 2002b; 2004 as discussed in Section 2.4), but many questions remain unanswered. First, it is unclear how alfalfa canopy reflectance relates to the yield components and
specifically those (i.e., shoot mass or shoot density) most commonly identified as being predictive of current yield and yield potential in future cuttings (Undersander et al., 1998; Berg et al., 2005). Second, it is unknown if this success can be replicated with and at the spectral and spatial resolution of currently available, “field-ready” sensors.

**Effects of Sensor Design on Canopy Reflectance Assessments**

In addition to the spectral reflectance of individual leaves and the dynamics of the canopy, reflectance measurements are affected by remote sensing platform and sensor design. Because of their wide field of view, remote sensing devices are subjected to reflectance from many sources. Some reflection may be specific to the remote sensing platform or device. Stray reflectance affecting “field-ready” ground-based spectrophotometers is an important consideration. The design of each “field-ready” device is different, primarily as it relates to differences in light source, viewing angles (field of view), output rate, and reflectance bands measured. As a result, some sources of stray reflectance may impact one “field-ready” sensor, but may not another.

All spectral sensors report \( R \) values as a fraction of the incident light received, \( R_\lambda/I_\lambda \) (i.e., light reflected in the \( \lambda \) wavelength/incident light in the \( \lambda \) wavelength) (Monteith and Unsworth, 1990). Ground-based sensors use photoelectric diodes that capture light reflected from the sensed area. The major differences between sensors, however, lie in how the incident light is measured. Remote sensing devices are classified into two general types, active and passive (Campbell, 2002). Active sensors are devices that provide an independent light source. These light sources reduce the need for corrections based on variations in incident radiation and eliminate error introduced by such corrections. In the case of ground-based systems, the light source is usually light emitting diodes (LED) of two or more specific wavelengths. Commercially available examples of active, ground-based sensors include the Crop Circle ASC-210 (Holland Scientific, Inc., Lincoln, NE) and GreenSeeker® (NTech Industries, Inc., Ukiah,
CA). In contrast, passive sensors rely solely on the reflection of incident light. Commercially available examples of passive, ground-based sensors include the CROPSCAN MSRx (CROPSCAN, Inc., Rochester, MN) and Yara FieldScan\(^2\) (Yara International ASA, Oslo, Norway). The passive sensors have photoelectric diodes that measure upward reflected radiation. Active sensors express the upward reflected radiation as a fraction of the light emitted by their light source. (Fig. 2-5). In addition to the differences in light source and data output, the GreenSeeker\(^\circledast\) (GS) and FieldScan (FS) sensors differ in wavelengths measured, the frequency of measurements, and viewing angles.

The GS device illuminates the canopy using two rows of LEDs, each emitting either red [650 nm ±10 nm full width half magnitude (FWHM)] and NIR (770 ± 15 nm FWHM) bands (NTech Industries, 2005). The device is mounted either on a rod (Model 505) or on an implement boom (Models RT100 and RT200). When positioned at the recommended operating height (0.6 - 1.0 m above the canopy), a linear 0.6 x 0.01 m strip is illuminated and sensed. A single photoelectric diode measures the fraction of the emitted light at these bands that is returned to the sensor from the sensed area. Manufacturer specifications indicate that the dimension of the sensed area remains constant with height. The sensor takes R measurements at a very high rate (approximately 1000 measurements per second) and outputs averaged measurements 10 times s\(^{-1}\). Output can be georeferenced by interfacing a GPS receiver to the data collection device. Handheld units use only one sensor unit, but numerous units can be mounted and georeferenced independently on an implement boom.

In contrast, the FS is designed to be mounted on the roof of a tractor cab (tec5USA, 2005). One photoelectric diode is centrally located with four optical inputs. Pairs of optical inputs are placed on each end of the FS, and each input is oriented at 45° relative to the central axis of the device (i.e., at 90° to the other input in the pair). Each input is downward looking at a viewing direction that is 64° from nadir and possess a 12° field of view. Because of these specifications,

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\(^2\) The Yara FieldScan is marketed in North America by tec5USA, a partner to Yara, Germany. Prior to Yara International ASA’s purchase of Hydro Agri, the FieldScan had been marketed as the Hydro-N-Sensor.
Fig. 2-5. The Hydro-N-Sensor (A) and GreenSeeker® (B) sensors mounted according to manufacturer specifications with a view of the bottom side showing the optical receptors. (Photo Credit: Dr. Timothy Stombaugh, Univ. of Kentucky).
the sensed area depends on sensor height. A second, upward looking photorelectric diode is centered on the device and measures incident light. The FS can measure R from up to 20 channels (±10 nm FWHM), of which 15 wavelength bands are standard and 5 are user-selected. Reflectance is averaged across the four optical inputs, rectified to the incident light measurement, and recorded once s⁻¹. As with the GS, the FS data can also be georeferenced by interfacing a GPS receiver to the user interface.

The lack of wavelength choice greatly limits the capabilities of the GS to provide R data. By comparison, the FS outputs enough wavelength bands to construct reflectance spectra of relatively high spectral resolution with bandwidths at ±10 nm. This also allows for calculating numerous vegetation indices. However, data collection from narrow strips at high output rates makes for much finer spatial resolution of the GS measurements as compared to the FS. Finer resolution can only be accomplished in the design of the FS by slowing the travel speed or lowering the height. However, lowering the height causes other problems.

Changes in the reflectance spectrum between the canopy and the detector due to atmospheric scattering are often problematic for aerial or satellite based sensors. Even though there are some differences in height between the recommended mounting of these devices, it is unclear if atmospheric scattering differs between these sensors and affect the R measured by each. In general, height alone will likely not impact R measurements. This is evidenced by the inconsistent effects on alfalfa R by varying the height of a handheld radiometer from 1.5 to 4 m above the canopy found by Guan and Nutter (2001). Nonetheless, they maintained that measurements should be taken at consistent heights. However, the viewing angle of the FS will be different from the angle of the leaves relative to the solar zenith in the alfalfa canopy. This may result in different reflectance spectra than one in parallel with the leaf angle, such as the GS. For example, the sensed area is perpendicular to the canopy surface and readings are taken from a very narrow strip by the GS, but the FS measures R over a larger area and at an angle to the canopy surface. Therefore, the FS may
not have as much non-target reflectance in its viewing area when data are gathered from areas of thin alfalfa stands or when LAI is low. In contrast, the GS data may record much higher NIR reflectance than the FS.

Viewing angles of the sensor and the angle relative to the solar zenith (i.e., solar zenith angle) are a major challenge to satellite-based R measurements. Numerous studies have evaluated sun/sensor geometry and the influence these angles have reflectance measurements (Ephiphano and Huete, 1995; Qi et al., 1995; Walter-Shea et al., 1997). At solar zenith angles greater than 30°, antisolar angles (angles where the sun is behind the sensor) and forward scattering angles (angles when the sun is in front of the sensor) significantly and anisotropically affect R values from alfalfa canopies when the respective angles exceed 20° (Ephiphano and Huete, 1995; Walter-Shea et al., 1997). Further, steep sun/sensor angles reduce red bands to a greater extent than NIR bands (Walter-Shea et al., 1997). Such has been shown to significantly affect indices that are defined by combinations of R values from these bands (Ephiphano and Huete, 1995; Qi et al., 1995; Walter-Shea et al., 1997).

Sun/sensor geometry issues pose more of a problem to satellite-based R measurements, since ground-based spectrophotometers can be used when solar zenith angles are minimized such as around mid-day (Walter-Shea et al., 1997). With simultaneous input from optics focused in four different directions, the design of the FS may enable viewing angle effects to cancel out the antisolar/forward scattering effects of its steep, 64° sensor angle. As the GS measures directly over the canopy, it may only be affected by solar zenith angles. However, it remains unclear if sun/sensor geometry issues significantly affect either of these devices.

Summary

In this section of the literature review, physical and biochemical factors that affect the reflectance properties of a plant leaf and crop canopies have been explored. Reflectance properties of individual leaves may be affected by soil
moisture and K deficits, but may contribute relatively little to the overall variation in canopy reflectance. It is more likely that soil moisture and K deficits will be expressed in canopy architecture, such as LAI. An equation that describes a canopy reflectance coefficient in terms of leaf architecture, leaf area, and non-target reflectance factors provides the framework for relating canopy reflectance elements to yield and stand (Monteith and Unsworth, 1990). The contrasting designs of ground-based multispectral sensors have implications in terms of their potential effects on canopy reflectance measurements. As was presented in Section 2.2, it is known that soil moisture and K deficits affect LAI and yield. What remains unclear, and ultimately is at question, is if LAI, as measured by canopy reflectance, is relevant to yield and stand properties.

2.4. USING CANOPY REFLECTANCE TO ASSESS CROP CONDITIONS IN ALFALFA

Overview

To reveal information about the condition of a crop using canopy reflectance (R), factors relevant to yield, yield components, or stand density variables would ideally be isolated from those that are not of interest. It is obvious from the discussion in Section 2.3 that this isolation is often difficult because of factors that interact or are confounded. However, a number of data analysis approaches have been pursued that attempt to at least minimize the effect of those factors that introduce prediction error. For example, over 50 vegetation indices (VIs) have been developed to provide a simplistic solution for extracting desired information from complex R spectra (Bannarti et al., 1995; Moran et al., 1997; Pinter et al., 2003; Gitelson, 2004). The successful use of many of these VIs to predict vegetative biomass, LAI, and other crop condition factors in a diverse range of crops has been well documented (reviewed in Bannarti et al., 1995; Verstraete et al., 1996; Moran et al., 1997; Pinter et al., 2003), even when soil reflectance is in the field of view (Huete, 1988; Qi et al., 1994). Approaches
that employ multispectral (i.e., reflectance at several wavelength bands) data in more complex algorithms have also been proposed and evaluated with significant success. These are most often employed to minimize unwanted signals from soil or negate the saturative effect of high amounts of biomass to improve nutrient, pest, or water stress identification (Horler et al., 1983; Adams et al., 1999; Pinter et al., 2003).

The purpose of this section is to highlight those successes and identify those that may apply to alfalfa. To accomplish this, VI and multispectral approaches are discussed and examples of significant developments are presented. The scope of this discussion focuses less on the application for which they were examined, but more on the potential of these methods to predict alfalfa yield, yield components, and stand variables.

**Vegetation Indices**

A VI is typically calculated from a difference, ratio, or other linear combination of reflected light in visible and NIR wavelength bands (Richardson and Wiegand, 1977; Tucker, 1979; Weigand et al., 1991; Bannarti et al., 1995; Verstraete et al., 1996; Moran et al., 1997; Pinter et al., 2003; Gitelson, 2004). Ideal VIs extract the independent information contained within these regions of the electromagnetic spectrum and reduce multi-band reflectance observations to a single numerical index that accounts for both reflection from green biomass and reflection from the soil.

Recall that, in terms of Eq. [2.4], the relative contribution of the green biomass, $\rho_c^*$, to that of the soil, $\rho_s$, depends on LAI. A convenient way to make this distinction is to compare reflected fractions at wavelength bands where green vegetation and soil reflect light differently. Reflection in the visible bands is one region where this distinction can be made, because green vegetation reflects less and soil reflects more light in the visible regions. This is especially true with respect to red bands, where chlorophyll absorbs nearly 95% of the light in this wavelength. However, a simple difference reveals little unless compared to reflectance in regions were similar amounts of light are reflected by both the
green vegetation and the soil, such as in the NIR bands. Therefore, comparing the NIR:red reflectance ratio within two or more pixels or viewing areas can provide a relatively simple approximation of the contribution of vegetation and soil.

This simple vegetation index, often referred to as the ratio vegetation index (RVI), is one of the first of such indices reported in the literature (Jordan et al., 1969) (Tables 2-5 and 2-6.). Though it is still commonly used, it has largely been replaced by the normalized difference vegetation index (NDVI) developed by Kriegler et al. (1969) and Rouse et al. (1973). This is mainly due to the convenient limits of NDVI to values between -1 and +1 and the usefulness for comparisons across different observation scenes (i.e., differences in time, Q_T, etc.). Both RVI and NDVI have been found to be well correlated with various vegetation variables, such as standing biomass (e.g., Tucker, 1979; Major et al., 1986; Mitchell et al., 1990; Stone et al., 1996; Ma et al., 2001; Raun et al., 2002, 2005), LAI (e.g., Asrar et al., 1984; Gower et al., 1999; Turner et al., 1999; Qi et al., 2000), and grain yield (e.g., Ma et al., 2001; Shanahan et al, 2001, 2003; Raun et al., 2002, 2005). One of the most often studied of these vegetation variables is the LAI, but studies have shown the complicated relationship between LAI and these VIs. In fact, it is this relationship with LAI that places limits on the use of canopy reflectance. This is revealed in Eq. [2.4] which demonstrates that at LAI = 0 and as canopy development reaches LAI', ρ_c reverts to ρ_s and ρ_c*, respectively.

As presented in Section 2.3, it is important to consider the baseline contribution of the canopy floor to canopy reflectance, especially when LAI is low. Characteristics of the canopy floor (i.e., soil type, litter organic matter, and moisture) determine the baseline reflectance (Huete, 1988; Baret and Guyot, 1991). This baseline is referred to in the literature as the “soil line” and is defined as the linear relationship that best fits the red and NIR reflectance values from the soil background or canopy floor when LAI = 0. In Fig. 2-6a, the relationship between red and NIR reflectance is shown for theoretical levels of LAI as calculated by Baret and Guyout (1991) using the Verhoef (1984) “SAIL” model.
Table 2-5. Equations and the reflectance (R) bands used for calculating selected vegetation indices and listed in chronological order of development.

<table>
<thead>
<tr>
<th>Index†</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ratio Vegetation Index</td>
<td>Jordan et al., 1969</td>
</tr>
<tr>
<td>( RVI = \frac{R_{NIR}}{R_{Red}} )</td>
<td></td>
</tr>
<tr>
<td>Normalized Difference Vegetation Index</td>
<td>Rouse et al., 1974</td>
</tr>
<tr>
<td>( NDVI = \frac{R_{NIR} - R_{Red}}{R_{NIR} + R_{Red}} )</td>
<td></td>
</tr>
<tr>
<td>Red-Edge Normalized Difference Vegetation Index</td>
<td>Gitelson and Merzlyak, 1994</td>
</tr>
<tr>
<td>( RENDVI = \frac{R_{NIR} - R_{Red-edge}}{R_{NIR} + R_{Red-edge}} )</td>
<td></td>
</tr>
<tr>
<td>Renormalized Difference Vegetation Index</td>
<td>Roujean and Breon, 1995</td>
</tr>
<tr>
<td>( RDVI = \left[ NDVI \left( R_{NIR} - R_{Red} \right) \right]^{0.5} )</td>
<td></td>
</tr>
<tr>
<td>Green Normalized Difference Vegetation Index</td>
<td>Gitelson et al., 1996</td>
</tr>
<tr>
<td>( GNDVI = \frac{R_{NIR} - R_{Green}}{R_{NIR} + R_{Green}} )</td>
<td></td>
</tr>
<tr>
<td>Very Atmospherically Resistant Index - Green</td>
<td>Gitelson et al., 2002</td>
</tr>
<tr>
<td>( VARI_{Green} = \frac{R_{Green} - R_{Red}}{R_{Green} + R_{Red} - R_{Blue}} )</td>
<td></td>
</tr>
<tr>
<td>Wide Dynamic Range Vegetation Index</td>
<td>Gitelson, 2004</td>
</tr>
<tr>
<td>( WDRVI_a = \frac{\alpha R_{NIR} - R_{Red}}{\alpha R_{NIR} + R_{Red}} )</td>
<td></td>
</tr>
</tbody>
</table>

† \( R_{Green} = \) fraction of light reflected at a green wavelength band, \( R_{NIR} = \) fraction of light reflected at a NIR wavelength band, \( R_{Red} = \) fraction of light reflected at a red wavelength band. \( R_{Red-edge} = \) fraction of light reflected at the red edge wavelength band.
Table 2-6. Equations and the reflectance (R) bands used for calculating selected vegetation indices that are adjusted to account for the contribution of soil reflectance in chronological order of development.

<table>
<thead>
<tr>
<th>Index†</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil Adjusted Vegetation Index</td>
<td>Huete, 1988</td>
</tr>
<tr>
<td>[ SAVI = \frac{R_{NIR} - R_{Red}}{R_{NIR} + R_{Red} + L}(1 + L) ]</td>
<td></td>
</tr>
<tr>
<td>Transformed Soil Adjusted Vegetation Index</td>
<td>Baret et al., 1989</td>
</tr>
<tr>
<td>[ TSAVI = \frac{a(R_{NIR} - aR_{Red} - b)}{R_{NIR} + R_{Red} - ab + L(1 + a^2)} ]</td>
<td></td>
</tr>
<tr>
<td>Modified Soil Adjusted Vegetation Index</td>
<td>Qi et al., 1994</td>
</tr>
<tr>
<td>[ MSAVI = \frac{2R_{NIR} + 1 - \sqrt{(2R_{NIR} + 1)^2 - 8(R_{NIR} - R_{Red})}}{2} ]</td>
<td></td>
</tr>
<tr>
<td>Generalized Soil Adjusted Vegetation Index</td>
<td>Gilabert et al., 2002</td>
</tr>
<tr>
<td>[ GESAVI = \frac{(R_{NIR} - bR_{Red} - a)}{R_{Red} + Z} ]</td>
<td></td>
</tr>
</tbody>
</table>

† \( a = \) slope of the soil line, \( b = \) intercept of the soil line, \( L = \) soil adjustment factor based on canopy closure (\( L = 1 \) for bare soil or very low vegetation densities, \( L = 0.5 \) at intermediate vegetation densities, or \( L = 0.25 \) at high densities), \( R_{NIR} = \) fraction of light reflected at a NIR wavelength band, \( R_{Red} = \) fraction of light reflected at a red wavelength band, \( Z = \) the negative of point that the soil line crosses the red reflectance axis.
Fig. 2-6. Graphical representation of NDVI (A) and SAVI (B). The open circles and dashed lines correspond to the calculated reflectance of theoretical canopies with different soil backgrounds, a median leaf angle (50°), and given LAI. The line for which LAI = 0 is, by definition, the soil line. Solid lines correspond to the constant value for the VI, having been calculated from the median value of red (and corresponding NIR value) of each LAI relationship. (Adapted from Baret and Guyot, 1991).
Note that the origin of all given NDVI values, calculated from the median reflectance value in the red band from each LAI relationship, intercept the axes at the origin and fail to match the origin of the LAI relationships. The high leaf angle (50°) that Baret and Guyot (1991) use in the regression of the red reflectance versus NIR reflectance at various LAIs likely exaggerates the differences, somewhat, as compared to the more horizontal leaf angle associated with alfalfa.

Nonetheless, the weakness of NDVI (and RVI) at evaluating low LAIs has been well recognized (e.g., Huete, 1988; Baret and Guyot, 1991; Qi et al., 1994; Moran et al., 1997). This issue led to the development of several soil-adjusted VIs, such as the soil-adjusted VI (SAVI: Huete, 1988), transformed SAVI (TSAVI: Baret et al., 1989), modified SAVI (MSAVI: Qi et al., 1994), and generalized SAVI (GESAVI: Gilabert et al., 2002) (Table 2-6). The SAVI and MSAVI indices attempt to minimize $\rho_s$ effects on the VI by means of incorporating either a soil-adjustment parameter ($L$). Huete's (1988) incorporation of $L$ allows the user to correct the VI based on range of canopy closure levels (i.e., $L$ decreases from 1 to 0 as canopy closure increases). This variable shifts the intercepts and the slopes of a given VI to more closely match the red versus NIR reflectance pattern of different LAI levels (Fig. 2-6b). Dissatisfaction with the arbitrary nature of $L$ led to VIs such as TSAVI and GESAVI that utilize the slope and intercept parameters of the soil line to similarly shift the intercepts and the slopes of the VI. The weakness of this approach is that the reflectance of bare soil differs substantially from the reflectance contributed by the dynamic conditions at the canopy floor (e.g., variations in soil moisture and crop residue). Nonetheless, these VIs slightly improve the LAI prediction efficiency (Gilabert et al., 2002).

Though the use of SAVI and MSAVI sacrifice some prediction efficiency, these indices have advantages for use with ground-based spectrophotometers. In contrast to the processing of satellite or aerial images where the soil line is estimated from pixels of bare areas in the viewing frame (e.g., Huete, 1988; Baret and Guyot, 1991), ground-based spectrophotometers calculate the soil line by taking measurements from bare ground that is representative of the canopy floor where canopy reflectance measures are being obtained. This process is
laborious and would not be feasible for use in farm applications. Such laborious accounting of specific soil line variables could be avoided by using SAVI or MSAVI, and pertinent variables could still be more accurately predicted.

**Other Indices and Techniques**

The success of RVI and NDVI led to the development of other VIs. Examples include the green normalized difference vegetation index (GNDVI: Gitelson et al., 1996; Schepers et al., 1996; Shanahan et al., 2001; Shanahan et al., 2003); the red-edge normalized difference vegetation index (RENDVI: Gitelson and Merzlyak, 1994); renormalized difference vegetation index (RDVI: Roujean and Breon, 1995), and very atmospherically resistant index (VARI: Gitelson et al., 2002). These indices, like RVI and NDVI, share a dependency on NIR and visible reflectance. NIR reflectance is typically an order of magnitude greater than red reflectance (Gates et al., 1965; Gausman and Allen, 1973; Wiegand and Richardson, 1984; Slaton et al., 2001; Gitelson, 2004) and it increases proportionately more than red reflectance, especially as the canopy reaches LAI’ (Gitelson, 2004). This led Gitelson (2004) to propose a weighting coefficient (‘α’) to scale-down NIR reflectance within the NDVI equation (Table 2-5). Gitelson’s (2004) Wide Dynamic Range Vegetation Index (WDRVI) slows the WDRVI’s rate of increase and widens the range over which the VI is responsive to changes in LAI.

**Previous Successes**

Management based on canopy reflectance has been applied to many areas of modern crop production (Moran et al., 1997; Pinter et al., 2003) including yield assessments and management of corn (e.g., Shanahan et al., 2001, 2003; Dobermann and Ping, 2004), soybean (e.g., Ma et al., 2001; Dobermann and Ping, 2004), and wheat (e.g., Stone et al., 1996; Raun et al., 2002, 2005). Perhaps the most notable example is the site-specific application of N to wheat based on the early estimates of yield (INSEY) from NDVI.
measurements and Growing Degree Days (e.g., Stone et al., 1996; Raun et al., 2002, 2005).

The successful integration of this technology has not been limited, however, to those three most important crops. Spurred by local processing cooperatives and the need for accurate assessments of production and quality levels, canopy reflectance is measured over approximately 75% of the sugar beet \((Beta vulgaris \text{ L.})\) acreage in North Dakota and the upper Midwest (Humburg, 2004). Canopy reflectance is also being used to define management zones for the site-specific application of plant growth regulators in aid of cotton harvest (Hanks et al., 2003; Pinter et al., 2003). Excluding thermal-infrared measures of canopy temperature to manage irrigation, alfalfa remains the only one of the most economically important crops in the USA without a commercial application for reflectance based tools. One possible explanation is the rather limited research effort devoted to this crop.

Few studies have evaluated the reflectance of alfalfa canopies. Because of the complexity of its canopy architecture, some researchers have used alfalfa as a model crop upon which they have evaluated the effects of canopy development, leaf angles, solar zenith angles, sensor viewing angles, and other factors affecting canopy reflectance (Kirchner et al., 1982; Moran et al., 1989; Walter-Shea et al., 1997). Though they outline many of the canopy related factors that affect alfalfa reflectance, little consideration is given to the agronomic implications or relationships that could be provided by the reflectance data. For example, Bédard and Lepointe (1987) showed that spectral reflectance may be used to determine biomass productivity in mixed-species grasslands, but they did not estimate the contribution of alfalfa.

Mitchell et al. (1990) was the first to address the feasibility of relating canopy reflectance to alfalfa yield and productivity. Using RVI and NDVI measurements and yield estimates from alfalfa under varying stocking rates, they established relationships between these indices and leaf and stem phytomass (Table 2-7). The relationships were generally better for NDVI than RVI. Mitchell et al. (1990) found that NDVI related well to lamb growth on alfalfa and found that
Table 2-7. Range of correlation coefficients between alfalfa phytomass components and two vegetation indices as calculated from reflectance data taken at different solar zenith angles (Adapted from Mitchell et al., 1990).

<table>
<thead>
<tr>
<th>Component</th>
<th>RVI</th>
<th>NDVI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>57° g m(^{-2})</td>
<td>69° g m(^{-2})</td>
</tr>
<tr>
<td>Leaf mass</td>
<td>0.94 - 0.95</td>
<td>0.96</td>
</tr>
<tr>
<td>Stem mass</td>
<td>0.64 - 0.73</td>
<td>0.66 - 0.74</td>
</tr>
<tr>
<td>Desiccated</td>
<td>0.69</td>
<td>0.67</td>
</tr>
<tr>
<td>Leaf + stems</td>
<td>0.88 - 0.94</td>
<td>0.89 - 0.92</td>
</tr>
<tr>
<td>Leaf + stems + desiccated</td>
<td>0.92</td>
<td>0.88</td>
</tr>
</tbody>
</table>
weight gains plateaued above NDVI values of 0.55. They concluded that spectral indices provided an excellent alternative to tedious sampling procedures used in stock density studies (Mitchell et al., 1990).

Guan and Nutter (2001, 2002a, 2002b, 2003 and 2004; Nutter et al., 2002) evaluated the utility of canopy reflectance to predict the occurrence of disease stress and its impact on alfalfa yield. Their studies imposed varying levels of leaf spot and defoliation damage as a result of varying application frequency of selected fungicides. They found relationships ($r^2$ generally $> 0.60$) between canopy reflectance at 810 nm and the severity of leaf spot and defoliation damage (Guan and Nutter, 2002a, 2002b, 2003 and 2004). Further, the use of reflectance at this wavelength virtually eliminated observer variability in assessing disease severity (Guan and Nutter, 2003). Guan and Nutter (2002a, 2002b, and 2004) also found 810 nm reflectance was linearly related to LAI ($r^2 = 0.58$) and yield ($r^2 = 0.62$).

These researchers indicate that canopy reflectance can be used to assess some variables pertinent to the management of alfalfa. However, the conditions of these studies may not be relevant to undisturbed alfalfa canopies. These studies highlight several issues remain unclear concerning canopy reflectance of alfalfa. For example, the work of Mitchell et al. (1990) was performed under conditions where alfalfa biomass varied tremendously (0 – 225 g m$^{-2}$) and few NDVI values above 0.80 were observed. It is unclear how these results translate to growing conditions where the canopy begins to close (i.e., as LAI approaches LAI'). Further, Guan and Nutter (2002a, 2002b, 2003, and 2004) correlated reflectance from individual spectral bands, but not VIs, to agronomic variables. It is also unclear if physiological or phytotoxic effects from the various fungicides and application rates that were used influenced the relationship between the reflectance at 810 nm and the measured responses.

Some insight into the relationship of various VIs to variables relevant to alfalfa yield at full canopy can be found in recent work by Payero et al. (2004), where the ability of several VIs to predict crop height in alfalfa were compared. In two successive regrowth patterns following harvest, alfalfa canopy reflectance
and canopy height were measured approximately every other day. From these reflectance values, 11 VIs were calculated and compared to the corresponding canopy height data. All 11 VIs were significantly related to the canopy heights of alfalfa ($R^2 > 0.90$), each showing a significant logarithmic response to increasing height (Fig. 2-7). This logarithmic curve exhibits the saturative nature of the VIs as LAI approaches LAI'. However, careful comparison of the shape of the response curves show discrepancies in the rate at which the indices tend to saturate. For example, NDVI plateaued above canopy surfaces at 0.3 m. In contrast, the rate at which RDVI values increased with canopy height slowed but did not stop. Although canopy height at harvest is not always well associated with harvested yield (Undersander et al., 1998, 2004; Berg et al., 2005), canopy height is a reasonable proxy for canopy development. Therefore, it can be expected that leading candidates that relate well to alfalfa yield and yield components may be identified in those VIs that remain responsive over the full range of canopy heights.

The data of Payero et al. (2004) also gives some of the only insight into the ability of reflectance data to identify thinning alfalfa stands, especially at the initial stages of regrowth. If it is assumed that thin stands (i.e., beyond the economic yield threshold for renovation) can form a closed canopy, then it follows that a better time to use reflectance to assess stand density is before the canopy closes and the VIs plateau. Payero et al. (2004) also observed that as canopy height (i.e., canopy development) increased, NIR reflectance asymptotically approached a maximum ($\rho_c^*$ for NIR). Furthermore, when regrowth was just beginning, red reflectance exceeded green reflectance but the converse was true as the canopy began to fill in. If the changes in reflectance that Payero et al. (2004) observed hold, thin stands should be located where red reflectance is greater than or approximately equal to green reflectance and NIR reflectance is less than 50% of $\rho_c^*$ provided measurements are made during the initial stages of regrowth ($< 0.2$ m). However, it is unclear if the combination of these trends offers a true indicator of stand thinness.
Fig. 2-7. Reflectance (A) and Vegetation Index (B; NDVI and RDVI) response to changes in plant height in alfalfa.
It is clear that canopy reflectance based management has been successful integrated into modern crop production. The potential use in alfalfa remains rather unclear, despite significant early successes, due to a paucity of data.

**Summary**

The vastness of canopy reflectance data has led to many algorithms that sieve the data, allowing the user to glean relevant information. Most applications of reflectance data have been relatively simple and associated with agronomically pertinent variables. The success of many remote sensing techniques in predicting yield and identifying moisture-, nutrient-, and pest-derived stresses has led to their incorporation into a range of modern management practices in many important crops.

Algorithms developed for specific crops cannot be used without verification or modification to predict yield, yield components, and stand longevity of alfalfa. Early results from applications in grazing and disease assessment indicate that canopy reflectance data has potential applications in alfalfa management. However, it remains unclear as to whether or not these portend success in the assessment of relatively undisturbed mature alfalfa canopies. The saturation of vegetation indices derived from canopy reflectance as canopies approach full closure presents a significant obstacle to applications because mature canopies of alfalfa are used for grazing, hay or silage. The literature indicates that some VIs may be better suited for alfalfa assessment than others. Further, the integration of multiple spectral bands or perhaps even the use of multiple vegetation indices or multiple sensings may be necessary to accurately assess alfalfa yield, yield components, and stand density.

**2.5. SUMMARY**

Evidence in the literature reveals that spatial variation in alfalfa productivity and persistence is often related to insufficient plant available soil moisture and K. This is especially germane to monitoring the effectiveness of
management tactics, such as a site-specific supplementation of soil moisture or variable rate K applications.

The literature also indicates that physiological responses of alfalfa to variation in soil moisture and K deficiency include changes in yield components such as leaf area, leaf mass, and shoot mass and these changes should influence spectral reflectance patterns in specific ways. The variability of alfalfa canopy reflectance may be lessened by taking measurements at a consistent time of day and set of conditions and accounting for non-target reflectance from the canopy floor. This allows for the extraction of independent bits of information from canopy reflectance spectra. The "standard" vegetation indices and approaches that have been successfully employed in other crops, however, may not adequately reveal the information within this “snapshot” assessment when dealing with the closed canopy of mature alfalfa. Unconventional approaches using reflectance measurements at multiple bands and the comparison of multiple VIs may be needed to adequately assess alfalfa yield, yield components, and stand variables, particularly when using “field-ready” multispectral sensors.
CHAPTER 3: THE EFFECT OF SUBSURFACE DRIP IRRIGATION (SDI) AND POTASSIUM NUTRITION ON ALFALFA YIELD

3.1. INTRODUCTION

Many studies have shown the benefits of irrigating alfalfa when soil moisture is limiting (e.g., Kisselbach et al., 1929; Lucey and Tesar, 1965; Carter and Sheaffer, 1983a; Undersander, 1987; Grimes et al., 1992; and Saeed and El-Nadi, 1997). However, irrigating alfalfa in the humid southeastern USA has resulted in increased yield (Kilmer et al., 1960; Jones et al., 1974), no effect on yield (Morris et al., 1992), or decreased yield because of increased disease and stand losses (Wahab and Chamblee, 1972; Rice et al., 1989). As a result, irrigating alfalfa in this region has been considered a marginal practice (Rice et al., 1989).

The association between potassium and disease resistance (e.g., Huber and Arny, 1985) and stand longevity (e.g., Lanyon and Smith, 1985; Berg et al., 2005) have been well established. The positive yield response to irrigation reported by Jones et al. (1974) was on soil high in plant available K. The effect of K fertility was not addressed in those studies where alfalfa yields declined in response to irrigation and increased disease pressure. In addition to potential positive impacts on disease resistance and stand longevity, irrigated alfalfa has been shown to be more responsive to K fertilization than when rainfed (Sheaffer et al., 1986). Work by Jones et al., (1974) suggests this increased responsiveness may be due to increased K removal from the soil from crop removal or leaching.

The cost of irrigation systems is another major limitation to the use of irrigation for alfalfa production in the southeastern USA (Rice et al., 1989; Morris et al., 1992). The irregular shape, small size, and terrain variability of fields in this region limit the use of center pivot or flood irrigation systems. However, micro-irrigation systems, such as subsurface drip irrigation (SDI), have gained recent interest because they are adaptive to field constraints and more economical than
center pivot or flood irrigation in small fields. SDI is defined as, the “application of water below the soil surface through emitters, with discharge rates generally in the same range as drip irrigation” (ASAE Standards, 1996). In addition to the adaptive nature and economics of the system, SDI has been shown to have significant advantages for alfalfa production, in the reduction in disease pressure, increasing water use efficiency (WUE); using low-quality or waste water from other farm enterprises; improving weed control; allowing irrigation before, during, and after harvest; and enhancing yields (Mead et al., 1992; Camp, 1998; Ayars et al., 1999; Alam et al., 2000; Alam et al., 2002a; 2002b; Lamm, 2002; and Godoy-Avilla et al., 2003).

The cost of the SDI systems and productivity relative to surface irrigation methods depend on the lateral spacing of the tapelines. Several studies have compared alfalfa yield from SDI and surface irrigation methods at various SDI tapeline spacings and depths (Hutmacher et al., 1992; Ayars et al. 1999; Hutmacher et al., 2001; Alam et al., 2000; 2002a; 2002b; Godoy-Avila et al., 2003) (Table 2-4). However, optimal spacing of emitters and spacing between tapelines has not been established. Research generally indicates that tapelines should be closer (1.0 - 1.5 m) and shallower (0.3 - 0.5 m) at higher water application rates (Alam et al., 2002a; 2002b; Trout et al., 2005). Recommendations by a leading manufacturer of SDI tape are for spacing tapelines on 1.0-m centers and at a depth of 0.30 - 0.63 m (T-Systems International, Inc. 2005). However, further research is needed to assess the optimum spacing for SDI of alfalfa. Because SDI tape spacing is fixed, proper planning is also needed to ensure that the distribution of the water between adjacent tapelines adequately accommodates the needs of various plant populations and row spacings of all likely crops (Lamm, 2002). The design of the system may need to be done site-specifically, as the optimum water application rate and tapeline spacing is dependent on the hydraulic properties of the soil (Alam et al., 2002a; 2002b; Trout et al., 2005).

The objectives of this study were to determine the feasibility of irrigating alfalfa in a humid region of the southeastern USA by studying the effect of SDI on
yield, determining if additional K fertilization is needed when SDI is used, assessing the impact of SDI and added K on crown density, and evaluating the effect of the water distribution provided by the system.

3.2. MATERIALS AND METHODS

This study was initiated at the University of Kentucky Animal Research Center (84° 44’ W long, 38° 4’ N lat) in April 2003 (Fig. 3-1). Although the 4.5-ha site consisted of one soil type (Maury silt loam, Typic hapludult, 2 to 6% slope) and had no apparent soil fertility trends, five blocks of two large plots (18.3 x 39.6 m) were delineated based on variations in the orientation of slope and depth to bedrock. Within a block, plots were randomly assigned rainfed (Rfed) and SDI (Irr) treatments.

Subsurface Drip Irrigation System Design

On 16, 17, and 23 April 2003, SDI tape (T-Tape 515-08-340, T-Systems International, Inc., San Diego, CA) was installed in the Irr plots (Fig. 3-2). The tape consisted of a 15.8-mm diameter tube with 380-μm thick walls and 13-mm emitter slits spaced at 0.20 m along the length of the tube. The tape was installed using a single parabolic chisel shank (Fig. 3-3a) along the plot length. The shank was attached to a toolbar, mounted on a 3-point hitch, and pulled using a tractor with ballast and front-wheel assist (John Deere Model 2755, Deere and Company, Moline, Ill.) (Fig. 3-3b). Since the installation shank was effectively a deep-tillage treatment, the shank was pulled through all plots with no tape installed in Rfed plots.

The shank was adjusted to install the tape at a depth of 0.38 m and tape lines were on 1.5-m centers. A shallower (0.30 m) and narrower spacing (1.0 m) is currently recommended for use in alfalfa production (T-Systems International, Inc., 2005). However, this design is a compromise between the 1.0- and 2.0-m spacings for which Hutmacher et al. (1992, 2001) and Ayars et al. (1999) found no consistent difference in alfalfa yields on a silty clay soil.
Fig. 3-1. Plot layout for the experiment evaluating SDI for use in alfalfa, including the blocks (grayscale), wholeplot irrigation treatments (irrigated as blue, rainfed as gray), and split-plots of four levels (0, 112, 336, and 448 kg of K$_2$O ha$^{-1}$) of potassium (K). The four split-plots in each of the whole-plots did not receive K treatment until late fall 2004, but were harvested as multiple observations in 2003 and 2004. Following the treatment with K, the split votes were harvested in 2005 and designated as experiment I. Also in 2005, experiment II consisted of four independent observations receiving similar K treatment that had been randomly located at each harvest on the opposite end of the whole-plot.
Fig. 3-2. The SDI tape (T-Tape 515-08-340, T-Systems International, Inc., San Diego, CA) used in the current study.
Fig. 3-3. A diagram of the parabolic shank used to install the SDI tape (A) (Adapted from a diagram on http://www.oznet.ksu.edu/sdi/) and a photo of a rainfed plot being subjected to the deep-tillage of the SDI shank (B) (Photo credit: Dr. Chad Lee, University of Kentucky). To treat the plots similarly with respect to the deep-tillage, the shank was pulled through all plots with no tape installed in Rfed plots.
Following the installation of the tape, a utility trencher was used to create a 46-cm trench perpendicular to the tape lines at the ends of the plots to locate pressure stabilization headers. Municipal water was filtered through three 3.2-mm² (200 mesh) stainless steel sieve filters placed in parallel and reduced in pressure to the recommended 55-70 kPa using a pressure reducing valve, before being routed to the headers. These specifications resulted in an application rate of 2.5 L hr⁻¹ m⁻¹ (3.7 mm ha⁻¹ h⁻¹). Irrigation was applied in a non-limiting manner based on an ET (open-pan estimate) replacement schedule and was adjusted for rainfall or stress-level canopy temperatures (Sheaffer et al., 1988).

Alfalfa Establishment and Management

Following the installation of SDI system, the site was prepared with conventional tillage and the alfalfa variety ‘Garst 631’ was planted using a Brillion seeder on 1 May 2003 at a rate of 20.2 kg ha⁻¹. Irrigation was not applied nor required during establishment. Weeds were suppressed in the establishment year with a tank-mixture of sethoxydim {2-[1-(ethoxyimino)butyl]-5-[2-(ethythio)propyl]-3-hyrdoxy-2-cyclohexen-1-one} and imaethapyr {(±)-2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1H-imidazol-2-yl]-5-ethyl-3-pyridine-carboxylic acid} at a rate of 0.6 kg ha⁻¹ and 0.1 kg ha⁻¹, respectively, 5 d following the first cutting. A post-harvest application of paraquat dichloride (1,1’-dimethyl-4,4’-bipyridinium dichloride) at a rate of 0.6 kg ha⁻¹ occurred on 27 June 2004 and 17 June 2005.

Two harvests were made in the establishment year of 2003, though the first was chopped and removed from the site on 24 June 2003 with no yield data collected because of substantial weed pressure. Before the second cutting on 27 August 2003, four 2.4 x 6.1 m split-plots with 0.6 m borders were flagged within each of the 10 alfalfa whole-plots. Split-plots were grouped together and randomly located within the larger whole plot, but the split-plots were oriented so that the harvest direction was parallel to the tapelines. The split-plots were harvested at each cutting thereafter; however, no treatments were applied to the split-plots until the fall of 2004. In 2004, four cuttings were taken: 18 May, 24
June, 2 August, and 23 September. Rainfall interrupted the 18 May 2004 harvest, leaving one replicate missing. Following the third harvest of 2004, soil samples (10-cm depth) indicated that plant available K (114 ppm) would limit alfalfa yield (Thom and Dollarhide, 1994). On 1 Oct. 2004, 0, 112, 336, and 448 kg K₂O ha⁻¹ were broadcast on sub-plots. In 2005, favorable harvest conditions enabled 5 harvests: 5 May, 15 June, 22 July, 23 August, and 30 September.

A second group of observations were harvested in 2005 and consisted of four, predetermined locations within each whole plot. These areas within the whole plots were all treated similarly and the locations were randomized for each cutting. The locations were harvested at the same time and in the same way as the split-plots. The two sets of observations in 2005, 2005_k (split-plots with four levels of topdress K) and 2005_o (random observation set) were analyzed separately.

All harvests in 2003 and 2004 were made at ½ bloom maturity, with the exception of 18 May 2004 which was at 1/10 bloom. All harvests in 2005 were made at 1/10 bloom maturity, with the exception of 23 August at ¼ bloom. All harvests were taken at a cutting height of 4 cm with a Hege Model 212 Forage Plot Harvester (Wintersteiger Ag, Niederlassung, Germany) and weighed to within ±0.1 kg. The cutting width of the plot harvester is 1.5 m. The length of the harvested area was restricted to 0.5 m from the ends of the plots and measured to within ±3 cm. Forage mass was corrected for dry weight after drying samples to a constant weight at 60° C in a forced air dryer.

**Shank vs. Between Comparisons**

Alfalfa stand estimates from four replicates per block of 0.1-m² quadrats on 26 June 2003 indicated that stem (710 ± 34 stems m⁻²) and apparent crown (445 ± 23 crowns m⁻²) densities did not differ (P > 0.05) between the plots prior to treatment. On 24 September 2004 and 21 April 2005, stem and crown density measurements were taken in two 0.1-m² quadrats randomly located in the area
directly over the zones subjected to the deep-tillage action of the SDI shank (Shank) and the area between these zones (Between).

Herbage samples were taken for yield estimation at a random Between and Shank location within each plot immediately prior to the second through fifth harvest of 2005. The two clippings were made at a height of 2 cm from 0.42 cm X 0.6-m strips using a Model HS 80 Stihl® (Stihl, Inc. Virginia Beach, VA) hedge trimmer. Herbage samples were placed in plastic bags and covered in ice within coolers for transport to a 2° C laboratory refrigerator. The number of apparent crowns in the clipped area was recorded. Within 1 wk of harvest, herbage samples were separated into alfalfa and weeds and for the determination of alfalfa yield components. Methods and results of the yield component analysis are described in Chapter 4. Herbage samples were dried to a constant weight at 60° C in a forced air dryer. Weed content of herbage samples were negligible and showed no discernable trend.

To determine if there was a significant difference between measured variables in Shank and Between locations the data were expressed as the normalized ratio (NR) as in Eq. [3.1].

\[
[3.1] \quad NR = \left( \frac{\text{Shank}}{\text{Between}} \right) - 1
\]

**Spatial Effects of Applied Water**

Within 1 wk of irrigation for the third cutting in 2005, visual patterns in crop color and growth revealed variable distribution of SDI-applied water. As the drought intensified during the fourth cutting, a sharp demarcation between well-watered alfalfa near the tapeline and that midway between the tapelines became apparent. On 8 August, in advance of a forecast rain event, flags were placed at the visually assessed edge of the well-watered alfalfa perpendicular to each of the 11 tape lines at both ends of whole-plots. On 17 August, the location of each flag was recorded to ±1.5 cm using an AgGPS® 214 High Accuracy RTK GPS system (Trimble Navigation Limited, Sunnyvale, CA) mounted to a range pole.
These data points were recorded on a handheld computer using Farm Site Mate (CTN Data Service, Inc.’s Farmworks Software, Hamilton, IN). Tapelines were georeferenced with ArcGIS 9.1 (Environmental Systems Research Institute, Inc., Redlands, CA) and used to estimate the area of well-watered alfalfa. The centroid of each line and the distance between the 11 centroids at each end of the plot was also estimated.

All data were analyzed using the PROC MIXED procedure in SAS 9.1 (Littell et al., 1996).

### 3.3. RESULTS AND DISCUSSION

Rainfall and the amount of irrigation applied in the 1 April - 30 September varied considerably between the growing seasons of 2003, 2004, and 2005 (Fig. 3-4). Rainfall in 2003 and 2004 during this period ranked as the 2nd and 6th wettest years in the 111 yr of available weather data (Agricultural Weather Center, 2005). However, rainfall was poorly distributed in 2003 and resulted in the application of 60 mm of water during the second growth cycle. Rainfall was well-distributed in 2004, requiring no irrigation. However, the growing season of 2005 was the 2nd driest year on record for central Kentucky. Rainfall during April-September 2005 totaled 343 mm, was poorly distributed, and was only 55% of the 111-yr average for this period (Agricultural Weather Center, 2005). No supplementary water was required during growth of the first harvest and less than 13 mm of water was applied to the second and fifth cuttings. However, dry conditions during both the third and fourth cutting required substantial supplementary water (74 and 98 mm, respectively).

**Irrigation Uniformity and Distribution**

Several researchers have reported that sediment, mineral accumulation, or root intrusion into the emitter slits resulted in irregular growth patterns directly over the tape and that blockage increased with system age (Camp, 1998). Growth pattern irregularities associated with emitter blockages were not
Fig. 3-4. Rainfall (blue bars) and irrigation (green bars) applications and harvest dates (black bars) of alfalfa for the 2003 (A), 2004 (B), and 2005 (C) growing seasons of 1 April - 30 September (Day 91-273).
observed in the 3 yr of this study. However, the close emitter spacing (20 cm), relative to the studies cited by Camp (1998), may have compensated for any blockages.

Analysis of the width of the well-watered alfalfa strips indicated no differences (P > 0.05) between blocks and an overall average of 82 cm (± 8.0 cm: 95% CI). From this data tapelines were calculated to be on 152 cm (± 3.0 cm: 95% CI) centers and is in agreement with the intended installation of tapelines on 1.5 m centers. Comparing the width of the well-watered alfalfa of the tapelines with the distance between tapelines shows that only 54% of the area was well-watered in the current study.

Nonetheless, these findings indicate that a tape spacing of 1.5 m was too wide to uniformly distribute the added water for alfalfa. These data provide evidence to suggest a spacing of 1.0-m would allow contiguous strips of well-watered alfalfa. However, the optimal spacing does not depend on a visual assessment of the well-watered extent, but rather requires consideration of yield differences across the spacing width.

Yield Response to Irrigation

Despite receiving some added water, alfalfa did not respond to SDI during the second cutting of the establishment year (Table 3-1). Because of adequate rainfall in 2004, alfalfa yields from the Irr plots did not significantly differ from the Rfed plots for any cutting or the seasonal total. In 2005, yield responses to the supplemented water were generally positive. No significant interactions between the effects of irrigation and K treatments were observed (Table 3-2). Therefore, the main effects of irrigation and K will be presented separately.

Total DM yield in 2005 was improved by SDI (11.07 vs. 9.93 Mg ha⁻¹) when averaged over K treatments in the split-plots of 2005ᵦ and when averaged across the multiple observations of 2005ₒ (11.93 vs. 9.79 Mg ha⁻¹). No irrigation was applied and no yield response was observed in the SDI plots of either observation set in harvest 1. Yield at the second harvest was found to be improved (P < 0.05) by SDI in the multiple observations of 2005ₒ, despite
Table 3-1. Average alfalfa dry matter yield and the standard error (SE$_d$) and probability (P) values for the difference in yield between the subsurface drip irrigated and rainfed plots for each cutting and seasonal total in 2003 and 2004 and two observation sets (2005$_{K}$ and 2005$_{o}$) in 2005.

<table>
<thead>
<tr>
<th>Year†</th>
<th>Treatment</th>
<th>Harvest</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>Irrigated</td>
<td>-</td>
<td>2.77</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Rainfed</td>
<td>-</td>
<td>2.56</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>SE$_d$</td>
<td>-</td>
<td>0.177</td>
<td>-</td>
<td>-</td>
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<td></td>
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<td>-</td>
<td>0.2985</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2004</td>
<td>Irrigated</td>
<td>3.85‡</td>
<td>3.18</td>
<td>3.02</td>
<td>0.92</td>
<td>-</td>
<td>8.71</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rainfed</td>
<td>5.28</td>
<td>3.60</td>
<td>3.32</td>
<td>0.93</td>
<td>-</td>
<td>9.27</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SE$_d$</td>
<td>0.698</td>
<td>0.467</td>
<td>0.253</td>
<td>0.235</td>
<td>-</td>
<td>0.831</td>
<td></td>
</tr>
<tr>
<td></td>
<td>P-value</td>
<td>0.0876</td>
<td>0.3966</td>
<td>0.3052</td>
<td>0.8989</td>
<td>-</td>
<td>0.5277</td>
<td></td>
</tr>
<tr>
<td>2005$_{K}$</td>
<td>Irrigated</td>
<td>3.23</td>
<td>2.71</td>
<td>1.52</td>
<td>2.15</td>
<td>1.46</td>
<td>11.07</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rainfed</td>
<td>3.41</td>
<td>2.77</td>
<td>1.37</td>
<td>0.75</td>
<td>1.63</td>
<td>9.93</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SE$_d$</td>
<td>0.434</td>
<td>0.166</td>
<td>0.123</td>
<td>0.153</td>
<td>0.049</td>
<td>0.520</td>
<td></td>
</tr>
<tr>
<td></td>
<td>P-value</td>
<td>0.6971</td>
<td>0.7209</td>
<td>0.2680</td>
<td>0.0008</td>
<td>0.0030</td>
<td>0.0425</td>
<td></td>
</tr>
<tr>
<td>2005$_{o}$</td>
<td>Irrigated</td>
<td>3.32</td>
<td>2.57</td>
<td>1.89</td>
<td>2.25</td>
<td>1.79</td>
<td>11.93</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rainfed</td>
<td>3.35</td>
<td>2.05</td>
<td>1.33</td>
<td>0.75</td>
<td>2.06</td>
<td>9.79</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SE$_d$</td>
<td>0.361</td>
<td>0.228</td>
<td>0.069</td>
<td>0.119</td>
<td>0.122</td>
<td>0.539</td>
<td></td>
</tr>
<tr>
<td></td>
<td>P-value</td>
<td>0.9301</td>
<td>0.0320</td>
<td>0.0009</td>
<td>&lt;0.0001</td>
<td>0.0892</td>
<td>0.0083</td>
<td></td>
</tr>
</tbody>
</table>

† In 2003 and 2004, yield measurements were taken from within each irrigated or rainfed plot at the same four, identically-treated locations at each harvest. On 1 October 2004, four rates of K topdressing were applied to each of these four locations creating split-plots within irrigated and rainfed whole-plots. In 2005, yield measurements were taken from these split-plots (2005$_{K}$). Additional yield measurements were made in 2005 (2005$_{o}$) at four locations within each irrigated or rainfed whole-plot (at the opposite end, relative to the K topdressing split-plots) and were randomly located for each growing cycle.

‡ The first harvest in 2004 was interrupted after the harvest of four replications.
Table 3-2. Probability (P) values for the effects of irrigation, K rate, and the interaction of those effects on alfalfa yield for the five cuttings and total yield in 2005.

<table>
<thead>
<tr>
<th>Location</th>
<th>Effect</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plot</td>
<td>Irrigation</td>
<td>0.6971</td>
<td>0.7209</td>
<td>0.2680</td>
<td>0.0025</td>
<td>0.0030†</td>
<td>0.0425</td>
</tr>
<tr>
<td>K rate</td>
<td></td>
<td>0.1196</td>
<td>0.2974</td>
<td>0.3770</td>
<td>0.1967</td>
<td>0.6426</td>
<td>0.0201</td>
</tr>
<tr>
<td>Irr*K rate</td>
<td></td>
<td>0.9325</td>
<td>0.3914</td>
<td>0.1721</td>
<td>0.8105</td>
<td>0.7663</td>
<td>0.8472</td>
</tr>
<tr>
<td>K rate</td>
<td>Linear</td>
<td>0.0603</td>
<td>0.1384</td>
<td>0.1541</td>
<td>0.1212</td>
<td>0.9351</td>
<td>0.0110</td>
</tr>
<tr>
<td></td>
<td>Quadratic</td>
<td>0.1301</td>
<td>0.7300</td>
<td>0.3250</td>
<td>0.3205</td>
<td>0.3710</td>
<td>0.0767</td>
</tr>
<tr>
<td></td>
<td>Cubic</td>
<td>0.7310</td>
<td>0.2457</td>
<td>0.8086</td>
<td>0.2805</td>
<td>0.3739</td>
<td>0.8566</td>
</tr>
<tr>
<td>SHANK</td>
<td>Irrigation</td>
<td>-</td>
<td>0.3626</td>
<td>0.0179</td>
<td>&lt;0.0001</td>
<td>0.5923</td>
<td>0.0145</td>
</tr>
<tr>
<td>K rate</td>
<td></td>
<td>-</td>
<td>0.1731</td>
<td>0.4688</td>
<td>0.0315</td>
<td>0.9632</td>
<td>0.4164</td>
</tr>
<tr>
<td>Irr*K rate</td>
<td></td>
<td>-</td>
<td>0.2477</td>
<td>0.2741</td>
<td>0.5732</td>
<td>0.3817</td>
<td>0.4873</td>
</tr>
<tr>
<td>K rate</td>
<td>Linear</td>
<td>-</td>
<td>0.0805</td>
<td>0.1351</td>
<td>0.0401</td>
<td>0.8170</td>
<td>0.1308</td>
</tr>
<tr>
<td></td>
<td>Quadratic</td>
<td>-</td>
<td>0.2916</td>
<td>0.7822</td>
<td>0.5732</td>
<td>0.6732</td>
<td>0.5369</td>
</tr>
<tr>
<td></td>
<td>Cubic</td>
<td>-</td>
<td>0.3291</td>
<td>0.7032</td>
<td>0.3611</td>
<td>0.8608</td>
<td>0.7406</td>
</tr>
<tr>
<td>CENTER</td>
<td>Irrigation</td>
<td>-</td>
<td>0.6512</td>
<td>0.3377</td>
<td>0.0673</td>
<td>0.4597</td>
<td>0.1463</td>
</tr>
<tr>
<td>K rate</td>
<td></td>
<td>-</td>
<td>0.0369</td>
<td>0.6241</td>
<td>0.6496</td>
<td>0.0788</td>
<td>0.0462</td>
</tr>
<tr>
<td>Irr*K rate</td>
<td></td>
<td>-</td>
<td>0.5082</td>
<td>0.4982</td>
<td>0.8927</td>
<td>0.2534</td>
<td>0.3197</td>
</tr>
<tr>
<td>K rate</td>
<td>Linear</td>
<td>-</td>
<td>0.0204</td>
<td>0.8588</td>
<td>0.3211</td>
<td>0.0374</td>
<td>0.0101</td>
</tr>
<tr>
<td></td>
<td>Quadratic</td>
<td>-</td>
<td>0.1432</td>
<td>0.2847</td>
<td>0.4363</td>
<td>0.0983</td>
<td>0.6425</td>
</tr>
<tr>
<td></td>
<td>Cubic</td>
<td>-</td>
<td>0.1373</td>
<td>0.4629</td>
<td>0.9108</td>
<td>0.9915</td>
<td>0.2783</td>
</tr>
<tr>
<td>NR</td>
<td>Irrigation</td>
<td>-</td>
<td>0.9093</td>
<td>0.3761</td>
<td>0.0433</td>
<td>0.1571</td>
<td>0.7172</td>
</tr>
<tr>
<td>K rate</td>
<td></td>
<td>-</td>
<td>0.7903</td>
<td>0.3054</td>
<td>0.6207</td>
<td>0.0603</td>
<td>0.7516</td>
</tr>
<tr>
<td>Irr*K rate</td>
<td></td>
<td>-</td>
<td>0.3057</td>
<td>0.8484</td>
<td>0.7395</td>
<td>0.4634</td>
<td>0.7048</td>
</tr>
<tr>
<td>K rate</td>
<td>Linear</td>
<td>-</td>
<td>0.5611</td>
<td>0.2066</td>
<td>0.4905</td>
<td>0.0324</td>
<td>0.4899</td>
</tr>
<tr>
<td></td>
<td>Quadratic</td>
<td>-</td>
<td>0.9239</td>
<td>0.1751</td>
<td>0.6459</td>
<td>0.0820</td>
<td>0.4973</td>
</tr>
<tr>
<td></td>
<td>Cubic</td>
<td>-</td>
<td>0.4252</td>
<td>0.6691</td>
<td>0.3056</td>
<td>0.9067</td>
<td>0.6265</td>
</tr>
</tbody>
</table>

† The significant difference between SDI and rainfed irrigation treatments from harvest 5 was negative (0.65 vs. 0.73, respectively).
receiving only 13 mm of water. However, the split-plots of 2005\textsubscript{K} failed (P > 0.05) to show the same response. Similarly, yield at the third harvest responded (P = 0.0009) to the SDI only in the 2005\textsubscript{o} observation set (1.89 vs. 1.33 Mg ha\textsuperscript{-1}), despite the application of 74 mm of water. During the last 10 d of the third growth cycle, a persistent storm system (remnants of hurricane ‘Dennis’) dropped 40 mm of rainfall and held temperatures cooler. This weather may have contributed to the discrepancy between yield response to SDI in the third cutting of the 2005\textsubscript{K} and 2005\textsubscript{o} observation sets. In addition, drought-suppressed growth patterns consistent with a response to shallow bedrock depths was observed to be more common at the random locations of observations in the 2005\textsubscript{o} dataset than in the plots of 2005\textsubscript{K}. This variability in depth to bedrock may have further contributed to the disparity between the yield responses to SDI in the 2005\textsubscript{K} and 2005\textsubscript{o} observation sets.

When averaged across the K treatments, yield responded (P = 0.0008) to SDI (2.15 vs. 0.75 Mg ha\textsuperscript{-1}) in the fourth harvest but were slightly depressed (P = 0.0030) by SDI (1.46 vs. 1.63 Mg ha\textsuperscript{-1}) at the fifth harvest in the split-plots of 2005\textsubscript{K}. In the additional observation set of 2005\textsubscript{o}, yields responded similarly to SDI in the fourth cutting but were only marginally depressed (P = 0.0892) by SDI in the fifth harvest. Alfalfa that has been previously stressed by drought has been observed to grow faster and yield more than non-stressed alfalfa (e.g., Metochis and Orphanos 1981; Takele and Kallenback, 2001). Such compensatory growth may explain the negative yield response to SDI during the fifth harvest, as 90 mm of rain fell within 9 d following the fourth harvest.

Somewhat similar yield results occurred in the analysis of clipped yields at the Shank and Between locations (Table 3-3). However, direct comparisons are limited between the whole-plot data and the hand-clipped samples because of differences in clipping height and a more complete biomass collection when done by hand. These sampling differences are most apparent in the third, fourth, and fifth harvests when drought-affected growth was much shorter. Nonetheless, the hand-clipped samples from the Shank and Between locations allow additional observations and of irrigation distribution variation.
Table 3-3. Mean alfalfa dry matter yield for each of the final four harvests and the sum of these yields between the subsurface drip irrigated and rainfed plots. Observations were taken from directly over zones subjected to deep-tillage (Shank) and zones near the mid-point between deep-tillage zones (Between) within the K split-plots in 2005 (2005k) and a normalized ratio (NR)† was calculated from the yields in these areas.

<table>
<thead>
<tr>
<th>Location</th>
<th>Treatment‡</th>
<th>Harvest</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Total§</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shank</td>
<td>Irrigated</td>
<td>2.82</td>
<td>2.34</td>
<td>2.82</td>
<td>2.47</td>
<td>9.80</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rainfed</td>
<td>2.49</td>
<td>1.76</td>
<td>1.14</td>
<td>2.69</td>
<td>8.08</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SE_d</td>
<td>0.349</td>
<td>0.230</td>
<td>0.215</td>
<td>0.388</td>
<td>0.647</td>
<td></td>
</tr>
<tr>
<td></td>
<td>P-value</td>
<td>0.3626</td>
<td>0.0179</td>
<td>&lt;0.0001</td>
<td>0.5923</td>
<td>0.0145</td>
<td></td>
</tr>
<tr>
<td>Between</td>
<td>Irrigated</td>
<td>2.89</td>
<td>2.07</td>
<td>2.14</td>
<td>2.63</td>
<td>9.74</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rainfed</td>
<td>2.72</td>
<td>1.80</td>
<td>1.28</td>
<td>2.26</td>
<td>8.09</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SE_d</td>
<td>0.372</td>
<td>0.268</td>
<td>0.864</td>
<td>0.479</td>
<td>0.715</td>
<td></td>
</tr>
<tr>
<td></td>
<td>P-value</td>
<td>0.6512</td>
<td>0.3377</td>
<td>0.0673</td>
<td>0.4597</td>
<td>0.0294</td>
<td></td>
</tr>
<tr>
<td>NR†</td>
<td>Irrigated</td>
<td>0.066 ns</td>
<td>0.265 ns</td>
<td>0.584 *</td>
<td>0.032 ns</td>
<td>0.046 ns</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rainfed</td>
<td>0.084 ns</td>
<td>0.036 ns</td>
<td>0.092 ns</td>
<td>0.224 *</td>
<td>0.013 ns</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SE_d</td>
<td>0.1531</td>
<td>0.2439</td>
<td>0.2336</td>
<td>0.1101</td>
<td>0.0921</td>
<td></td>
</tr>
<tr>
<td></td>
<td>P-value</td>
<td>0.9093</td>
<td>0.3761</td>
<td>0.0433</td>
<td>0.0907</td>
<td>0.7172</td>
<td></td>
</tr>
</tbody>
</table>

* ** *** Significant at the 0.05 0.01, and 0.001 probability levels, respectively.
† NR = (Shank/Between-1)
‡ SE_d = Standard error for the measured difference.
§ Total yield from the four harvests from which clippings were obtained.
In contrast to the yields of split-plots, the yields at the Shank location increased ($P = 0.0179$) with irrigation for the third harvest (2.34 vs. 1.76 Mg ha$^{-1}$), but the fifth harvest yields were unaffected ($P > 0.05$) (Table 3-2). In general, however, irrigation response at the Shank locations was similar to that of the whole-plots. As in the plot harvest, clipped yields at the fourth harvest were significantly ($P < 0.0001$) higher in the Irr plots at the Shank location as compared to the Rfed control (2.82 vs. 1.14 Mg ha$^{-1}$, respectively). This contributed to an irrigation effect ($P < 0.05$) for the four-harvest totals at the Shank locations (9.80 vs. 8.08 Mg ha$^{-1}$, respectively). Despite the lack ($P > 0.05$) of an irrigation effect on yields at the Between location at each cutting, the four-harvest total was significantly increased by irrigation (9.74 vs. 8.09 Mg ha$^{-1}$). Furthermore, the NR of the Irr plots at harvest 4 (0.584) was greater than zero ($P < 0.05$) and was different ($P < 0.05$) from the NR of the Rfed plots. This analysis of the NR, in combination with the absence of an irrigation effect at the Between location, indicates that not enough water was moving into the area between the tapelines during harvests 3 and 4 to enable growth in the Between locations to keep pace with growth in Shank locations. This contributed to the overall lack of irrigation effect in harvest 3 as observed from the yield measured from the entire plot. The poor inter-tapeline dispersion also reduced the effect of irrigation on the plot yields in harvest 4.

Therefore, it is clear from the results of harvests 3 and 4 that the 1.5-m lateral spacing was too wide to supply water to soil between the tapelines and a significant area of alfalfa in these zones appeared to be suffering soil moisture deficit during the height of the drought. These findings are in agreement with data from Alam et al. (2000, 2002a, 2002b), which showed a yield penalty when tapeline spacing was increased from 1.0 to 1.5 m in sandy loam soil. However, these findings are in conflict with the results of Hutmacher et al. (1992, 2001) and Ayars et al. (1999) who found no consistent difference between lateral spacings of 1.0 m and 2.0 m in a silty clay soil.

Comparing the differences in the silt loam soil type of the current study and the silty clay of Hutmacher et al. (1992, 2001) and Ayars et al. (1999), one
might suspect that the silty clay soil would have a more lateral water flow than in our silt loam soil type (Trout et al., 2005). One other difference is that the closer emitter spacing along the tapelines of the current study may have created an application rate that was substantially higher than that of Hutmacher et al. (1992, 2001) and Ayars et al. (1999). Data by Trout et al. (2005) suggest that application rates greater than 3.0 L hr⁻¹ m⁻¹ may decrease the horizontal:vertical distribution ratio and lead to less uniform application between tapelines. However, the application rate of the current study was 2.5 L hr⁻¹ m⁻¹ and near the region where the horizontal:vertical distribution ratio reached a maximum for the conditions studied by Trout et al. (2005).

Additional research will be required to determine the discrepancy between the current findings and that of Hutmacher et al. (1992, 2001) and Ayars et al. (1999). None-the-less, these findings indicate that the 1.5-m spacing of tapelines was too wide to uniformly distribute water for alfalfa under the prevailing conditions. Because the distribution of water between tapelines is not independent of the depth (Trout et al., 2005), further work is needed to determine optimum tapeline spacing. Further, differences in soil type and resultant variations in the hydraulic properties of the soil may require the depth and spacing to be optimized site-specifically between regions, farms, and perhaps within a field.

**Economic Analysis using Multiyear Weather Data**

To evaluate the SDI system over its design lifespan of 20 years (Lamm et al., 2002), potential alfalfa yield responses were estimated for 1986 - 2005 using data from the Kentucky Agricultural Experiment Station - Spindletop Research Farm weather station (84° 29' W 38° 8' N; about 24 km from research site). From 1986 - 2005, rainfall totals for the 30 d preceding three harvests on 15 June, 22 July, and 23 August were at or below the 2005 totals in 4, 15, and 5 years, respectively. If the yield response for these occasions were similar to the significant response observed in the second, third, and fourth harvests within the 2005₀ observation set, then an additional 18 Mg ha⁻¹ of alfalfa dry matter could have been harvested. At current prices ($225 - 310 Mg⁻¹) for premium quality
alfalfa (RFV = 170-180), gross returns over the 20 yrs would have increased by $4,050 - 5,580 ha⁻¹. Using 2005 irrigation data for these three harvests, over 16,500 m³ of irrigation water would be required. Assuming that SDI installation cost was $1,800 ha⁻¹ (Lamm et al., 2002) and the alfalfa value was $310 Mg⁻¹, the break-even price of water would be $0.23 m⁻³ [($5,580 - $1,800 ha⁻¹) / 16,500 m³ of water].

Thus, SDI would likely not be economically feasible in this region, unless placed in specific sites where the response to irrigation would be large relative to the cost of the water and irrigation system. Further work would be needed to determine if site-specific installation would yield a significant return.

**Yield Response to Potassium**

No significant (P > 0.10) K treatment effect on the yield of the sub-plots was observed in any of the five harvests (Table 3-2). However, a significant (P < 0.05) K effect was observed in the total plot yield for 2005. The total 2005 yield from plots provided no K were significantly lower than the 336 and 448 kg K₂O ha⁻¹ (9.63 vs. 11.25 and 10.86 Mg ha⁻¹, respectively), but was not different from 112 kg K₂O ha⁻¹ (10.54 Mg ha⁻¹) (Table 3-4). Although our data suggest a significant linear (P = 0.0110) and a smaller quadratic effect (P < 0.10), the lack of difference between the 112, 336, and 448 kg K₂O ha⁻¹ treatment levels indicate a yield response plateau above 112 kg K₂O ha⁻¹. This is consistent with the plateau reported by Thom and Dollarhide (1994) for this soil type and at similar plant available soil K levels.

Analysis of yield estimates at the Between location showed a K effect (P < 0.05) on the yields of the second harvest and the total yield of the four clippings. In both, the application of 336 kg K₂O ha⁻¹ resulted in significantly (P < 0.05) greater yield than in the 0 kg K₂O ha⁻¹ treatment. However, the yield from the second harvest and four-harvest total was not significantly (P > 0.05) different between the 0, 112, and 448 kg K₂O ha⁻¹ treatments. This occurred despite a significant linear trend (P < 0.05) in both harvests. Orthogonal contrasts indicated no quadratic trend (P > 0.05). In the Shank locations, only the fourth harvest exhibited a K treatment effect (P < 0.05), where the 448 kg K₂O ha⁻¹
Table 3-4. Average alfalfa dry matter yield from plots given 0, 112, 336, or 448 kg K₂O ha⁻¹ in Experiment I for each cutting and seasonal total for 2005.

<table>
<thead>
<tr>
<th>Location Effect</th>
<th>Harvest 1</th>
<th>Harvest 2</th>
<th>Harvest 3</th>
<th>Harvest 4</th>
<th>Harvest 5</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plot</td>
<td>0</td>
<td>112</td>
<td>336</td>
<td>448</td>
<td>LSD</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.82 ab</td>
<td>2.77 ab</td>
<td>3.29 a</td>
<td>2.22 a</td>
<td>0.365</td>
<td>0.213</td>
</tr>
<tr>
<td></td>
<td>2.27 a</td>
<td>2.03 a</td>
<td>1.93 a</td>
<td>2.02 a</td>
<td>0.366</td>
<td>0.240</td>
</tr>
<tr>
<td>Shank</td>
<td>0</td>
<td>112</td>
<td>336</td>
<td>448</td>
<td>LSD</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.98 b</td>
<td>2.36 ab</td>
<td>2.39 ab</td>
<td>2.99 ab</td>
<td>1.198</td>
<td>0.627</td>
</tr>
<tr>
<td></td>
<td>2.07 a</td>
<td>2.12 a</td>
<td>2.22 a</td>
<td>2.02 a</td>
<td>1.198</td>
<td>0.627</td>
</tr>
<tr>
<td>Between</td>
<td>0</td>
<td>112</td>
<td>336</td>
<td>448</td>
<td>LSD</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.99 ab</td>
<td>3.36 a</td>
<td>3.38 a</td>
<td>3.38 a</td>
<td>1.021</td>
<td>0.663</td>
</tr>
<tr>
<td></td>
<td>2.67 a</td>
<td>2.03 a</td>
<td>1.93 a</td>
<td>2.02 a</td>
<td>1.021</td>
<td>0.663</td>
</tr>
<tr>
<td>NR†</td>
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<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td></td>
</tr>
<tr>
<td></td>
<td>112</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td></td>
</tr>
<tr>
<td></td>
<td>336</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td></td>
</tr>
<tr>
<td></td>
<td>448</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td></td>
</tr>
</tbody>
</table>

*†*** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

**NR = (Shank/Between)⁻¹**
treatment improved yields over the 0 kg K₂O ha⁻¹ treatment (P < 0.05), but was similar to the 112 and 336 kg K₂O ha⁻¹ treatments.

However, there was no (P > 0.05) effect of K on the normalized ratio of Shank to Between locations for any harvest or the four-harvest total. Therefore, there is no evidence to suggest that K differentially affected yield at the Shank relative to Between locations. This lack of difference in yields between the well-watered Shank locations and drier Between locations and the absence of an interaction between K fertilization and irrigation, indicate that the yield response to K was independent of soil moisture and rainfall. These results are at odds with the findings of Sheaffer et al. (1986) who found that irrigated alfalfa was more responsive to K fertilization than rainfed alfalfa. The study by Sheaffer et al. (1986) was a much longer term evaluation and may have been influenced by K crop removal. Still, these results corroborate the importance of K fertilization in the maintenance of high alfalfa yields found by Sheaffer et al. (1986) and those of Thom and Dollarhide (1994) on a similar soil type and plant available K level, regardless of variations in available soil moisture.

**Effects of SDI and Potassium on Crown Density**

Alfalfa crown density did not differ (P > 0.05) at any time between irrigation or K treatments, regardless of location within the plot. The lack of response of crown density to irrigation is in contrast to the results of Wahab and Chamblee (1972); and Rice et al. (1989). The absence of response of crown density to K treatment may be a result of sufficient levels of plant available K in the soil (Berg et al., 2005). Nonetheless, crown density decreased substantially between 24 September 2004 and 15 June 2005 (46.8 ± 2.19 vs. 28.5 ± 1.31 crowns m⁻², respectively) and with each subsequent cutting (26.2 ± 0.90 vs. 23.9 ± 0.84 vs. 18.0 ± 0.62 crowns m⁻², respectively); however, this trend with stand age is well established and occurs even when soil fertility is not limiting (e.g., Berg et al., 2005).
3.4. CONCLUSION

When moderate or severe drought limits available soil moisture, SDI has the potential to increase DM yields by a factor of 1.3 to 3.0. This yield increase alone may not justify the installation of a SDI system throughout a field at this particular location. However, the adaptability and flexibility of the SDI system offers the opportunity to apply water to specific sites where poor water holding capacity chronically limits alfalfa yield.

Although others have shown the importance of higher potassium fertility to the long-term productivity of irrigated relative to rainfed alfalfa, our results indicate that potassium influences yield response regardless of available soil moisture. Nonetheless, our results corroborate the findings of others as to the importance of potassium fertility in the maintenance of high yields in alfalfa.

Unlike evaluations of surface irrigation in other parts of the southeastern USA, the use of SDI was not associated with losses in crown density. The lack of crown density response to K treatment or an interaction with SDI suggests plant available K in the soil was sufficient to sustain highly productive stands.

The tapeline spacing of 1.5-m, at least when placed at a 0.38-m depth in a silt loam soil type, does not sufficiently distribute water between the tapelines and may not optimize yields under severe drought conditions. Despite potential yield gains, closer tapeline spacing may not be economically feasible. Our data suggests that the fixed cost of the installed system could have been recovered during the previous 20-year period of 1986-2005. However, the use of SDI to supplement soil moisture for alfalfa would only be feasible in the southeastern USA if variable costs, such as maintenance, management, and the cost of water can be kept below $0.20 - 0.25 m⁻³ of added water.

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CHAPTER 4: THE EFFECT OF SOIL MOISTURE AND POTASSIUM DEFICIT ON THE COMPONENTS OF ALFALFA YIELD

4.1. INTRODUCTION

Researchers and producers have sought to identify a characteristic or set of easily measured characteristics that could predict alfalfa yield. Most approaches have focused on variables such as shoot length, stem diameter/strength, and LAI. Yet, these methods largely rely on empirical relationships between these variable(s) and alfalfa yield. By deconstructing yield into components and assessing how these components are affected by yield limiting factors, the mechanism behind yield variations and the associations between yield and yield components could be better understood.

Early yield component approaches described alfalfa yield as the product of three basic yield components: plant density, shoots plant\(^{-1}\), and mass shoot\(^{-1}\) (Volenec et al., 1987). More recent findings have shown that alfalfa yield rarely correlates well with plant density until stands have thinned beyond economic thresholds for renovation (Undersander et al., 1998; Berg et al., 2005). Undersander et al. (1998) recommends the use of the simplified variable of shoot density (shoots m\(^{-2}\)) because it was related to alfalfa yield and predictive of yields and stand density. Recent work by Berg et al. (2005) showed that mass shoot\(^{-1}\) was related (P < 0.0001) and explained much more of the variation in yield (avg. R\(^2\): 0.63 vs. 0.18, respectively) than shoot density (Berg et al., 2005).

Potassium is one of the most limiting nutrients to alfalfa production, and spatial variation in plant available soil K have been associated with variations in alfalfa yield (Lanyon and Smith, 1985; Leep et al., 2000; Undersander et al., 2004; Berg et al., 2005). Berg et al. (2005) analyzed the effects of P and K nutrition and their interaction on yield components in alfalfa. They found that the addition of P and K nearly always increased mass shoot\(^{-1}\) linearly and affected total alfalfa yield by a similar proportion (Berg et al., 2005). Unfortunately, the response of these yield components to soil moisture stress has not been
elucidated. This response is important to understand, as the evidence is clear that soil water-holding and supply capacities create variation in plant available soil moisture that are the largest source of yield variation within a field (e.g., Carlson, 1990; Mulla et al., 1992; Dale and Daniels, 1995).

Variability in yield limiting factors, such as plant available soil moisture and plant available soil K within a field, has spurred interest in site-specific management (SSM) strategies for alfalfa (Leep et al., 2002; South et al., 2002). To gauge the need for and the response to SSM strategies in alfalfa, monitoring and georeferencing yield variations within an alfalfa field are needed. Measurement of mass flow through or the dynamic weight change of forage harvest equipment has been used to measure forage yield, but these are subject to many sources of error and are not yet commercially available (e.g., Martel and Savoie, 2000; Savoie et al., 2002; Shinners et al., 2003). Devices such as the pasture ruler and rising plate meter are commercially available, but these devices do not provide sufficient accuracy and are not used at a sufficient resolution to characterize yield variations (Michalk and Herbert, 1977; Sanderson et al., 2001).

Advances in remote sensing and the availability of field-ready multispectral spectroradiometers may hold greater potential for the site-specific assessment of alfalfa yield. Remotely sensed canopy reflectance has been successfully related to alfalfa yield and shown to accurately depict yield variation in alfalfa pastures and hayfields (Mitchell et al., 1990; Guan and Nutter 2002a, 2002b, and 2004). For example, Guan and Nutter (2002a, 2002b, and 2004) found reflectance at a specific wavelength (810 nm) was linearly related to LAI ($r^2 = 0.58 \pm 0.21$ 95% CI) and yield ($r^2 = 0.62 \pm 0.18$ 95% CI). Earlier work by Mitchell et al. (1990) showed even better relationships ($r^2 > 0.80$) between alfalfa yield and combinations of reflectance values at red and NIR wavebands.

In each of the above systems, much is unknown regarding the links between the physiological and morphological responses to environmental stress, changes in yield components and the predictive ability of various models. Therefore, the objectives of this study were to i) evaluate the relationships between yield, yield components, and proxies for yield; ii) determine which
canopy variable is most relevant to and useful for predicting alfalfa yield under a wide range of soil moisture and plant available K levels, and iii) determine how variations in soil moisture and plant available K levels affect these yield components and proxies for yield.

4.2. MATERIALS AND METHODS

A project evaluating the effect of subsurface drip irrigation (SDI) on alfalfa and other cropping systems was initiated at the University of Kentucky Animal Research Center (84° 44’ W long, 38° 4’ N lat) in 2003 (Fig. 3-1). The 4.5-ha site consisted of one soil type (Maury silt loam, Typic hapludult, 2 to 6% slope) and minimal initial variation in soil fertility. However, five blocks of two large plots (18.3 x 39.6 m) were delineated for alfalfa based on variations in the orientation of slope and depth to bedrock in order to maximize SDI uniformity. Within a block, plots were randomly assigned rainfed (Rfed) and SDI (Irr) treatments.

In April 2003, SDI tape (T-Tape 515-08-340, T-Systems International, Inc., San Diego, CA) was installed in the Irr plots (Fig. 3-2). The tape had 13-mm emitter slits spaced at 0.20 m along the length of the tube and was installed using a single parabolic chisel shank (Fig. 3-3a) along the plot length. Because the installation shank is a deep-tillage treatment, the shank was pulled through all plots at a depth of 0.38 m and on 1.5 m centers, installing tapelines in the Irr but not Rfed plots. Municipal water was applied at a rate of 2.5 L hr⁻¹ m⁻¹ according to ET (open-pan estimate) and adjusted for rainfall, crop growth stage, or stress-level canopy temperatures (Sheaffer et al., 1988). Further details regarding the design and installation of the SDI system have been described in Chapter 3.

Alfalfa Establishment and Management

Following the installation of SDI system, the site was prepared with conventional tillage and the alfalfa cv ‘Garst 631’ was planted using a Brillion seeder on 1 May 2003 at a rate of 20.2 kg ha⁻¹. Irrigation was not applied nor required during establishment. Weeds were suppressed in the establishment
year with a tank-mixture of sethoxydim \( \{2-[1-\text{ethoxyimino}]\text{butyl}\}-5-[2-\text{ethythio}]/3-\text{hyrdoxy}-2\text{-cyclohexen-1-one} \) and imaethapyr \( \{(\pm)-2-[4,5\text{-dihydro}-4\text{-methyl}-4(1\text{-methylethyl})-5\text{-oxo-1H-imidazol-2-yl}\}-5\text{-ethyl}-3\text{-pyridine-carboxylic acid}\) at a rate of 0.6 kg ha\(^{-1}\) and 0.1 kg ha\(^{-1}\), respectively, 5 d following the first cutting. A post-harvest application of paraquat dichloride \( (1,1'\text{'-dimethyl}-4,4'\text{-bipyridinium dichloride}) \) at a rate of 0.6 kg ha\(^{-1}\) occurred on 27 June 2004 and 17 June 2005. Following the third harvest of 2004, 10 soil samples cores were taken to 10-cm depth on four split-plots of the Irr and Rfed whole plots. These showed water pH (6.7 ± 0.3) and P (192 mg kg\(^{-1}\), Mehlich III P) to be non-limiting, but indicated sub-optimal plant available soil K (114 mg kg\(^{-1}\), Mehlich III K) (Thom and Dollarhide, 1994). On 1 October 2004, KCl was broadcast at 0, 112, 336, and 448 kg K\(_2\)O ha\(^{-1}\) to randomly assigned split-plots, giving rise to a blocked split-plot experiment design during 2005 (referred to as 2005\(_K\) in the Chapter 3).

In 2005, two herbage samples (0.3 m\(^2\)) were clipped in each plot immediately before each of the final four harvests (15 June, 22 July, 23 August, and 30 September). One sample was taken from a random Shank location (above the area where the tapeline had been installed or subjected to deep-tillage) and the second was taken from a Between location (central area between these Shank zones) for the purpose of determining yield differences between these locations. Alam et al. (2002a; 2002b) found that applied water was unevenly distributed between tapelines (at 1.5-m centers), which led to lower stand density and lower yield directly over the tapelines relative to those areas between the tapelines. In the current study, only 54\% of the irrigated plot area was rated well-watered and accounted for a yield differential between the Shank and Between locations during harvest 4 (see Chapter 3).

All herbage samples were taken within a 3 h period and within 1 d of plot harvest, which occurred at 1/10 bloom, with the exception of harvest four which was at ¼ bloom. The samples were taken at 2 cm above the soil surface in 0.6 – 0.7-m strips using a Model HS 80 Stihl\(^{\circledR}\) (Stihl, Inc. Virginia Beach, VA) hedge trimmer. The mass from each clipping was weighed, placed in individually-labeled plastic bags in coolers and covered in ice for transport to a 2° C
refrigerator. The dimensions and number of viable crowns in the clipped area were counted and recorded. The effects of the treatments on yield and crown density have been presented in Chapter 3.

Within one week of sampling of the herbage the number of shoots in the herbage samples was counted and a subset of 10 shoots was randomly selected. Stem length, stem diameter above the first node, and number of fully-unrolled trifoliate leaves were recorded for each shoot in the subset. Weeds were separated from the total mass but their biomass was deemed insignificant.

Fully-expanded trifoliate leaves and petioles were removed from 10 stem subsamples from the 0 and 448 kg K$_2$O ha$^{-1}$ treatments and their leaf area measured to the nearest 0.01 cm$^2$ on a LICOR, LI-3100 area meter, consistent with the recent methods of Powell and Bork (2005). The LAI was determined from the leaf area per 10 stems and stems m$^{-2}$.

The dry mass from the 10 shoots (leaf and stem mass were combined for 0 and 448 kg K$_2$O ha$^{-1}$ treatments) was obtained following 3 d at 60° C in a forced air dryer. Average DM mass shoot$^{-1}$ was determined from the total dry weight of 10 shoots. Leaf:stem ratios (L:S ratio) were estimated from leaf DM mass shoot$^{-1}$ and stem DM mass shoot$^{-1}$ in each of the 0 and 448 kg K$_2$O ha$^{-1}$ treatments.

Yield components, stem length, stem diameter, and LAI were subjected to the PROC CORR procedure in SAS 9.1 (SAS Institute, 2003) to determine their relationship to alfalfa yield. Leaf and stem mass from the 0 and 448 kg K$_2$O ha$^{-1}$ treatment levels were also analyzed for correlation with yield. Yield components related to alfalfa yield were subjected to regression analysis for each harvest using the PROC REG procedure in SAS 9.1 (SAS Institute, 2003).

To determine if treatments had created significant differences between the Shank and Between measurements, while maintaining within the experimental design, the data were first expressed in the normalized ratio (NR) expressed in Eq. [4.1].

\[
\text{Eq. [4.1]} \quad \text{NR} = \left( \frac{\text{Shank}}{\text{Between}} \right) - 1
\]
When the NR within a treatment combination was significantly greater than zero or was significantly different from that observed in another treatment combination, the observations made for that cutting date at the Shank and Between locations were separately analyzed for treatment effects. All data were analyzed using the PROC MIXED procedure and the Satterthwaite degrees of freedom method in SAS 9.1 (Littell et al., 1996).

### 4.3. RESULTS AND DISCUSSION

Detail on the rainfall and irrigation events in 2005 are presented in Chapter 3. The 2005 growing season (1 April - 30 September) was the second driest on record and rainfall totaled 343 mm, which was only 55% of the 111-yr average for this period (Agricultural Weather Center, 2005) (Fig. 3-4c). Further, the rainfall was poorly distributed. No irrigation was required during growth of the first harvest and less than 13 mm of water was applied during either the second and fifth growing periods. However, drought during both the third and fourth growing periods required 74 and 98 mm, respectively. This led to a yield response ($P < 0.05$) to irrigation during 2005.

**Identification of Relevant Yield Components**

Identifying the mechanism by which soil moisture and K deficits alter herbage yield requires an evaluation of the relationships between yield components and yield. An initial analysis of the observations ($n=80$) within each cutting of the last four harvests of 2005 showed the relationship ($r < 0.20$) between stand density (crowns m$^{-2}$) and yield was not significant ($P > 0.10$) (Table 4-1). This lack of relationship does not necessarily negate the link between stand density and alfalfa yield as this relationship may be relevant to yield in older, thinner stands. However, the relationships between yield and shoots crown$^{-1}$ ($r > 0.33-0.51$; $P < 0.05$), shoots m$^{-2}$ ($r > 0.55-0.72$; $P < 0.001$), and mass shoot$^{-1}$ ($r > 0.64-0.85$; $P < 0.001$) were stronger and more relevant to alfalfa yield in 2005 in agreement with Undersander et al. (1998). Therefore, we simplified the yield component model of Volenec et al. (1987) by combining the plants m$^{-2}$ and shoots plant$^{-1}$ terms into shoots m$^{-2}$ as in Eq. [4.2].
Table 4-1. Correlation coefficients (r) between yield from clippings within alfalfa plots and the yield components and selected proxy variables in each (n = 80) of the last four harvests in 2005.

<table>
<thead>
<tr>
<th>Variable</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Yield Component</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crowns m⁻²</td>
<td>0.18</td>
<td>0.17</td>
<td>0.20</td>
<td>0.17</td>
</tr>
<tr>
<td>Shoots crown⁻¹</td>
<td>0.46***</td>
<td>0.33**</td>
<td>0.43***</td>
<td>0.51***</td>
</tr>
<tr>
<td>Shoots m⁻²</td>
<td>0.72***</td>
<td>0.55***</td>
<td>0.57***</td>
<td>0.68***</td>
</tr>
<tr>
<td>Mass shoot⁻¹</td>
<td>0.64***</td>
<td>0.81***</td>
<td>0.85***</td>
<td>0.69***</td>
</tr>
<tr>
<td>Leaf mass shoot⁻¹†</td>
<td>0.47**</td>
<td>0.73***</td>
<td>0.74***</td>
<td>0.60***</td>
</tr>
<tr>
<td>Stem mass shoot⁻¹†</td>
<td>0.63***</td>
<td>0.74***</td>
<td>0.84***</td>
<td>0.63***</td>
</tr>
<tr>
<td><strong>Proxy</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shoot length</td>
<td>0.38**</td>
<td>0.55***</td>
<td>0.83***</td>
<td>0.59***</td>
</tr>
<tr>
<td>Stem diameter</td>
<td>0.23</td>
<td>0.28*</td>
<td>0.75***</td>
<td>0.50***</td>
</tr>
<tr>
<td>LAI†</td>
<td>0.82***</td>
<td>0.91***</td>
<td>0.90***</td>
<td>0.91***</td>
</tr>
</tbody>
</table>

* *, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.
† Correlations between these variables and yield were made using only the 0 and 448 kg K ha⁻¹ treatment levels (n = 40).
Yield was linearly related (P < 0.001) to both shoots m\(^{-2}\) and mass shoot\(^{-1}\) in each of the harvests of 2005 in which herbage samples were taken (Table 4-2 and Fig. 4-1). The simplified yield component model (Eq. [4.2]) explained a significant (P < 0.001) amount of the variation in actual herbage yield [adjusted \(r^2 = 0.88\); root mean square error (RMSE) = 21.38 g m\(^{-2}\); actual yield = 1.124(predicted yield) - 2.476] over all four harvests.

The relationship between alfalfa yield and mass shoot\(^{-1}\) confirms recent work by Berg et al. (2005), who found that mass shoot\(^{-1}\) was the most critical yield component of high yielding alfalfa. In contrast to our data, however, Berg et al. (2005) found that shoots m\(^{-2}\) did not relate well to alfalfa yield. They indirectly measured shoots m\(^{-2}\) by dividing yield m\(^{-2}\) by the average mass of 50 shoot samples taken randomly from throughout their plots (Berg et al., 2005). By sampling in this way, the variation in shoot samples from random locations throughout the plot may have masked the contribution of shoots m\(^{-2}\) to yield at a specific location. Our findings of a significant relationship between shoots m\(^{-2}\) and alfalfa yield agrees with Undersander et al. (1998). They recommended that Wisconsin producers renovate alfalfa fields when shoot density falls below 430 shoots m\(^{-2}\) (40 stems ft\(^{-2}\)) (Undersander et al., 1998). Yet, we achieved high yields (9.8 – 12.7 Mg ha\(^{-1}\)), even when shoot density was less than 300 shoots m\(^{-2}\).

Other yield sub-components were also related to yield (Table 4-1). Observations from leaf and stem separations performed on the 0 and 448 kg K\(_2\)O ha\(^{-1}\) treatments showed that leaf mass shoot\(^{-1}\) (P < 0.001), and stem mass shoot\(^{-1}\) (P < 0.001) were related to yield. Shoot length and stem diameter were related (P < 0.05) to yield, but differed between harvests and were not good estimators of alfalfa yield (RMSE > 56.8 and 67.4 g m\(^{-2}\), respectively) (Table 4-2). Commercially-available devices, such as the pasture ruler and rising plate meter determine compressed canopy surface height and may be calibrated against...
Table 4-2. Linear regression models using mass shoot$^{-1}$, shoots m$^{-2}$, shoot length, and stem diameter as predictors of yield from clippings (n = 80) within alfalfa plots for each of the last four harvests in 2005.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Harvest</th>
<th>Intercept</th>
<th>b‡</th>
<th>SE$_{b}$</th>
<th>t value</th>
<th>Adjusted $r^{2}$</th>
<th>RMSE‡</th>
<th>Relative Error§</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoots m$^{-2}$</td>
<td>2</td>
<td>10.18</td>
<td>0.87 a</td>
<td>0.104</td>
<td>8.41***</td>
<td>0.51</td>
<td>107.5</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>8.49</td>
<td>0.60 b</td>
<td>0.105</td>
<td>5.75***</td>
<td>0.29</td>
<td>83.5</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>-29.34</td>
<td>0.54 b</td>
<td>0.090</td>
<td>6.07***</td>
<td>0.31</td>
<td>118.4</td>
<td>68</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>-2.55</td>
<td>0.65 b</td>
<td>0.080</td>
<td>8.17***</td>
<td>0.45</td>
<td>102.9</td>
<td>39</td>
</tr>
<tr>
<td>Mass (g) shoot$^{-1}$</td>
<td>2</td>
<td>-20.67</td>
<td>313 b</td>
<td>45.94</td>
<td>6.82***</td>
<td>0.40</td>
<td>118.4</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>4.50</td>
<td>307 b</td>
<td>25.35</td>
<td>12.01***</td>
<td>0.64</td>
<td>59.0</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>2.04</td>
<td>393 a</td>
<td>27.35</td>
<td>14.36***</td>
<td>0.72</td>
<td>76.9</td>
<td>44</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>13.21</td>
<td>363 ab</td>
<td>43.01</td>
<td>8.44***</td>
<td>0.47</td>
<td>101.3</td>
<td>39</td>
</tr>
<tr>
<td>Shoot length (cm)</td>
<td>2</td>
<td>-77.11</td>
<td>35.79</td>
<td>10.72</td>
<td>3.34**</td>
<td>0.13</td>
<td>100.9</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>-89.36</td>
<td>55.37</td>
<td>9.42</td>
<td>5.88***</td>
<td>0.30</td>
<td>58.6</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>-111.28*</td>
<td>44.70</td>
<td>3.40</td>
<td>13.08***</td>
<td>0.68</td>
<td>56.8</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>-338.20*</td>
<td>53.42</td>
<td>8.36</td>
<td>6.40***</td>
<td>0.34</td>
<td>80.3</td>
<td>31</td>
</tr>
<tr>
<td>Stem diameter (cm)</td>
<td>2</td>
<td>92.1</td>
<td>661 b</td>
<td>2223</td>
<td>1.92</td>
<td>0.04</td>
<td>106.1</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>94.6*</td>
<td>505 b</td>
<td>1251</td>
<td>2.60*</td>
<td>0.07</td>
<td>67.6</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>-234.8***</td>
<td>2505 a</td>
<td>1624</td>
<td>9.95***</td>
<td>0.55</td>
<td>67.4</td>
<td>39</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>-221.8*</td>
<td>2154 a</td>
<td>2706</td>
<td>5.13***</td>
<td>0.24</td>
<td>85.7</td>
<td>33</td>
</tr>
</tbody>
</table>

* ** *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.
† ‡ $§$ Linear regression coefficient.
RMSE divided by the average yield for the specific cutting.
Fig. 4-1. The linear relationship between the yield from clippings of alfalfa (n = 80) and shoots m\(^{-2}\) (A) and mass shoot\(^{-1}\) (B) taken immediately prior to the second, third, fourth, and fifth harvests of 2005.
herbage biomass. Using factory calibration sets in mixed pastures in the northeastern USA, Sanderson et al. (2001) found that these devices predicted yield with error levels of 26-33% when calibrated with clipped herbage mass from the same area. Our results suggest that poor relationships between shoot length or stem diameter and yield at a late vegetative/early reproductive maturity stage introduce errors in the prediction of alfalfa yield that are similar to or greater than that reported by Sanderson et al. (2001), even if the model was calibrated for each harvest.

In contrast, LAI was related (P < 0.001) to yield at each harvest, often having correlation coefficients (r) greater than 0.90 (Table 4-1). An explanation for the strong relationship between LAI and alfalfa yield can be found in the strong relationship between LAI and the primary yield component (mass shoot\(^{-1}\)) and elements of biomass density (leaf and stem mass m\(^{-2}\)) (Table 4-3). LAI was generally not as well-related or inconsistently (P > 0.05) related to other variables, such as L:S ratio, leaves shoot\(^{-1}\), leaf area leaf\(^{-1}\), and the leaf mass per unit leaf area (specific leaf area). This indicates the robustness of LAI as an estimator for alfalfa yield, as these variables varied considerably in response to changes in the growing conditions and harvest date but did not alter the relationship between LAI and yield.

Linear regression models of alfalfa yield based on LAI differed (P < 0.05) between cutting dates. Further, severe drought stress in the growth period prior to harvest four created conditions where the linear coefficient of the model developed from rainfed data was significantly (P < 0.01) greater (105.92 vs. 56.4 g m\(^{-2}\) LAI\(^{-1}\), respectively) than that from irrigated points (Table 4-4). Therefore, separate models are presented for the irrigated and rainfed plots within each cutting date. In general, models of alfalfa yield based on the LAI had higher adjusted \(r^2\) and lower RMSE values than models based on stem diameter, shoot length or yield components such as shoots m\(^{-2}\) or mass shoot\(^{-1}\) (Fig. 4-2; Table 4-4). In this analysis, the amount of prediction error in using LAI to model alfalfa yield was usually less than 20% of the mean yield for an individual harvest (Table 4-4).
Table 4-3. Correlation coefficients (r) between LAI and leaf and stem variables in each (n=40) of the last four harvests in 2005.

<table>
<thead>
<tr>
<th>Variable</th>
<th>2†</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoots m⁻²</td>
<td>0.11</td>
<td>0.57***</td>
<td>0.62***</td>
<td>0.72***</td>
</tr>
<tr>
<td>Mass shoot⁻¹</td>
<td>0.78***</td>
<td>0.91***</td>
<td>0.90***</td>
<td>0.91***</td>
</tr>
<tr>
<td>Leaf mass m⁻²</td>
<td>0.47*</td>
<td>0.89***</td>
<td>0.93***</td>
<td>0.94***</td>
</tr>
<tr>
<td>Stem mass m⁻²</td>
<td>0.81***</td>
<td>0.90***</td>
<td>0.83***</td>
<td>0.84***</td>
</tr>
<tr>
<td>L:S ratio</td>
<td>-0.18</td>
<td>-0.17</td>
<td>-0.36*</td>
<td>-0.04</td>
</tr>
<tr>
<td>Leaves shoot⁻¹</td>
<td>0.15</td>
<td>0.60***</td>
<td>0.75***</td>
<td>0.48**</td>
</tr>
<tr>
<td>Leaf area leaf⁻¹</td>
<td>0.71***</td>
<td>0.34*</td>
<td>0.91***</td>
<td>0.56***</td>
</tr>
<tr>
<td>Specific leaf area (g cm⁻²)‡</td>
<td>-0.47**</td>
<td>-0.26</td>
<td>-0.83***</td>
<td>-0.27</td>
</tr>
</tbody>
</table>

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.
† Though it was not quantified, leaf spot diseases appeared to be more severe in harvest 2 and may have led to substantial leaf loss. Therefore, the relationship between LAI and the yield components measured in harvest 2 may not be typical.
‡ Specific leaf density refers to the leaf mass (g) per unit leaf area (cm²).
Table 4-4. Linear regression models using LAI as a predictor of yield from clippings (n = 20) within irrigated and rainfed alfalfa plots for each of the last four harvests in 2005.

<table>
<thead>
<tr>
<th>Plot Type†</th>
<th>Harvest</th>
<th>Intercept</th>
<th>b‡</th>
<th>SE&lt;sub&gt;b&lt;/sub&gt;</th>
<th>t value</th>
<th>Adjusted r²</th>
<th>RMSE§</th>
<th>Relative Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irrigated</td>
<td>2</td>
<td>64.71</td>
<td>113.5 ab</td>
<td>13.41</td>
<td>8.47***</td>
<td>0.81</td>
<td>47.9</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>-5.72</td>
<td>144.2 a</td>
<td>19.93</td>
<td>7.23***</td>
<td>0.73</td>
<td>36.3</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>41.66</td>
<td>56.4 cd</td>
<td>7.5</td>
<td>7.52***</td>
<td>0.75</td>
<td>31.5</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>52.23</td>
<td>47.0 d</td>
<td>3.72</td>
<td>12.63***</td>
<td>0.89</td>
<td>32.2</td>
<td>13</td>
</tr>
<tr>
<td>Rainfed</td>
<td>2</td>
<td>105.93</td>
<td>84.1 bcd</td>
<td>41.18</td>
<td>2.57*</td>
<td>0.28</td>
<td>34.8</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>13.12</td>
<td>131.4 ab</td>
<td>12.15</td>
<td>10.82***</td>
<td>0.86</td>
<td>56.0</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>8.6</td>
<td>105.9 b</td>
<td>14.47</td>
<td>7.32***</td>
<td>0.73</td>
<td>43.0</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>-41.19</td>
<td>77.7 bcd</td>
<td>6.34</td>
<td>12.27***</td>
<td>0.89</td>
<td>29.1</td>
<td>10</td>
</tr>
</tbody>
</table>

* † ** *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.
† The model of yield based on LAI was made using the two observations from each of the 0 and 448 kg K ha⁻¹ treatment plots within either irrigated or rainfed plots.
‡ Linear regression coefficient.
§ Root mean square error between the measured yield and that predicted by the linear model.
¶ RMSE divided by the average yield for the specific cutting and irrigation treatment.
Fig. 4-2. The linear relationship between LAI and the yield from clippings of alfalfa (n=40) taken immediately prior to the second, third, fourth, and fifth harvests of 2005.
The range of LAI and alfalfa yield in our dataset at a given harvest date within the irrigated or rainfed plots may have been artificially large because of the range in K fertilization. The range within a production field may or may not be as large, depending on the presence of spatial variation in yield limiting factors. Yet, there must be some range in the dataset from which a LAI-based yield model is developed if the model is to be accurate. If the range within a field is not sufficient, an alteration of some management practice may be necessary to create such a range for calibration purposes.

Effect of Irrigation and K Fertilization on Alfalfa Yield Components

Since weather and harvest conditions varied between harvest dates, data were analyzed within individual harvests in a manner similar to the yield analysis in Chapter 3 (Table 4-5). Unlike yield data from harvest 4 the NR calculated between the individual yield components at the Shank and Between locations within a plot were not greater than zero (P > 0.10) and did not differ (P > 0.10) at any harvest date (data not shown). The reason for this is unclear. It is possible that changes in several yield components may have occurred simultaneously and, thus, cumulatively caused differences in yield. Nonetheless, the average of the Shank and Between observations within a plot was used in the analysis of treatment effects. There was also no significant interaction at any harvest between the effects of irrigation and K fertilization on any response variable discussed herein (Table 4-5). Therefore, these effects are presented separately.

Irrigation:

The number of shoots m\(^{-2}\) did not differ (P > 0.10) between irrigated and rainfed plots at any harvest (Table 4-5 and 4-6). Irrigation increased (P < 0.05) leaf and stem mass shoot\(^{-1}\) and significantly (P < 0.05) increased the mass shoot\(^{-1}\) (0.984 vs. 0.756 g shoot\(^{-1}\)) averaged over the 0 and 448 kg K\(_2\)O ha\(^{-1}\) treatments in harvest 2. However, when averaged over all K treatments, mass shoot\(^{-1}\) was not significantly improved by irrigation during harvest 2. In harvests 3 and 4,
Table 4-5. F Values from the ANOVA of irrigation and K fertilization effects, orthogonal contrasts of K fertilization, and the interaction of irrigation with K fertilization on selected yield components, LAI, and the L:S ratio measured from clippings taken immediately prior to the last four harvests in 2005.

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Shoots m⁻²</td>
<td>Mass shoot⁻¹</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Irrigation</td>
<td>0.13</td>
<td>0.31</td>
<td>1.74</td>
<td>0.03</td>
<td>2.01</td>
<td>8.72*</td>
<td>30.30***</td>
<td>0.01</td>
</tr>
<tr>
<td>K Rate</td>
<td>1.78</td>
<td>0.80</td>
<td>0.11</td>
<td>1.35</td>
<td>5.94**</td>
<td>1.64</td>
<td>3.93*</td>
<td>1.36</td>
</tr>
<tr>
<td>Linear</td>
<td>0.08</td>
<td>1.09</td>
<td>0.15</td>
<td>1.37</td>
<td>14.51***</td>
<td>4.84*</td>
<td>5.09*</td>
<td>0.58</td>
</tr>
<tr>
<td>Quadratic</td>
<td>0.32</td>
<td>0.33</td>
<td>0.12</td>
<td>2.58</td>
<td>2.70</td>
<td>0.02</td>
<td>6.12**</td>
<td>3.27</td>
</tr>
<tr>
<td>0 vs. &gt; kg K₂O ha⁻¹</td>
<td>0.07</td>
<td>2.12</td>
<td>0.03</td>
<td>3.63</td>
<td>16.15***</td>
<td>2.62</td>
<td>11.25**</td>
<td>0.26</td>
</tr>
<tr>
<td>Irrigation x K Rate</td>
<td>0.18</td>
<td>0.83</td>
<td>1.42</td>
<td>2.48</td>
<td>2.75</td>
<td>0.92</td>
<td>1.77</td>
<td>1.70</td>
</tr>
<tr>
<td></td>
<td>Leaf mass shoot⁻¹†</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Irrigation</td>
<td>5.77*</td>
<td>4.92*</td>
<td>50.38***</td>
<td>0.05</td>
<td>10.32*</td>
<td>7.43*</td>
<td>10.51*</td>
<td>0.09</td>
</tr>
<tr>
<td>K Rate</td>
<td>11.39**</td>
<td>1.97</td>
<td>3.82</td>
<td>3.33</td>
<td>13.38**</td>
<td>3.41</td>
<td>7.46*</td>
<td>5.85*</td>
</tr>
<tr>
<td>Irrigation x K Rate</td>
<td>0.79</td>
<td>0.20</td>
<td>1.31</td>
<td>0.01</td>
<td>1.22</td>
<td>3.65</td>
<td>0.58</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>Stem mass shoot⁻¹†</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Irrigation</td>
<td>10.12*</td>
<td>4.72*</td>
<td>41.21***</td>
<td>1.93</td>
<td>0.07</td>
<td>2.02</td>
<td>1.05</td>
<td>0.52</td>
</tr>
<tr>
<td>K Rate</td>
<td>26.87**</td>
<td>1.20</td>
<td>3.63</td>
<td>1.74</td>
<td>0.00</td>
<td>0.00</td>
<td>2.70</td>
<td>0.79</td>
</tr>
<tr>
<td>Irrigation x K Rate</td>
<td>2.00</td>
<td>0.01</td>
<td>2.94</td>
<td>5.03</td>
<td>0.07</td>
<td>2.92</td>
<td>2.97</td>
<td>2.81</td>
</tr>
</tbody>
</table>

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.
† Variables measured only on the 0 and 448 kg K ha⁻¹ treatment levels.
Table 4-6. Mean values for shoots m$^{-2}$, mass shoot$^{-1}$, leaf mass shoot$^{-1}$, stem mass shoot$^{-1}$, LAI, and the L:S ratio in the irrigated and rainfed plots as measured from clippings taken immediately prior to the last four harvests in 2005.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Shoots m$^{-2}$</td>
<td>Harvest</td>
<td>Mass (g) shoot$^{-1}$</td>
<td>LSD</td>
<td>Leaf mass (g) shoot$^{-1}$†</td>
<td>Stem mass (g) shoot$^{-1}$†</td>
<td>LAI†</td>
<td>L:S Ratio†</td>
</tr>
<tr>
<td>Irrigation</td>
<td>288</td>
<td>310</td>
<td>412</td>
<td>389</td>
<td>0.971</td>
<td>0.710 a</td>
<td>0.605 a</td>
<td>0.651</td>
</tr>
<tr>
<td>Rainfed</td>
<td>296</td>
<td>319</td>
<td>370</td>
<td>380</td>
<td>0.861</td>
<td>0.558 b</td>
<td>0.321 b</td>
<td>0.649</td>
</tr>
<tr>
<td>LSD</td>
<td>41.4</td>
<td>30.0</td>
<td>65.5</td>
<td>110.7</td>
<td>0.1589</td>
<td>0.1052</td>
<td>0.1051</td>
<td>0.1127</td>
</tr>
<tr>
<td>Irrigation</td>
<td>0.279 a</td>
<td>0.335 a</td>
<td>0.246 a</td>
<td>0.263</td>
<td>0.705 a</td>
<td>0.733 a</td>
<td>0.295 a</td>
<td>0.405</td>
</tr>
<tr>
<td>Rainfed</td>
<td>0.217 b</td>
<td>0.266 b</td>
<td>0.147 b</td>
<td>0.258</td>
<td>0.539 b</td>
<td>0.539 b</td>
<td>0.167 b</td>
<td>0.393</td>
</tr>
<tr>
<td>LSD</td>
<td>0.0545</td>
<td>0.0599</td>
<td>0.0294</td>
<td>0.0497</td>
<td>0.1093</td>
<td>0.1503</td>
<td>0.0841</td>
<td>0.0865</td>
</tr>
<tr>
<td>Irrigation</td>
<td>1.65 a</td>
<td>2.39 a</td>
<td>3.38 a</td>
<td>4.88</td>
<td>0.400</td>
<td>0.466</td>
<td>0.897</td>
<td>0.661</td>
</tr>
<tr>
<td>Rainfed</td>
<td>1.21 b</td>
<td>1.86 b</td>
<td>1.01 b</td>
<td>3.68</td>
<td>0.406</td>
<td>0.497</td>
<td>1.102</td>
<td>0.684</td>
</tr>
<tr>
<td>LSD</td>
<td>0.293</td>
<td>0.595</td>
<td>0.782</td>
<td>1.822</td>
<td>0.0488</td>
<td>0.0462</td>
<td>0.4238</td>
<td>0.0679</td>
</tr>
</tbody>
</table>

* *, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.
† Variables measured only on the 0 and 448 kg K ha$^{-1}$ treatment levels.
significant ($P < 0.05$) responses to irrigation were observed in the total mass shoot$^{-1}$, as well as the leaf and stem mass shoot$^{-1}$. Rainfall from the remnants of two hurricanes (Katrina and Rita) released the drought conditions that had affected harvests 3 and 4 shortly after the fourth harvest. As a result, irrigated plots were not significantly different from rainfed plots in any yield component or proxy variable measured at harvest 5.

Irrigation also increased LAI in harvests 2, 3, and 4 ($P < 0.05$), in a manner similar to that observed by Sheaffer et al. (1983a) (Table 4-5 and 4-6). However, the L:S ratio was not affected ($P > 0.10$) by irrigation at any harvest in the current study. Others have shown that a greater portion of alfalfa DM is partitioned to the leaves of water-stressed plants and the L:S ratio of drought affected alfalfa is higher than well-watered alfalfa (Vough and Marten, 1971; Sheaffer et al., 1983a). This has been attributed to decreased shoot height and stem diameters in drought stressed alfalfa (Vough and Marten, 1971; Sheaffer et al., 1983a). The lack of an effect on the L:S ratio in the current study occurred despite shorter shoots ($P < 0.01$) at harvest 3 and 4 (29.4 vs. 25.0 cm and 42.3 vs. 23.4 cm, respectively), decreased ($P < 0.01$) stem diameters in harvest 4 (0.184 vs. 0.147 cm), and an increased ($P < 0.01$) average number of fully-expanded, trifoliate leaves per cm of shoot height (5.7 vs. 4.7 leaves cm$^{-1}$ of shoot length) during harvest 4 in the rainfed relative to the irrigated plots. The reason for this discrepancy between our data and that of Vough and Marten (1971) and Sheaffer et al. (1983a) is unclear. Perhaps stress tolerance or other differences exist between the cultivars in the respective studies.

**Potassium:**

The number of shoots m$^{-2}$ was not affected ($P > 0.10$) by K fertilization at any harvest (Table 4-5 and 4-7). Mass shoot$^{-1}$ increased linearly ($P < 0.05$) in response to increasing K fertilization in harvests 2, 3, and 4, however, the response was more quadratic ($P < 0.01$) in harvest 4. A K fertilization effect ($P < 0.01$) was also observed in both leaf and stem mass shoot$^{-1}$ from the 0 and 448 kg K$_2$O ha$^{-1}$ treatments in harvest 2. However, leaf mass shoot$^{-1}$ was not affected
Table 4-7. Mean values for shoots m\(^{-2}\) and mass shoot\(^{-1}\) in the 0, 112, 336, and 448 kg K\(_2\)O ha\(^{-1}\) treatments and leaf mass shoot\(^{-1}\), stem mass shoot\(^{-1}\), LAI, and the L:S ratio in the 0 and 448 kg K\(_2\)O ha\(^{-1}\) as measured from clippings taken immediately prior to the last four harvests in 2005.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Harvest (kg K(_2)O ha(^{-1}))</th>
<th>Shoots m(^{-2})</th>
<th>Mass shoot(^{-1})</th>
<th>Leaf mass (g) shoot(^{-1})†</th>
<th>Stem mass (g) shoot(^{-1})†</th>
<th>LAI†</th>
<th>L:S Ratio†</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>299 ab 333 387 418</td>
<td>0.721 b 0.586 0.382 b 0.596</td>
<td>0.205 b 0.281 0.183 0.240</td>
<td>1.05 b 2.03 1.84 4.06</td>
<td>0.404 0.482 1.110 0.693</td>
<td></td>
<td></td>
</tr>
<tr>
<td>112</td>
<td>256 b 306 388 371</td>
<td>0.923 a 0.613 0.491 a 0.632</td>
<td>0.291 a 0.320 0.210 0.281</td>
<td>1.82 a 2.22 2.55 4.50</td>
<td>0.403 0.481 0.889 0.652</td>
<td></td>
<td></td>
</tr>
<tr>
<td>336</td>
<td>345 a 314 386 365</td>
<td>1.001 a 0.650 0.504 a 0.641</td>
<td>0.0545 0.0584 0.0294 0.0475</td>
<td>0.318 0.364 0.782 0.716</td>
<td>0.0639 0.0439 0.3734 0.0889</td>
<td></td>
<td></td>
</tr>
<tr>
<td>448</td>
<td>268 b 304 386 364</td>
<td>1.019 a 0.686 0.475 a 0.724</td>
<td>0.728 a 0.685 0.265 a 0.444 a</td>
<td>0.1221 0.1131 0.0524 0.0779</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LSD</td>
<td>60.5 42.4 78.3 91.4</td>
<td>0.1815 0.1276 0.0803 0.1478</td>
<td>0.0545 0.0584 0.0294 0.0475</td>
<td>0.318 0.364 0.782 0.716</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* ** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

† Variables measured only on the 0 and 448 kg K ha\(^{-1}\) treatment levels.
(P > 0.05) by K fertilization in harvests 3, 4, and 5. In contrast, stem mass shoot\(^{-1}\) was significantly increased by K fertilization in harvests 4 and 5. However, the L:S ratio was not affected by K fertilization. Grewal and Williams (2002) showed an increase in the L:S ratio with K fertilization in a soil low in plant available K. The low to moderate levels of plant available K in our plots may not have been sufficiently low to observe a response similar to that of Grewal and Williams (2002).

LAI was not as sensitive to K fertilization as it was to irrigation, showing a significant difference between the 0 and 448 kg K\(_2\)O ha\(^{-1}\) treatments only at harvest 2 (1.05 vs. 1.82, respectively) (Table 4-5 and 4-7). We noted that leaf spot diseases seemed be common in this harvest, however we did not measure its incidence. Nonetheless, the general lack of response in LAI to K fertilization in the current study is different from the findings of Kimbrough et al. (1971) who found that LAI increased with added K fertilizer. Again, the relatively moderate levels of plant available soil K may not have been low enough to affect LAI. However, the effect of disease pressure on leaf loss in harvest 2 agrees with the results of Kimbrough et al. (1971), and indicates that the effect of K on LAI may be a result of the prevention of leaf loss when disease pressure is high.

### 4.4. CONCLUSION

We observed that stand density had no effect on alfalfa yield in a 3 yr old alfalfa stand and we merged plants m\(^{-2}\) and shoots plant\(^{-1}\) into shoots m\(^{-2}\) in a modified yield component model of Volene et al. (1987). Both of the primary yield components (shoots m\(^{-2}\) and mass shoot\(^{-1}\)), as predicted by the simplified model, exhibited significant linear relationships with alfalfa yield in all harvests measured in 2005, across variations in both soil moisture and K deficits. When combined in the yield component model, the product of these terms accurately predicted alfalfa yield.

The relationship between LAI and alfalfa yield was shown to be significant, and a linear model derived to estimate yield within each cutting from LAI was more accurate than models based on individual yield components. With the
exception of the droughted fourth harvest, there were no significant differences between the linear regression coefficients of the models developed from rainfed or irrigated data.

Soil moisture deficit had no effect on shoots m⁻² but reduced leaf, stem, and total mass shoot⁻¹. As a result of the simultaneous reduction of both leaf and stem mass shoot⁻¹, drought stress had no significant effect on the L:S ratio. However, the LAI of alfalfa was significantly reduced by drought. Similarly, potassium deficit had no effect on shoots m⁻². Total mass shoot⁻¹ increased linearly in response to K fertilization in 3 of the 4 harvests, but the addition of K fertilizer did not significantly change the L:S ratio. LAI was generally increased by K fertilizer, but this was only significant in a harvest that appeared to suffer leaf loss from elevated disease pressure.

The strong linear relationship between LAI and alfalfa yield, and the finding that the L:S ratio was not altered by moisture or K stress, indicates that LAI should perform well as an estimator of alfalfa yield. However, separate calibrations of yield prediction models based on LAI may be necessary at each harvest date and when management or environmental extremes (e.g., irrigated vs. rainfed alfalfa when moisture stress is severe) result in distinct populations.
CHAPTER 5: RELATIONSHIPS BETWEEN CANOPY REFLECTANCE AND LEAF AREA AND YIELD OF ALFALFA: I. BLUE, RED, AND NIR REFLECTANCE

5.1. INTRODUCTION

Alfalfa (*Medicago sativa* L.) is one of the most important crops in the United States; ranking 3rd in both planted area and estimated value (National Agricultural Statistics Service, 2006). There are few (if any) commercially-available tools to estimate measure yield variation within alfalfa fields. However, several field-ready multi-spectral sensors are being used to determine vegetative biomass and nutrient needs of other economically-important grain crops (Pinter et al., 2003; Moges et al., 2004; Raun et al., 2005; Freeman et al., 2005; Zillman et al., 2006), and forage crops such as bermudagrass (*Cynodon dactylon* L.) (Mosali et al., 2005) and tall fescue (*Festuca arundinacea* Schreb.) (Payero et al., 2004; Flynn, 2006).

Virtually all green leaves reflect light in similar patterns within the visible and near-infrared (NIR) regions of the electromagnetic spectrum (e.g., Gates et al., 1965; Gausman and Allen, 1973; Hoffer, 1978). The two main plant pigments, chlorophyll a and b, absorb nearly 95% of blue (430-450 nm) and red (640-670 nm) light (Wiegand and Richardson, 1984; Monteith and Unsworth, 1990; Chappelle et al., 1992), but absorption in the green (530-560 nm) band is relatively low (75-80%) leading to a higher reflection in this region (Monteith and Unsworth, 1990). In contrast, cell wall structures reflect of up to 60% of the intercepted light in the NIR region (700-1300 nm) (Slaton et al., 2001).

Some researchers have successfully evaluated the relationships between reflectance at specific bands to agronomically-important variables. For example, Guan and Nutter (2001, 2002a, 2002b, 2003 and 2004; Nutter et al., 2002) found that canopy reflectance in a NIR band (810 nm) accurately predicted the occurrence and impact of disease stress on alfalfa yield. Most researchers, in contrast, use vegetation indices (VIs) estimated from the difference, ratio, or
other combination (linear or non-linear) of reflectance in the visible and NIR regions (Monteith and Unsworth, 1990). Ideally, the specific wavelength bands should be both related to and stable within a narrow range of values of a relevant variable (e.g., yield, LAI, yield component). Most researchers have chosen reflectance values from the red (650 - 680 nm) and NIR (750 - 850 nm) regions (Rouse et al., 1973; Moran et al., 1997; Pinter et al., 2003; Gitelson, 2004), although others have considered green (550 nm) reflectance (Gitelson et al., 1996).

The relationships between VIs and agronomically-relevant variables have been studied quite extensively in other economically important crops, but to a lesser extent in alfalfa. Mitchell et al. (1990) established a relationship between a VI derived from canopy reflectance in red and NIR bands and alfalfa yield and lamb growth at various stocking densities. Payero et al. (2004) calculated 11 VIs from red and NIR reflectance values taken every other day during two successive alfalfa regrowth cycles and compared these to canopy height data. All 11 VIs were logarithmically related to the canopy heights of alfalfa ($R^2 > 0.90$) (Payero et al., 2004).

There is little research into the use of canopy reflectance to measure variation in alfalfa yield and very little information about how canopy reflectance is related to alfalfa yield and yield components. The proportion of light at a given wavelength that is reflected by the canopy is a function of the leaf area of the canopy. Monteith and Unsworth (1990) defined the relationship (Eq. [5-1]) between canopy reflectance ($\rho_c$) and LAI:

\[
[5.1] \quad \rho_c = \rho_c^* - (\rho_c^* - \rho_s) e^{-2(LAI)A}
\]

in terms of the limiting (i.e., asymptotic maximum or minimum) coefficient of reflection ($\rho_c^*$), the coefficient of reflection by the soil and canopy floor ($\rho_s$), and the canopy attenuation coefficient ($A$) (which is analogous to Beer's extinction
coefficient, $\varepsilon^3$). The sensitivity of $\rho_c$ to changes in LAI is advantageous as it has been established that alfalfa yield is directly related to LAI (see Chapter 4).

My goal is to use commercially-available multispectral sensors to measure yield variation within an alfalfa field. In this study, I seek to establish quantitative relationships between canopy reflectance in the visible and NIR regions and alfalfa yield and LAI. More specifically, the objective of this study was to evaluate the relationships between the reflectance from alfalfa canopies and alfalfa yield by determining i) which canopy reflectance wavelength bands exhibit the strongest relationship with alfalfa yield, and ii) how variations in canopy reflectance are related to the leaf area and yield components.

5.2. MATERIALS AND METHODS

Stands of alfalfa cv ‘Garst 631’ were established on 1 May 2003 at the University of Kentucky Animal Research Center (84° 44’ W long, 38° 4’ N lat) in a 4.5-ha site consisting of one soil type (Maury silt loam, Typic hapludult, 2 to 6% slope). Prior to alfalfa establishment, five blocks of two large whole-plots (18.3 x 39.6 m) were delineated. The whole-plots were randomly assigned to receive irrigation (Irr) via subsurface drip irrigation (SDI) or to be rainfed (Rfed). On 16-17 April 2003, SDI tapelines were installed in the Irr plots at a depth of 0.38 cm and on 150 cm centers using a single parabolic shank. Since the installation Shank was effectively a deep-tillage treatment, the shank was also pulled through the Rfed plots though no tape was installed. Further details regarding the design and installation of the SDI system have been described in Chapter 3.

Within each whole-plot, two sets of observations were obtained in 2005. One set of observations, 2005<sub>K</sub>, was obtained from four split-plots (2.4 x 6.1 m) that had received randomly assigned topdressings of 0, 112, 336, or 448 kg K<sub>2</sub>O ha<sup>-1</sup> on 1 October 2004 in a blocked, split-plot design. A second group of observations, 2005<sub>0</sub>, was obtained from four, predetermined locations (randomized for each regrowth cycle) within each whole plot. The observations of

---

3 Monteith and Unsworth (1990) use the character of K in their equation. To avoid confusion with reference to potassium (K), the character A is used as an alternate.
2005\textsubscript{o} differed only in assignment of block and whole plot treatment (Irr vs. Rfed) in a randomized complete block design.

**Yield Measurements**

Favorable harvest conditions enabled 5 harvests in 2005 (2005\textsubscript{K} and 2005\textsubscript{o}): 5 May (H1), 15 June (H2), 22 July (H3), 23 August (H4), and 30 September (H5). All harvests in 2005 were made at 1/10 bloom maturity, with the exception of 23 August which was taken at ¼ bloom. All harvests were taken at a cutting height of 4 cm made with a Hege Model 212 Forage Plot Harvester (Wintersteiger Ag, Niederlassung, Germany) and weighed to within ±0.1 kg. The cutting width of the plot harvester is 1.5 m. The length of the harvested area was restricted to 0.5 m from the ends of the plots and measured to within ±3 cm. Forage mass was corrected for dry weight after drying samples to a constant weight at 60° C in a forced air dryer.

**Leaf Area Index and Yield Component Measurements**

In 2005, two herbage samples (0.3 m\textsuperscript{2}) were clipped in each plot of the 2005\textsubscript{K} observation set immediately before each of the final four harvests (H2 - H5). One sample was taken from a random “Shank” location (directly above the tapeline or subsoiler slit) and the second was taken from a “Between” location (defined as the midpoint between these Shank locations). All herbage samples were taken within a 3 h period and within 1 d of plot harvest. The samples were taken at 2 cm above the soil surface in 0.6 - 0.7-m strips using a Model HS 80 Stihl\textsuperscript{®} (Stihl, Inc. Virginia Beach, VA) hedge trimmer. The mass from each clipping was weighed, placed in individually-labeled plastic bags in coolers and covered in ice for transport to a 2° C refrigerator. The number of viable alfalfa crowns in and the dimensions of the clipped area were counted and recorded. Within 1 wk of sampling of the herbage the number of shoots in the herbage samples was counted and a subset of 10 shoots was randomly selected. Stem length, stem diameter above the first node, and number of fully-expanded
trifoliate leaves were recorded for each shoot (i.e., leaves shoot\(^{-1}\)). Weeds were hand-separated from the total mass but their biomass was insignificant.

Fully-expanded trifoliate leaves and petioles were removed from 10 stem sub-samples from the 0 and 448 kg K\(_2\)O ha\(^{-1}\) treatments and their leaf area measured to the nearest 0.01 cm\(^2\) on a LICOR, LI-3100 area meter, consistent with the recent methods of Powell and Bork (2005). The LAI was determined from the leaf area per 10 stems and stems m\(^{-2}\).

The dry mass from the 10 shoots (leaves and stems were pooled for 0 and 448 kg K\(_2\)O ha\(^{-1}\) treatments) was obtained following 3 d at 60° C in a forced air dryer. Average DM mass shoot\(^{-1}\) was determined from the 10 shoots. Leaf:stem ratios (L:S ratio) were estimated from leaf DM mass shoot\(^{-1}\) and stem DM mass shoot\(^{-1}\). Yield components, stem length, stem diameter, and LAI data were analyzed using the CORR and REG procedures in SAS 9.1 (SAS Institute, 2003) to determine their relationship to alfalfa DM yield. The results of this analysis are presented in Chapter 4.

**Description of Multispectral Sensor**

The Yara Hydro-N-Sensor (NS: Yara International ASA, Oslo, Norway) is a field-ready multispectral sensor that was used to determine alfalfa canopy reflectance. The NS is a passive device that utilizes two, factory-calibrated, diode-array spectrophotometers (tec5USA, 2005). The first sensor (S1) measures the quantity and quality of light reflected from the target and captured in the viewing area of four optical inputs. Pairs of optical inputs, oriented at 45° relative to the central axis of the device (i.e., 90° relative to each other), are located at each end of a toolbar. Each input possesses a 12° field of view and is downward directed at a viewing angle that is 64° from nadir. A second, upward-directed sensor (S2) is centered on the NS device and measures incident light. The two sensors measure reflectance in up to 20 wave bands (±10 nm FWHM), of which 15 wave bands are standard and an additional five bands between 450 and 900 nm can be selected by the user (Table 5-1). Reflectance is averaged across the four optical inputs using a 4:1 bifurcated light fiber at S1, rectified to
Table 5-1. The wavebands of canopy reflectance determined by Hydro-N-Sensor (Yara International ASA, Oslo, Norway) and used in this study.

<table>
<thead>
<tr>
<th>Wavelength Bands†</th>
<th>nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard</td>
<td>450, 500, 550, 600, 620, 640, 660, 680, 700, 720, 740, 760, 780, 800, and 850</td>
</tr>
<tr>
<td>Selected</td>
<td>530, 650, 770, and 810</td>
</tr>
</tbody>
</table>

† Reflectance measured at these wavelength bands are at a resolution of ± 10 nm full width half magnitude (FWHM).
the incident light measured at S2, and the fraction of incident light that was reflected (S1/S2) is recorded at a frequency of 1 Hz. Four wavelength bands in green (530 nm), red (650 nm), and NIR (770 and 810 nm) regions were selected to complement the standard bands recorded by the NS. Further, a Holux GM-210 (HOLUX Technology, Inc., Taipei, Taiwan) GPS receiver was used to georeference (± 2 m) the data.

The area sensed by the NS varies with toolbar height (tec5USA, 2005). To accommodate the plot width, the sensor toolbar was mounted parallel to the ground on a specially created four-wheeled cart and oriented 60° to the plot length (Figs. 5-1 and 5-2). The sensor height was adjusted to 0.5 m above the crop canopy. The cart carrying the sensor was then pushed at a comfortable walking pace, resulting in 7 to 10 observations per plot.

**Canopy Reflectance Measurements**

Canopy reflectance was recorded on both plot sets 1 d before each of the five harvests (Table 5-2) on days and times when the weather was “mostly sunny” to “partly cloudy.” When clouds were present (29 Jun, 3 Aug, and 22 Aug), data were only taken when plots were in full sun. To ensure that only the area to be harvested was scanned, the optical inputs distal to the plot were closed. Closing one pair of optical inputs on the NS reduces the measured light reflected from the target by one-half (i.e., S1 x 0.5). True lambertian reflectance from a target can be determined by multiplying the recorded values by two. Isolating one pair of optical inputs causes the viewing geometry to be asymmetrical and makes any non-lambertian surface (such as a crop canopy) sensitive to changes in solar azimuth (S. Reusch, personal comm., 2006). To minimize these effects, the collection of canopy reflectance data was limited to within ± 1 h of solar noon and recorded in opposing (NE and SE) directions along the plot length. This protocol also is well within the timeframe established by Guan and Nutter (2001), who recommend that alfalfa canopy reflectance should be taken between 1100 and 1500 h. Data were converted to ASCII text files (.csv) and post-processed using ArcGIS 9.0 (ESRI, Inc., Redlands, CA).
Fig. 5-1. Orientation and travel direction of the Hydro-N-Sensor relative to the width of the harvested area of the plots. The center of the sensor was placed at a 60° angle to the plot. The sensor was maintained at 0.5 m above the canopy, placing the viewing areas of 2 optical inputs in the center of the harvested area. The other end of the sensor was blocked so that only the area within the plot was sensed.
Fig. 5-2. Photo of the Hydro-N-Sensor mounted on the sensor cart.
Table 5-2. Radiant flux characteristics while reflectance was measured from alfalfa canopies on the day before harvest.†

<table>
<thead>
<tr>
<th>Dates</th>
<th>Growth Cycle</th>
<th>Mean† MJ m⁻² h⁻¹</th>
<th>CV %</th>
<th>SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 May</td>
<td>1</td>
<td>3.14</td>
<td>15.6</td>
<td>0.219</td>
</tr>
<tr>
<td>14 Jun</td>
<td>2</td>
<td>2.78</td>
<td>12.6</td>
<td>0.156</td>
</tr>
<tr>
<td>21 Jul</td>
<td>3</td>
<td>3.13</td>
<td>8.2</td>
<td>0.115</td>
</tr>
<tr>
<td>22 Aug</td>
<td>4</td>
<td>2.43</td>
<td>20.9</td>
<td>0.226</td>
</tr>
<tr>
<td>28 Sep</td>
<td>5</td>
<td>2.22</td>
<td>8.9</td>
<td>0.089</td>
</tr>
</tbody>
</table>

† Source: University of Kentucky Research Farm Climate Data (Agricultural Weather Center. 2005).
‡ Mean of hourly measurements at 1100, 1200, and 1300 h.
Following the exclusion of measurements taken 0.3 m or less from inside the plot edge, the recorded values were averaged for each plot and then rectified for the closure of one pair of optical inputs.

Data Summary and Analysis

Yield and canopy reflectance data were summarized using the PivotTable function in Microsoft® Office Excel 2003 (Microsoft Corporation, 2003) and PROC MEANS in SAS 9.1 (SAS Institute, 2003). Assumptions of normality were evaluated using the Shapiro-Wilks (W) analysis option in PROC MEANS (SAS Institute, 2003). A repeated measures analysis was performed using the MIXED models procedure in SAS 9.1 (SAS Institute, 2003) to analyze for treatment effects on canopy reflectance in the multiple harvests. Regression equations were obtained using the REG procedure in SAS 9.1 (SAS Institute, 2003).

To be useful in relating to alfalfa yield, the ideal wavelength band or bands would be one whose reflectance values are both related to alfalfa yield and relatively stable at specific yield levels (i.e., low variance within a narrow range of yield values). To summarize the change in the canopy reflectance spectrum as yield increases, reflectance spectra of canopies were grouped into yield classes. These yield classes were developed by segmenting the range in DM yield into segments of 0.25 Mg ha\(^{-1}\). These yield segments (i.e., classes) were established by rounding yield values to the nearest multiple of 0.25 Mg ha\(^{-1}\). Within these yield classes, the mean reflectance value was determined at each of the 19 wavelengths measured by the NS. Yield classes with less than four observations were not included in the summary. Similarly, the coefficient of variation (cv) at each of the 19 wavelengths measured by the NS was determined from the variability (standard deviation) within each individual yield class. This summary was performed for irrigated and rainfed treatments for both the complete dataset and within individual harvests.
5.3. RESULTS AND DISCUSSION

Yield response to SDI (observation sets: 2005_o and 2005_k) and K topdressing rates (2005_k) are detailed in Chapters 3 and 4. Although plant available K in the soil was in a responsive range (114 mg kg^{-1}) for alfalfa (Thom and Dollarhide, 1994), yield within individual harvests was unaffected by K application. Similarly, a repeated measures analysis of the data from observation set 2005_k indicated that alfalfa canopy reflectance values were not significantly (P > 0.05) affected by K application at any harvest (data not shown). Therefore, unless otherwise indicated, potassium treatment data presented herein were pooled across both observation sets (2005_o and 2005_k). Harvest date also had a significant effect (P < 0.05) on canopy reflectance, but this is likely a result of differences in yield between harvests.

Alfalfa Yield

Yield data from the five harvests in 2005 are summarized in Table 5-3. As a result of the severe drought in 2005 the yield range of the dataset was large (5.55 Mg ha^{-1}). Yield range was relatively large for each harvest, but only H4 plots with no biomass. The large yield response to irrigation in H4 resulted in a pronounced bimodal distribution (W = 0.941; P < 0.001). Yet, within the Rfed and Irr treatments H4 yields were normally distributed (W = 0.976 and 0.977, respectively; P > 0.05).

Canopy Reflectance

In both the complete and H4 datasets, the reflectance spectrum of rainfed alfalfa increased most notably in the NIR region (750 - 850 nm) (Figs. 5-3 and 5-4). In contrast, reflectance in the blue (450 nm) and red (650 - 680 nm) wavelength bands was lower in higher yield classes, though these differences were more subtle than the changes in the NIR region. This is consistent with the work of Guan and Nutter (2002a, 2002b, and 2004), who found NIR (810 nm) reflectance values were positively and most consistently related to alfalfa yield.
<table>
<thead>
<tr>
<th>Harvest‡</th>
<th>Treatment</th>
<th>Mean</th>
<th>Min</th>
<th>Max</th>
<th>n</th>
<th>SE</th>
<th>Kurtosis</th>
<th>Skewness</th>
<th>W§</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>All</td>
<td>2.13</td>
<td>0</td>
<td>5.55</td>
<td>400</td>
<td>0.049</td>
<td>0.162</td>
<td>0.483</td>
<td>0.983***</td>
</tr>
<tr>
<td></td>
<td>Rfed</td>
<td>1.95</td>
<td>0</td>
<td>5.55</td>
<td>200</td>
<td>0.076</td>
<td>0.305</td>
<td>0.682</td>
<td>0.967***</td>
</tr>
<tr>
<td></td>
<td>Irr</td>
<td>2.38</td>
<td>0.81</td>
<td>4.60</td>
<td>200</td>
<td>0.058</td>
<td>-0.158</td>
<td>0.585</td>
<td>0.966***</td>
</tr>
<tr>
<td>H1</td>
<td>Both</td>
<td>3.49</td>
<td>1.89</td>
<td>5.50</td>
<td>80</td>
<td>0.087</td>
<td>-0.054</td>
<td>0.396</td>
<td>0.975</td>
</tr>
<tr>
<td></td>
<td>Rfed</td>
<td>3.38</td>
<td>1.89</td>
<td>5.55</td>
<td>40</td>
<td>0.138</td>
<td>-0.057</td>
<td>0.529</td>
<td>0.971</td>
</tr>
<tr>
<td></td>
<td>Irr</td>
<td>3.59</td>
<td>2.11</td>
<td>4.60</td>
<td>40</td>
<td>0.108</td>
<td>-0.771</td>
<td>-0.020</td>
<td>0.959</td>
</tr>
<tr>
<td>H2</td>
<td>Both</td>
<td>2.53</td>
<td>0.73</td>
<td>3.91</td>
<td>80</td>
<td>0.075</td>
<td>0.071</td>
<td>-0.276</td>
<td>0.980</td>
</tr>
<tr>
<td></td>
<td>Rfed</td>
<td>2.41</td>
<td>0.73</td>
<td>3.73</td>
<td>40</td>
<td>0.112</td>
<td>-0.356</td>
<td>-0.293</td>
<td>0.979</td>
</tr>
<tr>
<td></td>
<td>Irr</td>
<td>2.64</td>
<td>0.98</td>
<td>3.91</td>
<td>40</td>
<td>0.099</td>
<td>0.639</td>
<td>-0.130</td>
<td>0.964</td>
</tr>
<tr>
<td>H3</td>
<td>Both</td>
<td>1.59</td>
<td>0.53</td>
<td>2.79</td>
<td>80</td>
<td>0.083</td>
<td>-0.573</td>
<td>0.296</td>
<td>0.977</td>
</tr>
<tr>
<td></td>
<td>Rfed</td>
<td>1.47</td>
<td>0.53</td>
<td>2.31</td>
<td>40</td>
<td>0.073</td>
<td>-0.276</td>
<td>0.422</td>
<td>0.966</td>
</tr>
<tr>
<td></td>
<td>Irr</td>
<td>1.71</td>
<td>0.83</td>
<td>2.79</td>
<td>40</td>
<td>0.080</td>
<td>-0.741</td>
<td>0.138</td>
<td>0.975</td>
</tr>
<tr>
<td>H4</td>
<td>Both</td>
<td>1.54</td>
<td>0</td>
<td>4.16</td>
<td>80</td>
<td>0.103</td>
<td>-0.749</td>
<td>0.243</td>
<td>0.955**</td>
</tr>
<tr>
<td></td>
<td>Rfed</td>
<td>0.75</td>
<td>0</td>
<td>1.82</td>
<td>40</td>
<td>0.066</td>
<td>0.133</td>
<td>0.314</td>
<td>0.979</td>
</tr>
<tr>
<td></td>
<td>Irr</td>
<td>2.32</td>
<td>1.30</td>
<td>4.16</td>
<td>40</td>
<td>0.083</td>
<td>2.582</td>
<td>0.794</td>
<td>0.946</td>
</tr>
<tr>
<td>H5</td>
<td>Both</td>
<td>1.74</td>
<td>0.81</td>
<td>2.49</td>
<td>80</td>
<td>0.037</td>
<td>0.137</td>
<td>0.251</td>
<td>0.976</td>
</tr>
<tr>
<td></td>
<td>Rfed</td>
<td>1.85</td>
<td>1.08</td>
<td>2.49</td>
<td>40</td>
<td>0.054</td>
<td>-0.625</td>
<td>0.060</td>
<td>0.977</td>
</tr>
<tr>
<td></td>
<td>Irr</td>
<td>1.63</td>
<td>0.81</td>
<td>2.38</td>
<td>40</td>
<td>0.043</td>
<td>1.841</td>
<td>0.054</td>
<td>0.964</td>
</tr>
</tbody>
</table>

* *, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.
† Combines the observations from 2005o and 2005k datasets.
‡ All = All observations from the five harvests; H1, H2, H3, H4, and H5 designate the respective harvest.
§ Shapiro-Wilks test statistic for normality.
Fig. 5-3. Reflectance profiles (A) in the visible and NIR spectrum for subsurface drip irrigated (blue) and rainfed (yellow) alfalfa across a classified range of all observations in 2005 (2005K and 2005O) and the coefficients of variation (c.v.) of the reflectance values (B) within the yield classes.
Fig. 5-4. Reflectance profiles (A) in the visible and NIR spectrum for subsurface drip irrigated (blue) and rainfed (yellow) alfalfa across a classified range of observations from Harvest 4 in 2005 (2005_k and 2005_o) and the coefficients of variation (c.v.) of the reflectance values (B) within the yield classes.
Further, the coefficient of variability (cv) for reflectance within grouped yield classes at specific wavelength bands differed substantially. Blue-green (500 nm) reflectance values exhibited a wide cv range within H4 (2 - 76%); and within all harvests (29 - 90%). Within all yield classes in H4, cvs of reflectance values in other wavelength bands were generally low (< 12%). However, when the observations from all five harvests were included, cvs of reflectance data in visible bands were sharply higher in yield classes greater than 3.75 Mg ha\(^{-1}\). Cvs of NIR (750 - 850 nm) reflectance were higher in yields between 1.50 and 2.75 Mg ha\(^{-1}\), but remained relatively low (c.v. < 18%) within all yield classes.

Most conventional vegetation indices are calculated from a difference, ratio, or other combination (linear or non-linear) of reflected light in the red (650 - 680 nm) and NIR (750 - 850 nm) regions (Richardson and Wiegand, 1977; Tucker, 1979; Weigand et al., 1991; Bannart et al., 1995; Stone et al., 1996; Verstraete et al., 1996; Moran et al., 1997; Raun et al., 2002, 2005; Pinter et al., 2003; Gitelson, 2004). Others have proposed the use of green (550 nm) reflectance in vegetation indices (Gitelson et al., 1996). Based on their relatively low cvs and precedence in the literature, the following wavelength bands were chosen for further analysis: blue (450 nm), green (550 nm), and red (660 nm) in the visible spectrum and three representative NIR bands (770 nm, 810 nm, and 850 nm).

**Relationships between Canopy Reflectance and Alfalfa Yield**

Yields within each harvest were regressed on each of the selected wavelength bands (Table 5-4 and Figs. 5-5 and 5-6). No significant relationship was found between reflectance in the green (550 nm) band and alfalfa yield within any harvest. For the blue (450 nm), red (660 nm), and NIR (770, 810, and 850 nm) bands, significant relationships were found only for the third (P < 0.05) and fourth (P < 0.0001) harvests. Although the yield data ranges within H3 and H4 were generally no greater than the other harvests, both included more yield values that were less than 1.5 Mg ha\(^{-1}\).
Table 5-4. Best fit regression equations, adjusted $r^2$ values, $P$ values, and root mean square error for the relationship between alfalfa yield from five harvests (H1, H2, ... H5) in 2005 and canopy reflectance at 450, 550, 770, and 810 wavelength bands obtained 1 d prior to each harvest.

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>Harvest</th>
<th>Equation</th>
<th>Adj. $r^2$</th>
<th>$P$ value</th>
<th>RMSE †</th>
</tr>
</thead>
<tbody>
<tr>
<td>nm</td>
<td></td>
<td></td>
<td>Mg ha$^{-1}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>450</td>
<td>All</td>
<td>$y = -125.2x + 4.868$</td>
<td>0.33</td>
<td>&lt;0.0001</td>
<td>0.796</td>
</tr>
<tr>
<td></td>
<td>H1</td>
<td>$y = -71.56x + 4.544$</td>
<td>0.03</td>
<td>0.0873</td>
<td>0.779</td>
</tr>
<tr>
<td></td>
<td>H2</td>
<td>$y = 25.93x + 4.868$</td>
<td>0.00</td>
<td>0.3751</td>
<td>0.620</td>
</tr>
<tr>
<td></td>
<td>H3</td>
<td>$y = -67.82x + 2.941$</td>
<td>0.07</td>
<td>0.0122</td>
<td>0.495</td>
</tr>
<tr>
<td></td>
<td>H4</td>
<td>$y = -171.5x + 5.939$</td>
<td>0.64</td>
<td>&lt;0.0001</td>
<td>0.525</td>
</tr>
<tr>
<td></td>
<td>H5</td>
<td>$y = 1.705x + 1.690$</td>
<td>0.00</td>
<td>0.8540</td>
<td>0.329</td>
</tr>
<tr>
<td>660</td>
<td>All</td>
<td>$y = 1980x^2 - 212.8x + 5.757$</td>
<td>0.34</td>
<td>&lt;0.0001</td>
<td>0.786</td>
</tr>
<tr>
<td></td>
<td>H1</td>
<td>$y = 17523x^2 - 702.1x - 10.16$</td>
<td>0.03</td>
<td>0.1025</td>
<td>0.776</td>
</tr>
<tr>
<td></td>
<td>H2</td>
<td>$y = -11140x^2 + 498.4x - 2.759$</td>
<td>0.06</td>
<td>0.0722</td>
<td>0.602</td>
</tr>
<tr>
<td></td>
<td>H3</td>
<td>$y = -76.62x + 3.185$</td>
<td>0.20</td>
<td>&lt;0.0001</td>
<td>0.459</td>
</tr>
<tr>
<td></td>
<td>H4</td>
<td>$y = 3113x^2 - 295.1x + 6.945$</td>
<td>0.78</td>
<td>&lt;0.0001</td>
<td>0.405</td>
</tr>
<tr>
<td></td>
<td>H5</td>
<td>$y = -4298x^2 + 212.6x - 0.6653$</td>
<td>0.01</td>
<td>0.2969</td>
<td>0.326</td>
</tr>
<tr>
<td>770</td>
<td>All</td>
<td>$y = 3.623x + 0.311$</td>
<td>0.09</td>
<td>&lt;0.0001</td>
<td>0.933</td>
</tr>
<tr>
<td></td>
<td>H1</td>
<td>$y = -12.31x^2 + 6.825x + 2.950$</td>
<td>0.05</td>
<td>0.0640</td>
<td>0.766</td>
</tr>
<tr>
<td></td>
<td>H2</td>
<td>$y = 1.526x - 1.759$</td>
<td>0.00</td>
<td>0.3616</td>
<td>0.620</td>
</tr>
<tr>
<td></td>
<td>H3</td>
<td>$y = 6.246x - 0.9763$</td>
<td>0.15</td>
<td>0.0002</td>
<td>0.473</td>
</tr>
<tr>
<td></td>
<td>H4</td>
<td>$y = 13.59x^2 - 2.449x - 0.5189$</td>
<td>0.79</td>
<td>&lt;0.0001</td>
<td>0.405</td>
</tr>
<tr>
<td></td>
<td>H5</td>
<td>$y = -19.30x^2 + 23.31x - 5.241$</td>
<td>0.03</td>
<td>0.1421</td>
<td>0.323</td>
</tr>
<tr>
<td>810</td>
<td>All</td>
<td>$y = 3.363x + 0.386$</td>
<td>0.09</td>
<td>&lt;0.0001</td>
<td>0.934</td>
</tr>
<tr>
<td></td>
<td>H1</td>
<td>$y = 4.901x^2 - 9.801x + 7.002$</td>
<td>0.04</td>
<td>0.0803</td>
<td>0.768</td>
</tr>
<tr>
<td></td>
<td>H2</td>
<td>$y = 1.164x - 1.930$</td>
<td>0.00</td>
<td>0.3779</td>
<td>0.620</td>
</tr>
<tr>
<td></td>
<td>H3</td>
<td>$y = 5.360x - 0.6833$</td>
<td>0.12</td>
<td>0.0010</td>
<td>0.480</td>
</tr>
<tr>
<td></td>
<td>H4</td>
<td>$y = 9.461x^2 + 0.6151x - 1.167$</td>
<td>0.77</td>
<td>&lt;0.0001</td>
<td>0.418</td>
</tr>
<tr>
<td></td>
<td>H5</td>
<td>$y = -15.52x^2 + 19.44x - 4.298$</td>
<td>0.02</td>
<td>0.1770</td>
<td>0.324</td>
</tr>
<tr>
<td>850</td>
<td>All</td>
<td>$y = 3.088x + 0.460$</td>
<td>0.08</td>
<td>&lt;0.0001</td>
<td>0.935</td>
</tr>
<tr>
<td></td>
<td>H1</td>
<td>$y = 36.61x^2 - 42.87x + 15.66$</td>
<td>0.04</td>
<td>0.0904</td>
<td>0.774</td>
</tr>
<tr>
<td></td>
<td>H2</td>
<td>$y = -16.21x^2 + 21.01x - 4.085$</td>
<td>0.00</td>
<td>0.3871</td>
<td>0.620</td>
</tr>
<tr>
<td></td>
<td>H3</td>
<td>$y = 4.381x - 0.3456$</td>
<td>0.09</td>
<td>0.0044</td>
<td>0.489</td>
</tr>
<tr>
<td></td>
<td>H4</td>
<td>$y = 4.231x^2 + 4.921x - 2.167$</td>
<td>0.75</td>
<td>&lt;0.0001</td>
<td>0.443</td>
</tr>
<tr>
<td></td>
<td>H5</td>
<td>$y = -11.14x^2 + 14.77x - 3.103$</td>
<td>0.01</td>
<td>0.2181</td>
<td>0.324</td>
</tr>
</tbody>
</table>

* * * Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.
† Root mean square error.
Fig. 5-5. Relationships between canopy reflectance at blue (450 nm), green (550 nm), red (660 nm), and three NIR (770, 810, and 850 nm) wavelength bands and the yield from all alfalfa harvests in 2005.
Fig. 5-6. Relationships between canopy reflectance at blue (450 nm), green (550 nm), red (660 nm), and three NIR (770, 810, and 850 nm) wavelength bands and the yield from the fourth alfalfa harvest in 2005.
The disparity between harvests can be explained using Eq. [5-1], which shows that $\rho_c$ at a given wavelength asymptotically approaches $\rho_c^*$ when LAI increases toward the upper limit of LAI (LAI') (Monteith and Unsworth, 1990). Although LAI' may vary with environment and regrowth period, the LAI of alfalfa at harvest will be very near the regrowth period specific-LAI'. Therefore, only those harvests where growth limitations have created a range in LAI would demonstrate the relationship modeled in Eq. [5-1]. A positive effect of irrigation on LAI was found in H2, H3, and H4 (P < 0.05; see Chapter 4). The range in LAI was greatest for the severely drought affected growth in H4, with very low LAIs in some rainfed plots, and LAIs near or at LAI' in the irrigated plots. Thus, relationships were determined between canopy reflectance in the selected wavelength bands and yield were determined for H4 data and compared with relationships derived from all harvests.

A linear model (P < 0.0001) explained the relationship between yield and the amount of blue light reflected from the crop canopy for the H4 data (adj. $r^2 = 0.65$ and RMSE = 0.523 Mg ha$^{-1}$). However, a quadratic model (P < 0.0001) provided a better fit for red reflectance and yield from H4 (adj. $r^2 = 0.78$; RMSE = 0.408 Mg ha$^{-1}$). These relationships held (P < 0.0001) when yield data from all harvests were regressed on blue and red reflectance values, although the fit was inferior (adj. $r^2 = 0.33$; RMSE = 0.796 Mg ha$^{-1}$ and adj. $r^2 = 0.34$; RMSE = 0.786 Mg ha$^{-1}$, respectively). Quadratic models (P < 0.0001) best explained the relationships between H4 yield and the three NIR bands (770, 810, and 850 nm) evaluated (770 nm: adj. $r^2 = 0.79$ and RMSE = 0.405; 810 nm: adj. $r^2 = 0.77$ and RMSE = 0.418; and 850 nm: adj. $r^2 = 0.75$ and RMSE = 0.443 Mg ha$^{-1}$). When data from all harvests were regressed, linear models (P < 0.0001) best described the relationship between yield and reflectance in these NIR bands.

**Relationships between Canopy Reflectance and the Leaf Area of Alfalfa**

The relationships between canopy reflectance and yield illustrate how the quantity and quality of light reflected differs with ground cover (Fig. 5-6). The canopy floor (i.e., bare soil, crop residue), reflects more NIR than red light and
more red than blue light (i.e., $\rho_{s, \text{NIR}} > \rho_{s, \text{Red}} > \rho_{s, \text{Blue}}$; Bowers and Hanks, 1965; Lobell and Asner, 2002). Chlorophyll and, to a lesser degree, other plant pigments absorb most of the incoming blue and red light (Wiegand and Richardson, 1984; Monteith and Unsworth, 1990; Chappelle et al., 1992). This results in a $\rho_{c}^*$ that is lower than $\rho_{s}$ for these wavelengths. In contrast, leaves absorb very little NIR, but transmit about half of the intercepted NIR and deflect the rest (Wiegand and Richardson, 1984; Slaton et al., 2001). Deflection and reflection increases as successive layers of leaves develop in the canopy. As a result, $\rho_{c}^*$ for NIR is higher than $\rho_{s}$. The inverse relationships between alfalfa biomass and blue and red reflectance and the positive relationships between alfalfa biomass and NIR seen in Figs. 5-5 and 5-6 demonstrate the respective differences between $\rho_{c}^*$ and $\rho_{s}$.

When LAI ranges from LAI’ to zero, $\rho_{c}^*$ and $\rho_{s}$ can be approximated from the relationship between LAI and reflectance in Eq. [5-1] (Fig. 5-7 and Table 5-5). When LAI is zero, the observed reflectance is equal to $\rho_{s}$, and at LAI’, $\rho_{c}$ is near the reflectance limit of the canopy, $\rho_{c}^*$. The intercept of the quadratic relationships between LAI and canopy reflectance at a blue (450 nm), red (660 nm), and NIR (770 nm) band provides an estimate of $\rho_{s}$ for the respective bands. LAI’ was estimated from quadratic equations by taking the first derivative, setting it equal to zero, and solving for LAI. The resultant estimate of LAI’ (blue: 3.83, red: 3.81, and NIR: 4.14) was then used to predict $\rho_{c}^*$ from the reflectance model.

The canopy extinction coefficient, “A”, was estimated by rearranging Eq. [5-1] to express A in terms of $\rho_{c}$, $\rho_{c}^*$, $\rho_{s}$, and LAI in Eq. [5-2].

$$[5-2] \quad A = -\frac{\ln \left( \frac{\rho_{c} - \rho_{c}^*}{\rho_{c}^* - \rho_{s}} \right)}{2 * LAI}$$

The mean estimates of A for the blue, red, and NIR wavelength band were 0.374 ±0.201, 0.368 ±0.124, and 0.301 ±0.136 LAI⁻¹, respectively. Estimates of $\rho_{c}^*$ and $\rho_{s}$ and A were then used in Eq. [5-1] to predict reflectance. The predicted reflectance values were then compared with the observed values. The Monteith
Fig. 5-7. The relationship between LAI and reflectance at blue (450 nm), red (660 nm), and NIR (770 nm) bands. Included for each wavelength band is the best fit regression equation (dotted line) and Monteith and Unsworth’s (1990) equation (solid line) using parameters ($\rho_c$, $\rho_s$, and $A$) derived from the quadratic regression equations.
Table 5-5. Quadratic regression equations describing the relationship between LAI and reflectance at blue (450 nm), red (660 nm), and NIR (770 nm) bands and Monteith and Unsworth’s (1990) equation† (Y_m) using parameters (\(\rho_c\), \(\rho_s\), and A) derived from the quadratic equation.

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>Equation</th>
<th>adj. r²</th>
<th>RMSE‡</th>
<th>Relative Error§</th>
</tr>
</thead>
<tbody>
<tr>
<td>450</td>
<td>(Y = 5.66 \times 10^{-4}(\text{LAI}^2) - 4.34 \times 10^{-3}(\text{LAI}) + 0.0309)</td>
<td>0.44</td>
<td>0.00241</td>
<td>9.5</td>
</tr>
<tr>
<td></td>
<td>(Y_m = 0.0226 - (0.0226 - 0.0309)e^{-2\text{LAI}(0.374)})</td>
<td>0.47</td>
<td>0.00231</td>
<td>9.1</td>
</tr>
<tr>
<td>660</td>
<td>(Y = 1.44 \times 10^{-3}(\text{LAI}^2) - 1.10 \times 10^{-2}(\text{LAI}) + 0.04045)</td>
<td>0.58</td>
<td>0.00468</td>
<td>17.7</td>
</tr>
<tr>
<td></td>
<td>(Y_m = 0.0195 - (0.0195 - 0.0405)e^{-2\text{LAI}(0.368)})</td>
<td>0.65</td>
<td>0.00427</td>
<td>16.2</td>
</tr>
<tr>
<td>770</td>
<td>(Y = -0.013(\text{LAI}^2) + 0.108(\text{LAI}) + 0.3336)</td>
<td>0.59</td>
<td>0.0499</td>
<td>10.4</td>
</tr>
<tr>
<td></td>
<td>(Y_m = 0.5567 - (0.5567 - 0.3336)e^{-2\text{LAI}(0.301)})</td>
<td>0.65</td>
<td>0.0459</td>
<td>9.6</td>
</tr>
</tbody>
</table>

† \(\rho_c = \rho_c^* - (\rho_c^* - \rho_s)e^{-2\text{LAI}(A)}\) where: \(\rho_c\) = the observed canopy reflectance at a specific wavelength band, \(\rho_c^*\) = the limiting (i.e., asymptotic maximum) coefficient of reflection for the canopy at a specific wavelength band, \(\rho_s\) = the coefficient of reflection by the soil at a specific wavelength band, and A = the canopy attenuation coefficient (analogous to Beer’s extinction coefficient, \(\varepsilon\).  
‡ Root mean square error.  
§ RMSE/Mean reflectance.
and Unsworth’s (1990) model (Eq. [5-1]), using these estimates of $\rho_c^*$, $\rho_s$, and A, resulted in a better definition of the relationship between the blue, red, and NIR wavelength bands and LAI than the quadratic model (Table 5-5).

**Relationships between Canopy Reflectance and Alfalfa Yield Components**

In Chapter 4, it was demonstrated that yield was linearly related to both shoots m$^{-2}$ and mass shoot$^{-1}$ and that the product of these yield components explained much ($r^2 = 0.88$) of the variation in herbage yield. Shoot density was not related ($P > 0.05$) to canopy reflectance at any waveband, however, significant ($P < 0.0001$) correlations between mass shoot$^{-1}$ and canopy reflectance at all wavebands, except at 500, 530, and 600 nm, were found in each harvest in which yield components were measured (H2 - H5; Fig. 5-8). As mass shoot$^{-1}$ increased, the canopy reflectance of blue and red bands decreased as NIR canopy reflectance increased. In each case, the responses were best described by quadratic models and they were significant ($P < 0.0001$) for H4 and for data pooled across all harvests (Figs. 5-8 and 5-9). Components of mass shoot$^{-1}$, such as leaves stem$^{-1}$ and shoot length, also shared this non-linear effect ($P < 0.0001$) on reflectance in the blue, red, and NIR bands for H4 and pooled data (Figs. 5-8 and 5-9). Additional sub-components of mass shoot$^{-1}$, leaf mass shoot$^{-1}$ and stem mass shoot$^{-1}$, demonstrated a similar quadratic relationship ($P < 0.0001$) with blue, red, and NIR reflectance at H4 and for pooled data (not shown).

**5.4. CONCLUSION**

Reflectance levels in all wavelength bands measured, with the exception of the blue-green band (550 nm), were consistent within narrow ranges ($\pm 0.125$ Mg ha$^{-1}$) of alfalfa yield. However, reflectance in the visible region was more variable (cv > 20%) within yield classes above 3.75 Mg ha$^{-1}$.

Blue (450 nm) and red (660 nm) reflectance declined significantly as alfalfa yield increased, though this trend was linear for blue reflectance but
Fig. 5-8. The relationship between alfalfa canopy reflectance at blue (450 nm), red (660 nm), and NIR (770 nm) wavelength bands and mass (g) shoot\(^{-1}\), leaves stem\(^{-1}\), and shoot length (cm) from alfalfa 1 d prior to the last four harvests in 2005.
Fig. 5-9. The relationship between alfalfa canopy reflectance at blue (450 nm), red (660 nm), and NIR (770 nm) wavelength bands and mass (g) shoot$^{-1}$, leaves stem$^{-1}$, and shoot length (cm) in rainfed and subsurface drip irrigated alfalfa 1 d prior to the fourth harvest in 2005.
quadratic for red reflectance. Reflectance at NIR bands (770, 810, and 850 nm) increased curvilinearly with alfalfa yield. Reflectance in each of these bands also showed similar non-linear responses to increases in LAI. Monteith and Unsworth's (1990) canopy reflectance model, with estimates of $\rho_c^*$, $\rho_s$, and $A$ derived from the data, provided the best fit for the relationship between LAI and reflectance at blue, red, and NIR bands.

Alfalfa yield components (mass shoot$^{-1}$, leaf mass shoot$^{-1}$, stem mass shoot$^{-1}$, leaves shoot$^{-1}$ and shoot length) exhibited strong relationships with reflectance in the red (660 nm) waveband and NIR reflectance. Though the relationship between these response variables and reflectance in blue (450 nm) wavelength bands exhibited similar and significant trends, their effects on blue reflectance were not as consistent as those found at other bands.

These results indicate that blue (450 nm), red (660 nm) and NIR (770 nm) bands are most strongly related to alfalfa yield and yield components. These bands should provide the basis for canopy reflectance-based approaches to the prediction alfalfa yield, yield components, and LAI.
CHAPTER 6: RELATIONSHIPS BETWEEN CANOPY REFLECTANCE AND LEAF AREA AND YIELD OF ALFALFA: II. BLUE- AND RED-BASED VEGETATION INDICES

6.1. INTRODUCTION

Variability in yield limiting factors, such as plant available soil moisture and nutrients, within a field has spurred interest in site-specific management (SSM) strategies for alfalfa (*Medicago sativa* L.; Leep et al., 2000; Dolling et al., 2005). To gauge the need for and the response to SSM strategies in alfalfa, a tool for gauging and georeferencing yield variations within an alfalfa field is needed. Several devices have been developed to measure forage DM yield (e.g., Michalk and Herbert, 1977; Martel and Savoie, 2000; Sanderson et al., 2001; Savoie et al., 2002; Shinners et al., 2003), but are either not commercially available/viable or too time-consuming to be used at a sufficient resolution to characterize yield variations throughout a field.

Advances in remote sensing and the availability of field-ready multispectral spectroradiometers hold great potential for the site-specific assessment of alfalfa yield. The literature contains numerous vegetation indices (VIs) that have been shown to relate canopy reflectance to agronomically-relevant variables (Bannarti et al., 1995; Moran et al., 1997; Pinter et al., 2003; Gitelson, 2004). In general, these indices have been developed to use the disparity between canopy reflectance in NIR regions and blue, green, or red wavebands to extract information about the amount of biomass and/or nutrient status of the plant (Moran et al., 1997; Pinter et al., 2003). Since NIR reflectance increases and red and blue reflectance decrease with vegetative biomass (Chapter 5), the difference between reflectance in these regions is often superiorly related to phytomass. Consequently, VIs are usually calculated as the difference, ratio, or other combination (linear or non-linear) of reflected NIR light and one or more bands from within the visible region of the electromagnetic spectrum (Monteith and Unsworth, 1990).
One of the first and most prevalent VIs in the literature, the Normalized Difference Vegetation Index (NDVI), is the normalized difference between NIR and red reflectance (Rouse et al., 1973; Table 6-1). For example, researchers have used NDVI to estimate alfalfa canopy height during regrowth (Payero et al., 2004), DM availability in variably stocked pastures (Mitchell et al., 1990), and yield in hayfields stressed by pests (Leep et al., 2000).

However, VIs demonstrate a saturative response (exponential rise to max) to vegetative biomass (Moran et al., 1997; Pinter et al., 2003; Gitelson, 2004). This is because canopy reflectance asymptotically approaches a wavelength-specific limit as the leaf area index (LAI) approaches a maximum (LAI'; Monteith and Unsworth, 1990; Chapter 5). The saturative nature of canopy reflectance, therefore, confines the assessment of vegetation biomass to those conditions where LAI is substantially less than LAI'. Presumably, alfalfa is at or near LAI' at harvest, unless limited by stress (Chapter 5).

The NDVI and NDVI-type indices, such as the green- (GNDVI; Gitelson, 1996) and blue-based (BNDVI: Yang et al., 2004) versions, are very sensitive to“saturation” (Gitelson, 2004). NIR reflectance is typically an order of magnitude greater than red reflectance (Gates et al., 1965; Gausman and Allen, 1973; Wiegand and Richardson, 1984; Slaton et al., 2001; Gitelson, 2004) and it increases proportionately more than red reflectance, especially as the canopy reaches LAI' (Gitelson, 2004; Chapter 5). This led Gitelson (2004) to propose a weighting coefficient ('α') to scale-down NIR reflectance within the NDVI equation (Table 6-1). Gitelson’s (2004) Wide Dynamic Range Vegetation Index (WDRVI) slows the WDRVI's rate of increase and widens the range over which the VI is responsive to changes in phytomass. This recent modification of NDVI holds great potential for detecting yield variability within stressed alfalfa canopies.

The goal of my research is to evaluate the use of commercially-available multispectral sensors to measure yield variation within an alfalfa field. As I have previously established that blue (450 nm), red (660 nm), and NIR (770, 810, and 850 nm) reflectance are related to the LAI, yield components, and yield of alfalfa,
Table 6-1. Equations and the reflectance (R) bands used for calculating the normalized difference vegetation indices (NDVI) and wide dynamic range vegetation indices (WDRVI) used in this analysis.

<table>
<thead>
<tr>
<th>Index†</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normalized Difference Vegetation Index (NDVI)</td>
<td>Rouse et al., 1973</td>
</tr>
</tbody>
</table>
| \[
\text{NDVI} = \frac{R_{\text{NIR}} - R_{\text{Red}}}{R_{\text{NIR}} + R_{\text{Red}}}
\] |
| Blue - Normalized Difference Vegetation Index (BNDVI) | Yang et al., 2004 |
| \[
\text{BNDVI} = \frac{R_{\text{NIR}} - R_{\text{Blue}}}{R_{\text{NIR}} + R_{\text{Blue}}}
\] |
| Wide Dynamic Range Vegetation Index (WDRVI) | Gitelson, 2004 |
| \[
\text{WDRVI}_\alpha = \frac{\alpha R_{\text{NIR}} - R_{\text{Red}}}{\alpha R_{\text{NIR}} + R_{\text{Red}}}
\] |
| Blue - Wide Dynamic Range Vegetation Index (BWDRVI) | |
| \[
\text{BWDRVI}_\alpha = \frac{\alpha R_{\text{NIR}} - R_{\text{Blue}}}{\alpha R_{\text{NIR}} + R_{\text{Blue}}}
\] |

† \(R_{\text{NIR}}\) = fraction of light reflected at a NIR (770 nm) wavelength band; \(R_{\text{Red}}\) = fraction of light reflected at a red (660 nm) wavelength band; \(R_{\text{Blue}}\) = fraction of light reflected at a blue (450 nm) wavelength band; Three levels of weighting coefficients (‘\(\alpha\)’) for NIR reflectance were used in the calculation of the red- and blue-based WDRVIs: ‘\(\alpha\)’ = 0.1, 0.05, and 0.01.
I seek to determine the relationships between alfalfa yield and LAI and blue- and red-based NDVIs and WDRVIs at three levels of ‘α’ (0.1, 0.05, and 0.01).

Specifically, the objectives of this work were to i) evaluate how the canopy reflectance of alfalfa at a NIR band relates to reflectance at blue and red wavelength bands and influences these blue- and red-based VIs; ii) to characterize the relationship between the LAI, yield components, and yield of alfalfa to blue- and red-based NDVIs and WDRVIs, iii) to determine if these VIs differ in the range of yield values for which they can be considered effective, iv) and to evaluate the ability of these VIs to characterize alfalfa yield within their effective ranges.

6.2. MATERIALS AND METHODS

Canopy reflectance measurements were taken 1 d prior to harvest from 3-yr-old stands of alfalfa cv ‘Garst 631’ at the University of Kentucky Animal Research Center (84° 44’ W long, 38° 4’ N lat). Yield measurements were made at five harvests in 2005: 5 May (H1), 15 June (H2), 22 July (H3), 23 August (H4), and 30 September (H5). Two sets of reflectance and yield observations were obtained from subsurface drip irrigated (SDI) and rainfed whole plots in 2005. One set of observations, 2005K, was obtained from four split-plots (2.4 x 6.1 m) that had received randomly assigned topdressings of 0, 112, 336, or 448 kg K₂O ha⁻¹ on 1 October 2004 in a blocked, split-plot design. A second group of observations, 2005o, was obtained from four, predetermined locations (randomized for each regrowth cycle) within each SDI and rainfed plot. Further details regarding the design and installation of the SDI system, the experimental layout of 2005K, and yield measurements have been described in Chapter 3. The determination of leaf area index (LAI) and the measurement of yield component variables are described in Chapter 4.

Canopy reflectance measurements were made with two field-ready multispectral sensors: the Yara Hydro-N-Sensor (NS: Yara International ASA, Oslo, Norway) and the GreenSeeker® Model 505 (GS: NTech Industries, Inc.,
Ukiah, CA). A description of and the methods used to obtain canopy reflectance measurements with the NS are presented in Chapter 5. The GS differs from the HN in four fundamental ways. First, the GS is an “active” device in that it illuminates the target with red and NIR light in a linear 0.6 x 0.01 m strip using two rows of light-emitting diodes (NTech Industries, 2005). Second, a single, factory-calibrated photoelectric diode measures the fraction of the emitted light that is reflected from the red [660 nm ±10 nm full width half magnitude (FWHM)] and NIR (770 ± 15 nm FWHM) bands (NTech Industries, 2005). This is in contrast to the passive HN sensor, which rectifies the reflected light to a measurement of incident radiation from a second, upward-facing sensor and records fractional canopy reflectance (i.e., reflected/incident) in up to 20 wavelength bands (± 10 nm FWHM; tec5helma, 2005). Third, the viewing angle of the GS is 0° from nadir, while the HN has optical inputs that are angled at 64° to nadir. Finally, reflectance measurements are made by the GS at a very high rate (1000 measurements s⁻¹), but records an average NDVI at a frequency that matches the update rate of the GPS receiver. In this study, a GPSCapture® software (NTech Industries, Inc., Ukiah, CA) and Holux GM-270 (HOLUX Technology, Inc., Taipei, Taiwan; update rate of 1 Hz) was used to capture and georeference (± 2 m) the NDVI measurements.

As with the NS, NDVI measurements were taken from each plot in both directions at a comfortable walking pace. Measurements were taken in a strip directly above the SDI tapeline or subsoiler slit (SDI and Rainfed plots, respectively; “Shank” locations) and from a strip located halfway between these Shank locations. Data were converted to ASCII text files (.csv) and post-processed using ArcGIS 9.0 (ESRI, Inc., Redlands, CA) where measurements taken 0.3 m or less from inside the plot edge were excluded and an averaged NDVI for each plot was recorded. Measurements using the GS were taken within 5 min of measurements of the NS. The NS measurements were always taken first, as GS measurements resulted in trampling the standing crop and would have altered canopy reflectance.
Vegetation Indices

Canopy reflectance was measured with the NS at blue (450 nm), red (660 nm), and NIR (770 nm) wavelength bands (± 10 nm FWHM) because these bands exhibited the strongest relationship with alfalfa yield and yield components (Chapter 5). These bands were used to determine eight vegetation indices (VIs), including blue- and red-based normalized difference vegetation indices (NDVI\text{NS} and BNDVI, respectively) and wide dynamic range vegetation indices (WDRVI\text{a} and BWDRVI\text{a}, respectively) at each of three levels of ‘\(\alpha\)’ (0.1, 0.05, and 0.01) (Rouse et al., 1974; Gitelson, 2004; Table 6-1). These VIs were in addition to the NDVI recorded by the GS (NDVI\text{GS}).

Data Analysis

A repeated measures analysis was performed using the MIXED models procedure in SAS 9.1 (SAS Institute, 2003) to analyze for treatment effects on the VIs across the multiple harvests. Regression equations were obtained using the MODEL and REG procedures in SAS 9.1 (SAS Institute, 2003). A quadratic-plateau analysis was performed using the NLIN procedure and standard errors for the joint points were calculated using an IML procedure script created by P.L. Cornelius (personal comm., 2006) in SAS 9.1 (SAS Institute, 2003).

6.3. RESULTS AND DISCUSSION

Yield response to SDI (observation sets: 2005\text{o} and 2005\text{K}) and K fertilization levels (2005\text{K}) are detailed in Chapters 3 and 4. Though the level of plant available K in the soil was in a responsive range (114 mg kg\(^{-1}\)) for alfalfa (Thom and Dollarhide, 1994), yield within a harvest (Chapter 3) and reflectance from those canopies (Chapter 5) were unaffected (\(P > 0.05\)) by K application. Repeated measures analysis of observation set 2005\text{K} indicated that vegetation indices were not affected (\(P > 0.05\)) by K application at any harvest (data not shown). Unless otherwise indicated, data were pooled across both observation sets (2005\text{o} and 2005\text{K}). Harvest date also had a significant effect (\(P < 0.05\)) on
the vegetation indices, but this is likely a result of differences in yield between harvests.

**Relationship between NIR and Blue and Red Reflectance**

Within each cutting date, the fraction of blue (450 nm) and red (660 nm) light reflected by the crop canopies was significantly (P < 0.0001) related to the fractional reflectance in the NIR (770 nm) wavelength band. However, in H1, H2, and H5, blue and red increased proportionally with NIR reflectance (blue: r = 0.80, 0.82, and 0.97 vs. red: r = 0.57, 0.85, and 0.97, respectively), while in H3 and H4 the correlation was negative (blue: r = -0.32 and -0.78 vs. red: r = -0.37 and -0.85, respectively). When data from all harvests were combined, blue and red reflectance demonstrated a significant (P < 0.0001) quadratic relationship to NIR reflectance (r² = 0.36; RMSE = 0.0036 vs. r² = 0.46; RMSE = 0.0040, respectively; Fig. 6-1). By setting the first derivatives of the quadratic equations for the blue and red relationship to NIR reflectance equal to zero, these data indicate that blue and red reflectance were positively associated with NIR reflectance values above 0.473 and 0.503, respectively.

It is difficult to ascertain the cause of this shift from a negative to a positive relationship above NIR reflectance of 0.5. These data indicate that blue and red reflectance was shown to asymptotically approach a minimum reflectance value of 0.0226 and 0.0195, respectively, as LAI approached LAI’. It is noteworthy that the shift from a negative to positive relationship with NIR occurs very near these estimated minimum values for blue and red reflectance. The occurrence of this minimum was also coincident with the absorption maximum at LAI’.

Gitelson (2004) reported a similar decline in red reflectance as NIR reflectance increased from corn, soybean, and wheat canopies. However, Gitelson’s (2004) dataset had few (< 15) NIR observations greater than 0.5. Gitelson (2004) proposed that the saturative nature of NDVI at higher vegetation fractions could be mediated by scaling-down NIR reflectance to the values of red reflectance. This approach makes NDVI much more sensitive to changes in red reflectance and is intended to extend the range of vegetative fractions in which
Fig. 6-1. The relationship between the fraction of incident light reflected from alfalfa crop canopies at NIR (770 nm) and blue (450 nm) and red (660 nm) as measured 1 d prior to each of five harvests in 2005.
canopy reflectance is related to canopy variables. Gitelson (2004) demonstrated that as scaling coefficients ($\alpha$) approach zero, the exponential relationship between the Wide Dynamic Range Vegetation Index (WDRVI) and LAI becomes more gradual and saturates later than NDVI.

Implicit in the calculation of NDVI is the dominance of NIR reflectance. As a result, the use of NIR reflectance values of 0.5 or above in calculations of NDVI has no significant consequence because an increase in NIR is at least an order of magnitude greater than the corresponding increase in red reflectance (Fig. 6-1). However, the use of a scalar that reduces NIR reflectance to or below the scale of red reflectance values causes an increase in red reflectance to exert greater influence on the vegetation index. This effect is demonstrated in the relationships between NIR reflectance observed in the current study and the responses of NDVI and WDRVIs calculated using $\alpha$ levels of 0.1, 0.05, and 0.1 (Fig. 6-2). An exponential function best described the relationship between NIR and NDVI and WDRVI$_{\alpha=0.1}$. In contrast, increases in red reflectance when NIR reflectance increased above 0.55 caused a decline in WDRVI$_{\alpha=0.05}$ and WDRVI$_{\alpha=0.01}$ and resulted in these indices demonstrating a quadratic response to NIR reflectance. This phenomenon was also exhibited by the blue-based NDVI and WDRVIs calculated using these ‘$\alpha$’ levels (Fig. 6-3). However, the effect of the quadratic relationship between blue and NIR reflectance is exacerbated for blue-based VIs because the range in blue reflectance values is narrower than in red reflectance values (i.e., Blue $\rho_c^*$ - Blue $\rho_s$ < Red $\rho_c^*$ - Red $\rho_s$). As a result, a scalar of 0.1 caused BWDRVI$_{\alpha=0.1}$ to demonstrate a quadratic relationship with NIR reflectance, in contrast to the equivalent red-based VI (Figs. 6-2 and 6-3).

These results demonstrate that if one uses scalars for NIR reflectance in VIs then one must take into account the possibility that red reflectance may increase rather than decrease with NIR reflectance. This, along with the proven benefit of the WDRVI to extend the range of VIs (Gitelson, 2004), warrants further research to determine optimum scalar values.
Fig. 6-2. The influence of NIR (770 nm) reflectance on NDVI and WDRVIs calculated using ‘α’ values of 0.1, 0.05, and 0.1. Canopy reflectance was measured from alfalfa 1 d prior to each of five harvests in 2005.
Fig. 6-3. The influence of NIR (770 nm) reflectance on BNDVI and BWDRVIs calculated using ‘α’ values of 0.1, 0.05, and 0.1. Canopy reflectance was measured from alfalfa 1 d prior to each of five harvests in 2005.
Relationships between the Red- and Blue-Based Vegetation Indices and Leaf Area and Yield Components of Alfalfa

Every VI investigated showed a significant ($P < 0.0001$) saturative exponential response (exponential rise to max) to LAI in alfalfa (Figs. 6-4, 6-5, and 6-6). It is not surprising that similar relationships were found between LAI and alfalfa yield components (Chapter 4). All of the VIs also exhibited a significant ($P < 0.0001$) saturative response to mass shoot$^{-1}$ (Figs. 6-4, 6-5, and 6-6), as well as leaf mass shoot$^{-1}$ and stem mass shoot$^{-1}$ (data not shown). This is similar to the findings of Mitchell et al. (1990) who found NDVI and leaf, stem, and total mass m$^{-2}$ were significantly correlated in grazed pastures. Further, each VI exhibited a strong ($r^2 = 0.66 - 0.82$) saturative exponential response to shoot length (Figs. 6-4, 6-5, and 6-6). Recently, Payero et al. (2004) reported that each of 11 red-based vegetation indices (WDRVI was not evaluated) very accurately ($r^2 > 0.92$) tracked the height of an alfalfa canopy during regrowth when an exponential model was used.

As would be predicted from the relative strength of the relationship between red reflectance and LAI, shoot height, and yield component variables (see Chapter 5), the red-based VIs exhibited a stronger relationship (higher $r^2$ and lower RMSE) than their blue-based counterparts. The relationship between NDVI calculated by the GS was slightly, but consistently stronger for each yield component (Fig. 6-4). However, this may be partly attributable to the larger number of NDVI$_{GS}$ observations as a result of the higher data recording rate of the GS.

As predicted by Gitelson (2004), decreasing the weighting coefficient ($\alpha$) in the red- and blue-based WDRVIs resulted in a more gradual exponential response to each yield component. However, decreasing the dominance of NIR in the VI calculation by decreasing ‘$\alpha$’ diminished the predictivity, especially of blue-based WDRVIs.
Fig. 6-4. Relationship of the blue- and red-based NDVIs to LAI, mass shoot\(^{-1}\), and shoot length.
Fig. 6-5. Relationship of red-based WDRVIs at ‘α’ levels of 0.1, 0.05, and 0.01 to LAI, mass shoot$^{-1}$, and shoot length.
Fig. 6-6. Relationship of blue-based WDRVIs at ‘α’ levels of 0.1, 0.05, and 0.01 to LAI, mass shoot-1, and shoot length.
Relationships between Alfalfa Yield and Red- and Blue-Based Vegetation Indices

The saturative responses of each VI to increasing LAI and alfalfa yield (Figs. 6-7, 6-8, and 6-9) were similar. A splice quadratic-plateau model was chosen to describe the saturative response of VIs to increases in alfalfa yield.

The quadratic-plateau model closely approximates a saturative exponential function, but identifies the yield \( \text{Yield}_{\text{max}} \) above which the VI does not respond to increases in yield. Thus, \( \text{Yield}_{\text{max}} \) (i.e., the point at which the quadratic function joins the plateau) estimates the upper limit of the range in which a given VI predicts alfalfa yield. To determine \( \text{Yield}_{\text{max}} \) using the greatest possible data range, a spliced quadratic-plateau model was fitted to the response of each VI to the pooled yield dataset across all harvest dates. The spliced quadratic-plateau model explained much of the observed variation \( (r^2 > 0.65) \) in each of the blue- and red-based NDVIs and WDRVIs ('\( \alpha' = 0.1, 0.5, \) and 0.01). Further, these VIs demonstrated a range in \( \text{Yield}_{\text{max}} \) values (Table 6-2).

For NDVI\(_{\text{GS}}\) and NDVI\(_{\text{NS}}\), \( \text{Yield}_{\text{max}} \) values indicate that these VIs should only be used when alfalfa yields are in the range of 0 - 1.83 (± 0.118) and 1.82 (± 0.122) Mg ha\(^{-1}\), respectively. Decreasing the weighting coefficient ('\( \alpha' \)) increased \( \text{Yield}_{\text{max}} \) in both the red- and blue-based WDRVIs (Table 6-2). These more gradual changes in VI in response to alfalfa yield is consistent with the results of Gitelson (2004) with corn, soybean, and wheat. Interestingly, the blue-based VIs exhibited larger \( \text{Yield}_{\text{max}} \) values than the red-based counterparts. In Chapter 5, it was shown that blue reflectance was linearly related to yield, but red reflectance was curvilinear. Their relationships with yield may be because the canopy floor (i.e., soil, plant residue, etc.) reflects larger amounts of red light than blue (i.e., Blue \( \rho_s < \text{Red} \rho_s \)). The wider useful range of blue-based VIs may be a result of this relationship.
Fig. 6-7. Quadratic-plateau functions describing the relationship between alfalfa yield and NDVI as measured by the GreenSeeker® (NDVI_{GS}) and Hydro-N-Sensor (NDVI_{NS}). Canopy reflectance measurements were made 1 d prior to each of the five harvests during 2005.
Fig. 6-8. Quadratic-plateau functions describing the relationship between alfalfa yield and WDRVIs calculated using one of three weighting coefficients (‘α’ = 0.1, 0.05, and 0.01). Canopy reflectance measurements from which the indices are calculated were made 1 d prior to each of the five harvests during 2005.
Fig. 6-9. Quadratic-plateau functions describing the relationship between alfalfa yield and blue (450 nm) reflectance based vegetative indices [BNDVI and BWDRVI calculated using one of three weighting coefficients \( \alpha = 0.1, 0.05, \) and 0.01]. Canopy reflectance measurements from which the indices are calculated were made 1 day prior to each of the five harvests during 2005.
Table 6-2. Values of alfalfa yield above which the selected vegetative indices plateau.

<table>
<thead>
<tr>
<th>Vegetation Index</th>
<th>Yield(_{\text{max}})†</th>
<th>SE</th>
<th>95% CI‡</th>
</tr>
</thead>
<tbody>
<tr>
<td>NDVI(_G)</td>
<td>1.83</td>
<td>0.060</td>
<td>± 0.118</td>
</tr>
<tr>
<td>NDVI(_N)</td>
<td>1.82</td>
<td>0.061</td>
<td>± 0.122</td>
</tr>
<tr>
<td>WDRVI((\alpha=0.1))</td>
<td>2.28</td>
<td>0.081</td>
<td>± 0.160</td>
</tr>
<tr>
<td>WDRVI((\alpha=0.05))</td>
<td>2.47</td>
<td>0.139</td>
<td>± 0.274</td>
</tr>
<tr>
<td>WDRVI((\alpha=0.01))</td>
<td>2.76</td>
<td>0.129</td>
<td>± 0.254</td>
</tr>
<tr>
<td>BNDVI</td>
<td>2.60</td>
<td>0.102</td>
<td>± 0.200</td>
</tr>
<tr>
<td>BWDRVI((\alpha=0.1))</td>
<td>3.12</td>
<td>0.137</td>
<td>± 0.270</td>
</tr>
<tr>
<td>BWDRVI((\alpha=0.05))</td>
<td>3.35</td>
<td>0.160</td>
<td>± 0.314</td>
</tr>
<tr>
<td>BWDRVI((\alpha=0.01))</td>
<td>3.74</td>
<td>0.210</td>
<td>± 0.413</td>
</tr>
</tbody>
</table>

† Yield\(_{\text{max}}\) = The joint point in the quadratic-plateau response of a given VI to increases in yield. This value defines the upper limit of the effective predictive range for the given VI, as yield values above Yield\(_{\text{max}}\) do not result in any change in the value of the VI.

‡ The 95% confidence interval (CI).
Evaluation of Red- and Blue-Based Vegetation Indices for Predicting Alfalfa Yield within Their Effective Range

After establishing $Y_{\text{max}}$ and the effective range for a specific VI, alfalfa yield was regressed on each VI within its effective yield range for each harvest and with data pooled across all harvests (Table 6-3). Significant quadratic relationships were established between each VI and alfalfa yield in H3 ($P < 0.05$), H4 ($P < 0.0001$), and when data were pooled across all harvests. Though the quadratic relationship between $\text{NDVI}_{\text{GS}}$ and alfalfa yield was the strongest ($r^2 = 0.68$) of all VIs when the data were pooled across all harvests, only 164 (41%) of 400 possible observations fell within the effective yield range of the $\text{NDVI}_{\text{GS}}$ (Table 6-3). The relationship between $\text{NDVI}_{\text{NS}}$ and alfalfa yield explained less of the variation ($r^2 = 0.58$).

As expected, the wider range of the blue-based VIs allowed the inclusion of more observations than the red-based counterparts. The wider effective yield range of the WDRVIs included nearly 60% more data points for red-based VIs and over 25% more observations for blue-based VIs. Further, the blue-based indices maintained significant ($P < 0.0001$) relationships with alfalfa yield within H3 ($r^2 \geq 0.18$), H4 ($r^2 \geq 0.81$), and across all harvests ($r^2 \geq 0.55$). In addition, the use of a weighting coefficient generally enhanced the fit of the quadratic models within harvests where a significant relationship was found.

The relative error of the significant quadratic models [(RMSE of the model / mean of yield values included) x 100] for each VI was less than 30%. The level of error for the models based on these VIs was at or slightly less than the error (25 - 40%) reported for conventional in situ forage biomass measurement devices, such as the pasture ruler, capacitance meter, and rising plate meter (e.g., Michalk and Herbert, 1977; Sanderson et al., 2001). An alfalfa producer would likely need to calibrate the VIs against yield at each harvest date.
Table 6-3. Best fit regression equations, F ratios, fit statistics, and the number and mean value of yield observations included in the analysis of the relationship between blue- and red-based vegetative indices and alfalfa yield. Analysis included only those observations for which the yield value fell within the effective range of the respective indices. The analysis was performed within each of 5 harvests in 2005 (H1, H2, ... H5) and on data pooled across all harvests (All).

<table>
<thead>
<tr>
<th>Vegetative Index†</th>
<th>Harvest</th>
<th>Equation</th>
<th>F ‡</th>
<th>adj. r²</th>
<th>n§</th>
<th>Mean¶</th>
<th>RMSE ††</th>
</tr>
</thead>
<tbody>
<tr>
<td>NDVI&lt;sub&gt;GS&lt;/sub&gt;</td>
<td>All</td>
<td>y = 0.063x&lt;sup&gt;2&lt;/sup&gt; + 3.171x - 1.261</td>
<td>160.81****</td>
<td>0.68</td>
<td>164</td>
<td>1.25</td>
<td>0.280</td>
</tr>
<tr>
<td></td>
<td>H1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>H2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>H3</td>
<td>y = 0.323x&lt;sup&gt;2&lt;/sup&gt; + 2.218x - 0.609</td>
<td>5.43*</td>
<td>0.14</td>
<td>58</td>
<td>1.27</td>
<td>0.299</td>
</tr>
<tr>
<td></td>
<td>H4</td>
<td>y = 6.511x&lt;sup&gt;2&lt;/sup&gt; - 4.649x + 0.933</td>
<td>112.05****</td>
<td>0.83</td>
<td>47</td>
<td>0.87</td>
<td>0.255</td>
</tr>
<tr>
<td></td>
<td>H5</td>
<td>y = -321.7x&lt;sup&gt;2&lt;/sup&gt; + 568.5x - 249.6</td>
<td>1.32</td>
<td>0.01</td>
<td>53</td>
<td>1.55</td>
<td>0.195</td>
</tr>
<tr>
<td>NDVI&lt;sub&gt;NS&lt;/sub&gt;</td>
<td>All</td>
<td>y = 18.67x&lt;sup&gt;2&lt;/sup&gt; - 23.60x + 7.384</td>
<td>112.90****</td>
<td>0.58</td>
<td>164</td>
<td>1.25</td>
<td>0.280</td>
</tr>
<tr>
<td></td>
<td>H1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>H2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>H3</td>
<td>y = -229.9x&lt;sup&gt;2&lt;/sup&gt; + 413.2x - 184.4</td>
<td>3.97*</td>
<td>0.09</td>
<td>58</td>
<td>1.27</td>
<td>0.299</td>
</tr>
<tr>
<td></td>
<td>H4</td>
<td>y = 33.41x&lt;sup&gt;2&lt;/sup&gt; - 47.24x + 16.66</td>
<td>63.06****</td>
<td>0.73</td>
<td>47</td>
<td>0.87</td>
<td>0.255</td>
</tr>
<tr>
<td></td>
<td>H5</td>
<td>y = -253.51x&lt;sup&gt;2&lt;/sup&gt; + 468.9x - 215.2</td>
<td>0.05</td>
<td>0.00</td>
<td>53</td>
<td>1.55</td>
<td>0.195</td>
</tr>
<tr>
<td>BNDVI</td>
<td>All</td>
<td>y = 67.94x&lt;sup&gt;2&lt;/sup&gt; - 101.4x + 37.72</td>
<td>174.49****</td>
<td>0.55</td>
<td>280</td>
<td>1.66</td>
<td>0.404</td>
</tr>
<tr>
<td></td>
<td>H1</td>
<td>y = -0.332x&lt;sup&gt;2&lt;/sup&gt; - 0.733x + 2.980</td>
<td>0.01</td>
<td>-0.07</td>
<td>17</td>
<td>2.30</td>
<td>0.189</td>
</tr>
<tr>
<td></td>
<td>H2</td>
<td>y = -5525x&lt;sup&gt;2&lt;/sup&gt; + 10230x - 4728</td>
<td>10.89***</td>
<td>0.38</td>
<td>33</td>
<td>2.18</td>
<td>0.349</td>
</tr>
<tr>
<td></td>
<td>H3</td>
<td>y = 252.0x&lt;sup&gt;2&lt;/sup&gt; - 438.0x + 191.6</td>
<td>9.41***</td>
<td>0.18</td>
<td>80</td>
<td>1.51</td>
<td>0.447</td>
</tr>
<tr>
<td></td>
<td>H4</td>
<td>y = 124.8x&lt;sup&gt;2&lt;/sup&gt; - 197.1x + 77.81</td>
<td>154.31****</td>
<td>0.81</td>
<td>71</td>
<td>1.34</td>
<td>0.337</td>
</tr>
<tr>
<td></td>
<td>H5</td>
<td>y = 945.4x&lt;sup&gt;2&lt;/sup&gt; - 1734x + 796.4</td>
<td>1.11</td>
<td>0.00</td>
<td>79</td>
<td>1.73</td>
<td>0.326</td>
</tr>
<tr>
<td>WDRVI_{\alpha=0.1}</td>
<td>All</td>
<td>( y = 0.413x^2 + 2.444x + 0.583 )</td>
<td>136.91****</td>
<td>0.55</td>
<td>225</td>
<td>1.47</td>
<td>0.352</td>
</tr>
<tr>
<td>H1</td>
<td>( y = 51.27x^2 - 46.33x + 12.49 )</td>
<td>2.78</td>
<td>0.34</td>
<td>8</td>
<td>2.14</td>
<td>0.100</td>
<td></td>
</tr>
<tr>
<td>H2</td>
<td>( y = -38.64x^2 + 35.15x - 6.116 )</td>
<td>0.48</td>
<td>0.00</td>
<td>11</td>
<td>1.67</td>
<td>0.448</td>
<td></td>
</tr>
<tr>
<td>H3</td>
<td>( y = 1.102x^2 + 1.726x + 0.821 )</td>
<td>9.23***</td>
<td>0.19</td>
<td>73</td>
<td>1.43</td>
<td>0.387</td>
<td></td>
</tr>
<tr>
<td>H4</td>
<td>( y = 3.950x^2 + 1.905x + 0.337 )</td>
<td>151.03***</td>
<td>0.84</td>
<td>59</td>
<td>1.12</td>
<td>0.267</td>
<td></td>
</tr>
<tr>
<td>H5</td>
<td>( y = 16.639x^2 - 14.011x + 4.605 )</td>
<td>0.51</td>
<td>0.00</td>
<td>74</td>
<td>1.69</td>
<td>0.285</td>
<td></td>
</tr>
</tbody>
</table>

| BWDRVI_{\alpha=0.1} | All | \( y = 3.031x^2 + 3.131x + 0.217 \) | 206.00**** | 0.56 | 318 | 1.80 | 0.457 |
| H1 | \( y = -191.7x^2 + 181.7x - 40.39 \) | 3.07 | 0.12 | 30 | 2.56 | 0.325 |
| H2 | \( y = -175.4x^2 + 153.7x - 31.08 \) | 7.59** | 0.21 | 50 | 2.42 | 0.441 |
| H3 | \( y = 9.348x^2 - 2.659x + 1.376 \) | 9.47*** | 0.18 | 80 | 1.51 | 0.447 |
| H4 | \( y = 6.524x^2 + 2.168x + 0.166 \) | 197.00**** | 0.83 | 79 | 1.49 | 0.351 |
| H5 | \( y = 33.92x^2 - 26.91x + 7.013 \) | 1.18 | 0.00 | 79 | 1.73 | 0.326 |

| WDRVI_{\alpha=0.05} | All | \( y = -0.215x^2 + 2.783x + 1.510 \) | 158.84**** | 0.55 | 262 | 1.60 | 0.390 |
| H1 | \( y = -0.287x^2 + 0.293x + 2.220 \) | 0.03 | 0.00 | 15 | 2.26 | 0.170 |
| H2 | \( y = -41.92x^2 + 12.69x + 1.350 \) | 3.18 | 0.15 | 25 | 2.07 | 0.420 |
| H3 | \( y = 3.935x^2 + 2.801x + 1.546 \) | 13.34*** | 0.24 | 78 | 1.48 | 0.410 |
| H4 | \( y = 3.684x^2 + 4.433x + 1.432 \) | 188.65**** | 0.85 | 66 | 1.26 | 0.284 |
| H5 | \( y = 33.29x^2 - 7.8219x + 2.109 \) | 2.06 | 0.03 | 78 | 1.72 | 0.313 |

<p>| BWDRVI_{\alpha=0.05} | All | ( y = 2.739x^2 + 4.957x + 1.593 ) | 242.59**** | 0.59 | 337 | 1.88 | 0.481 |
| H1 | ( y = -12.55x^2 + 7.125x + 1.933 ) | 0.94 | 0.00 | 45 | 2.79 | 0.440 |
| H2 | ( y = -125.6x^2 + 31.27x + 0.707 ) | 8.45*** | 0.22 | 53 | 2.46 | 0.454 |
| H3 | ( y = 6.670x^2 + 3.128x + 1.527 ) | 9.49*** | 0.18 | 80 | 1.51 | 0.447 |
| H4 | ( y = 4.468x^2 + 5.804x + 1.611 ) | 185.99**** | 0.82 | 80 | 1.51 | 0.369 |
| H5 | ( y = 24.39x^2 - 3.638x + 1.809 ) | 1.22 | 0.01 | 79 | 1.73 | 0.326 |</p>
<table>
<thead>
<tr>
<th></th>
<th>All y = ( -9.589x^2 - 7.057x + 1.136 )</th>
<th>175.39***</th>
<th>0.55</th>
<th>292</th>
<th>1.70</th>
<th>0.423</th>
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<tbody>
<tr>
<td>H1</td>
<td>( y = -16.01x^2 - 19.90x - 3.756 )</td>
<td>0.58</td>
<td>0.00</td>
<td>21</td>
<td>2.37</td>
<td>0.236</td>
</tr>
<tr>
<td>H2</td>
<td>( y = -121.6x^2 - 138.3x - 36.81 )</td>
<td>9.81***</td>
<td>0.33</td>
<td>37</td>
<td>2.24</td>
<td>0.366</td>
</tr>
<tr>
<td>H3</td>
<td>( y = 10.13x^2 + 18.86x + 9.638 )</td>
<td>15.21***</td>
<td>0.26</td>
<td>80</td>
<td>1.51</td>
<td>0.423</td>
</tr>
<tr>
<td>H4</td>
<td>( y = 7.675x^2 + 18.40x + 10.31 )</td>
<td>216.44***</td>
<td>0.85</td>
<td>75</td>
<td>1.41</td>
<td>0.313</td>
</tr>
<tr>
<td>H5</td>
<td>( y = 69.39x^2 + 82.31x + 26.07 )</td>
<td>1.56</td>
<td>0.01</td>
<td>79</td>
<td>1.73</td>
<td>0.324</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>All y = ( 1.784x^2 + 11.70x + 8.608 )</th>
<th>249.08****</th>
<th>0.59</th>
<th>353</th>
<th>1.96</th>
<th>0.524</th>
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<tr>
<td>H1</td>
<td>( y = -78.02x^2 - 80.91x - 17.92 )</td>
<td>1.92</td>
<td>0.03</td>
<td>55</td>
<td>2.93</td>
<td>0.484</td>
</tr>
<tr>
<td>H2</td>
<td>( y = -254.2x^2 - 300.7x - 86.23 )</td>
<td>4.97*</td>
<td>0.12</td>
<td>59</td>
<td>2.58</td>
<td>0.563</td>
</tr>
<tr>
<td>H3</td>
<td>( y = 15.90x^2 + 26.66x + 12.24 )</td>
<td>9.52***</td>
<td>0.18</td>
<td>80</td>
<td>1.51</td>
<td>0.447</td>
</tr>
<tr>
<td>H4</td>
<td>( y = 2.109x^2 + 12.89x + 9.274 )</td>
<td>180.91****</td>
<td>0.82</td>
<td>80</td>
<td>1.51</td>
<td>0.373</td>
</tr>
<tr>
<td>H5</td>
<td>( y = 64.26x^2 + 79.81x + 26.45 )</td>
<td>1.31</td>
<td>0.01</td>
<td>79</td>
<td>1.73</td>
<td>0.325</td>
</tr>
</tbody>
</table>

*, **, *** Significant at the 0.05, 0.01, 0.001, and 0.0001 probability levels, respectively.
†  Vegetative indices used in this analysis were calculated from canopy reflectance at red (660 nm) and NIR (770 nm)
wavebands obtained 1 d prior to each harvest.
‡  F ratio of the model.
§  Number of observations within a given harvest or within the complete dataset (All) where the yield value fell within the
effective range of the specific vegetative index. Each harvest contained 80 observations and the complete dataset
contained 400 observations.
¶  Mean of the yield values that fell within the effective range of the specific vegetative index.
†† Root mean square error.
6.4. CONCLUSION

Though blue and red reflectance is generally reported to be negatively related to NIR reflectance, we observed that this trend reverts to a positive relationship when NIR reflectance exceeds 0.5 and was coincident with canopies at maximum LAI. Thus, the use of a NIR reflectance scalar for calculating more robust VIs may cause red reflectance to exert too great an influence on the VI and lead to error when NIR reflectance is greater than 0.5. The benefit of using a weighting coefficient (‘α’) for NIR reflectance to extend the useful range of a VI warrants more precise determination of the appropriate scalar.

Increases in LAI, and related variables, such as mass shoot$^{-1}$ and shoot height, caused the VIs to exhibit a saturative exponential response (exponential rise to max). The relationships between the variables were stronger with red-based VIs than the blue-based counterparts. Decreasing a weighting coefficient (‘α’) for NIR reflectance caused the exponential increase in the red- and blue-based WDRVIs to be more gradual in response to each modeled variable, but an ‘α’ level of 0.01 decreased the ability of the model, especially in the blue-based WDRVIs, to describe the data.

Through the use of spliced quadratic-plateau models of the relationship between alfalfa yield and the evaluated VIs, I found that these VIs differed substantially in the range of yield values for which they can be considered effective. Decreasing the weighting coefficient (‘α’) for NIR reflectance increased the effective range of both red- and blue-based WDRVIs. Further, the linear relationship between blue reflectance and alfalfa yield resulted in the exhibition of a larger effective range for blue-based VIs than red-based counterparts. In addition to the inclusion of more data points, the fit of quadratic WDRVVI models was greater than NDVI-based models. Still, the relative error for the yield models of all the evaluated VIs was at or slightly less than the error (25 - 40%) reported for other forage biomass measurement devices.
I conclude that red-based WDRVIs at an ‘α’ level of 0.05 to 0.01 covers a wide effective range (up to 2.76 Mg ha$^{-1}$) and accurately quantifies yield variations of alfalfa that result from soil moisture deficits.
CHAPTER 7: SUMMARY AND IMPLICATIONS

In this final chapter, I present a summary of my objectives, the approach taken, and the highlights of the findings. Finally, I will offer some potential implications this work has for site-specific management (SSM) of alfalfa and outline further research that is needed.

7.1. OBJECTIVES

i. Examine the feasibility of supplementing soil moisture to increase yield in alfalfa without decreasing stand longevity;

ii. Determine how variation in soil moisture deficits and K fertility affect alfalfa and alfalfa yield components, specifically with regards to the physiological responses that may influence or alter spectral reflectance patterns;

iii. Characterize variations in alfalfa canopy reflectance, as measured by “field-ready” multispectral sensors, to identify specific wave bands that exhibit the strongest relationship with alfalfa yield, yield components, and canopy variables;

iv. Evaluate vegetation indices that use these wavelength bands for their strength and robustness in their relationships to the LAI, yield components, and yield of alfalfa.

7.2. APPROACH

A randomized complete block design was initiated at the University of Kentucky Animal Research Center in 2003 with five replicates of subsurface drip irrigation (SDI) and rainfed treatments of alfalfa. The SDI tape (T-Tape 515-08-340, T-Systems International, Inc., San Diego, CA) was installed 0.38 m deep and on 1.5 m centers. One harvest was taken in the establishment year and four in 2004. Although the 2003 harvest received some supplementary water during
SDI system evaluation, alfalfa did not require irrigation in 2004. After soil tests at the end of the 2004 growing season revealed plant available potassium (K) was in a responsive range, KCl was broadcast on 1 October 2004 at four rates (0, 112, 336, and 448 kg K₂O ha⁻¹) in a split-plot arrangement. In 2005, five harvests (H1 - H5) were taken from each split-plot (2005ₜ) and four additional random locations (2005ₗₚ) within each SDI and rainfed plot. One day prior to each harvest, canopy reflectance was recorded in each plot. Herbage was sampled from 0.25 m² directly above and halfway between irrigation tapelines prior to each of the last four harvests of 2005ₜ plots. Alfalfa yield, yield components, and related variables were determined on herbage samples. Leaf area index (LAI) was determined for alfalfa supplemented with 0 and 448 kg K₂O ha⁻¹. Low and poor distribution of precipitation during the 2005 growing season necessitated some irrigation (< 13 mm) for the second and fifth growth periods and substantial irrigation (> 74 mm) for the third and fourth growth periods.

7.3. FINDINGS

During the drought year of 2005, DM yields from the SDI plots were significantly higher than DM yields of the rainfed plots in two harvests and for the seasonal total. Alfalfa growth patterns indicated uneven distribution of water between tapelines. Potassium fertilization did not significantly improve yields at any specific harvest regardless of rainfed or irrigation treatment. Crown density was not affected by irrigation or K fertilization. I concluded that SDI may increase yields by up to 300% without reducing stands, but it is likely not economically feasible unless it can be employed site-specifically.

Herbage dry matter (DM) yield was strongly associated with shoots m⁻² (r > 0.55-0.72; P < 0.001) and DM mass shoot⁻¹ (r > 0.64-0.85; P < 0.001). However, shoots m⁻² was not affected by irrigation treatment or plant available soil K. Total, leaf, and stem mass shoot⁻¹ were consistently (P < 0.05) reduced by soil moisture deficits. DM mass shoot⁻¹ increased linearly (P < 0.05) in response to added K. Soil moisture or K levels did not (P < 0.05) affect the Leaf:Stem DM (L:S) ratio. LAI responded to soil water and K levels in a similar manner to mass
shoot\textsuperscript{-1}. Models of yield estimated from LAI were more accurate than models using other single yield component dependent variables. I concluded that LAI or LAI-based dependent variables could be used to estimate alfalfa yield if L:S ratio is not altered by moisture or K stress.

Canopy reflectance within all wavebands, with the exception of blue-green (550 nm), exhibited low variance within narrowly (± 0.125 Mg ha\textsuperscript{-1}) defined yield ranges. Reflectance in the visible region was more variable (cv > 20%) when yields were above 3.75 Mg ha\textsuperscript{-1}. Reflectance in blue (450 nm) and red (660 nm) bands declined significantly with DM yield while reflectance in NIR bands (770, 810, and 850 nm) increased with increases in alfalfa DM yield, LAI and yield components. Results indicate that blue (450 nm), red (660 nm), and NIR bands were most strongly related to the LAI, yield components, and yield of alfalfa.

Blue- and red-based Normalized Difference Vegetation Indices (NDVIs) and Wide Dynamic Range Vegetation Indices (WDRVIs) at three levels of a NIR reflectance scalar (‘\(\alpha\)’ = 0.1, 0.05, or 0.01) exhibited significant (\(P < 0.0001\)) saturative (exponential rise to max) responses to LAI, yield components, and DM yield. However, models of red-based VIs were superior to blue counterparts. Decreasing ‘\(\alpha\)’ widened the effective range of both blue- and red-based WDRVIs in relationship to alfalfa yield, and slowed the saturative relationship with the other modeled variables. Significant (\(P < 0.0001\)) regression models within the effective range of the VIs were found for two drought-stressed harvests and for data pooled across all harvests. These results indicate that VIs are related to the LAI of alfalfa and that VIs may be used to estimate alfalfa yield within VI-specific ranges of effectiveness. Moreover, red-based WDRVIs at a ‘\(\alpha\)’ level of 0.05 to 0.01 extended the range up to 2.76 Mg ha\textsuperscript{-1} and accurately quantified yield variations of alfalfa that resulted from soil moisture deficits.
7.4. IMPLICATIONS AND FUTURE RESEARCH DIRECTION

Subsurface Drip Irrigation

Soil water-holding and drainage capacity, plant nutrient availability, and soil acidity are the main causes of spatial variability in alfalfa yield. The drought of 2005, and the response of alfalfa to the SDI, indicated that at least the equivalent of one harvest was lost to drought stress. Some questions remain about SDI. First, would the yield response to irrigation have been greater if the tapelines were closer? Two SDI plots exhibited a marked yield difference between “Between vs. Shank” yields these positions (Fig. 7-1b) but two other SDI plots showed virtually no difference in yield between the Between and Shank positions (Fig. 7-1a). I am confident that the answer to that question is “yes,” but it may not have been true at all sites.

Thus the second question is: could the optimal tapeline depth and spacing be site-specific? In other words, does it need to be shallower and closer in areas where water-holding capacity is low and deeper and wider in areas less prone to drought? I suggest that the answer is again, “yes,” but further work is needed to evaluate this issue.

My observations led to another question: would the irrigation response have differed if this study had it been in an area of the field with a lower water-holding capacity? The soil survey indicates the entire plot area of this study was on a Maury silt loam soil, however, soil of the two blocks along the western side were more highly eroded and compacted than the other blocks. In these eroded blocks, non-irrigated alfalfa growth was nearly totally inhibited during the fourth growth cycle (Fig. 7-2). I believe this severe drought response was the result of shallow soil (shallow bedrock), higher clay content, and soil compaction. In other blocks, the drought had a much less pronounced effect on alfalfa growth. There were also major differences in alfalfa growth between the split-plots of the 2005K observation set and the sampling sites of 2005K within the same block (Fig. 7-3). I believe this was a result of spatial variations in the depth of the bedrock. This contributed to the significant SDI effects at harvests 2 and 3 in 2005K but not in
Fig. 7-1. Photos of two SDI plots: A) plot exhibiting little difference between alfalfa growing in shank (over the SDI tapelines) and center (between tapelines) positions, and B) plot exhibiting large differences between alfalfa grown in shank and center positions. Both pictures were taken on 11 August 2005, 11 days prior to the fourth harvest.
Fig. 7-2. Example of an area in the plots where yield was severely reduced by drought stress. This photo was taken on 29 June 2005, two weeks into the third regrowth cycle.
Fig. 7-3. Photo of slightly drought-stressed alfalfa in a split-plot from the 2005<sub>K</sub> observation set (white flags in foreground) and severely drought-stressed alfalfa within a random sampling location for the 2005<sub>P</sub> observation set (orange flags in background). This photo was taken on 11 August 2005, 11 days prior to the fourth harvest.
It was apparent to me that the probability an alfalfa producer would get a return on the investment would be greater if SDI installation was targeted to droughty sites. I believe that this research at the present site should be continued for a number of years; however, it should be complemented with work on sites that are more prone to drought.

The Value of Measuring Yield Components and Leaf Area Index of Alfalfa

Measuring the 12 different yield components and “proxy” variables (see Chapter 4 for the list) proved to be invaluable as I attempted to determine how alfalfa responded to the soil moisture deficit and to plant available soil K. Very little work has been published on how the yield components of alfalfa or other forage crops respond to different environmental stresses. Spatial and temporal variability (Berg et al., 2005; Chapter 4) and cultivar differences (Volenec et al., 1987) complicate this critical autecological issue and has led to the paucity of research in this area. Further, the determination of yield components is incredibly tedious and time-consuming work. For example, we clipped and processed samples from each of the last four harvests in 2005 for the purpose of recording these variables. The collection and processing of these samples involved ~200 hours of labor per harvest. As yield component analysis offers great insight into autecological responses and may lead to improvements in forage quality and crop management, research is needed to develop more expedient techniques and to identify variables of key importance.

There is very little known about how LAI changes with environmental conditions. For example, is LAI’ consistent across harvests? Average LAI and the maximum LAI increased with each harvest date (data not shown), suggesting that LAI’ is not static. Thus, more research is needed to better understand LAI responses in alfalfa.

In this study, the LAI data helped explain how differences between canopies contributed to canopy reflectance patterns and provided the critical link between the SDI and remote sensing studies. Yet, in retrospect, having more LAI
observations that were linked to specific canopy reflectance data points (as opposed to plot averages) would have been preferable. Unfortunately, the influence of LAI on canopy reflectance is rarely examined in the literature. Based on my experience, I would not recommend (if ever asked) any canopy reflectance paper for publication without a substantive analysis of the role of LAI in the observed response.

**Identification of Wavelength-Specific Trends in Alfalfa Canopy Reflectance**

One of the contributions that this research makes to the literature is an evaluation of wavelength-specific relationships to the LAI and vegetation mass of alfalfa. Further, the use of Monteith and Unsworth’s (1990) equation (or similar, earlier models) to aid the explanation of LAI’s effect on canopy reflectance is rare in the literature. The analysis of the relationship between blue reflectance and canopy properties is rare, if not unique. The use of blue reflectance has significant potential, though blue reflectance is lower (often much lower) than longer wavelengths and needs more precise measurement. By comparison, the quantity of blue reflectance is similar to that of red reflectance at LAI’, but does increase as much as red reflectance with declining LAI values (i.e., $\text{Blue } \rho_c - \text{Blue } \rho_s < \text{Red } \rho_c - \text{Red } \rho_s$) because the soil does not reflect as much blue light as red light. Nonetheless, I suggest more research on blue reflectance is warranted for alfalfa and other crops.

Further work is also needed on the relationships between canopy reflectance and canopy properties. For example, if reflectance at a given waveband varies considerably (> 30%) when alfalfa yield is $1.00 \pm 0.125 \text{ Mg ha}^{-1}$ and varies more when yield is $1.25 \pm 0.125 \text{ Mg ha}^{-1}$, then the use of that band in differentiating between these yield levels will be limited. The literature often fails to identify the roles (or variability) of the wavelengths that were the basis of the VI used in empirical analyses.
The Effective Range and Strength of the Relationship between Vegetation Indices and Alfalfa Yield

The saturative nature of canopy reflectance limits the conditions under which VIs are related to canopy variables. My work is one of the first analyses of VIs (WDRVI) that widen this range of conditions. The use of WDRVI holds great promise for analyzing canopies that are highly developed (i.e., near LAI'). Specifically, effort should be devoted to measuring WDRVI using new upgrades to the GreenSeeker® (NTech Industries, Inc., Ukiah, CA), CropCircle™ (Holland Scientific, Lincoln, NE), or similar devices that sample smaller areas.

Based on my research, I recommend that pre-harvest canopy reflectance measures of alfalfa should be taken only if the yield range is expected to include values well below the VI-specific values for Yield_{max} (Chapter 6) or determine canopy reflectance early in the regrowth cycle of alfalfa prior to its development of LAI'.
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VITA

Dennis W. Hancock

Date of Birth: July 11, 1975
Place of Birth: Madisonville, KY

EDUCATION

B.S., Agriculture  Cum Laude  1997
Berea College, Berea, KY

PUBLICATIONS AND PAPERS

PEER-REVIEWED JOURNALS


PEER-REVIEWED PROCEEDINGS


INVITED PRESENTATIONS/PAPERS


EXTENSION PUBLICATIONS


MEETING PAPERS AND RESEARCH PRESENTATIONS (LAST 3 YRS)

**PROPOSALS DEVELOPED***
- Collins, M., **D.W. Hancock**, M.H. Hall, and G. Aiken. Improving Assessments of Forage Stand, Quality, and Bale Weight. $77,000. USDA-Risk Management Agency (Submitted Aug. 03).
- Dillon, C.R., S.A., Shearer, M. Kanakasabai, and **D.W. Hancock**. Optimal Management Zone Delineation for Precision Agriculture. USDA-NRI: Competitive Grants Program $197,213 (Submitted Nov. 02)

**MEMBERSHIPS AND CERTIFICATIONS**
- Crop Science Society of America
  - 2005-07 CSSA-Young Crop Scientist Award Committee (#C454)
- ESRI-ArcGIS Certified User
- American Red Cross CPR/First-Aid
HONORS AND AWARDS

- American Forage and Grassland Council (AFGC):
  o 1st Place: Emerging Scientist Competition (2006)

- Potash & Phosphate Institute:
  o J. Fielding Reed Fellowship Award Recipient (2006)

- Crop Science Society of America (CSSA):
  o Gerald O. Mott Meritorious Graduate Student Award in Crop Science (2006)

- Kentucky Association of County Agriculture Agents (KACAA):
  o Communications Award: Best Fact Sheet, Individual (2001)
  o Communications Award: Best Web Site (2001)

- University of Kentucky College of Agriculture:
  o Research Challenge Trust Fund Fellowship (1998)
  o Agronomy Department Assistantship (1998-1999)

- Undergraduate Awards/Honor Societies:
  o American Society of Animal Scientists, Student of the Year (1997)
  o Crawford Prize in Conservation (1997)
  o M.A. Wilson Dairy Science Award (1997)
  o BC Agriculture Union, Freshman of the Year (1994)
  o Phi Kappa Phi (1996)
  o Delta Tau Alpha (1994)