AN EVALUATION OF PERENNIAL WHEAT AND INTERMEDIATE WHEATGRASS AS DUAL-PURPOSE, FORAGE-GRAIN CROPS UNDER ORGANIC MANAGEMENT

by

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ABSTRACT

AN EVALUATION OF PERENNIAL WHEAT AND INTERMEDIATE WHEATGRASS AS DUAL-PURPOSE, FORAGE-GRAIN CROPS UNDER ORGANIC MANAGEMENT

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The adoption of perennial grain presents farmers with environmental and economic opportunities and risks. If crops such as perennial wheat (*Triticum aestivum* x *Thinopyrum elongatum*; Pwheat) and intermediate wheatgrass (*Thinopyrum intermedium* IWG), two novel perennial grains, can thrive as dual-purpose forage-grain crops, many of these risks will be alleviated. Annual winter wheat (*Triticum aestivum* L.) is used as a dual-purpose forage-grain crop and IWG is a successful perennial forage in the southern Great Plains. Researchers at Washington State University (WSU) and The Land Institute (TLI) have developed Pwheat by crossbreeding annual wheat and tall wheatgrass and bred IWG for improved grain production.

To evaluate potential of these novel species for dual-purpose forage-grain use, a field experiment to determine robustness of plant growth and perennial regrowth, as well as quality and quantity of harvested grain and forage for two cutting regimes, was conducted fall 2010-12 in southwest Michigan at Kellogg Biological Station (KBS). Compared with IWG, Pwheat produced more grain (Pwheat≈238.70 g/m^2, IWG≈103.55 g/m^2), but was less able to initiate late-season regrowth, and thus maintain perenniality (Pwheat≈59% regrowth, IWG≈100% regrowth), and tended to produce lower quality forage in smaller quantities (Pwheat≈560.71 g/m^2, IWG≈797.72 g/m^2), especially after the first year of growth (year 2 Pwheat≈391.23 g/m^2, year 2 IWG≈956.20 g/m^2). Cutting generally did not have a long-term effect on plant growth. Overall, species choice must depend on the goals of a specific farm, since there are unique benefits for each species.

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LIST OF ABBREVIATIONS

ADF: Acid detergent fiber

AIC: Akaike's Information Criterion

ANOVA: Analysis of variance

C: Celsius

cm: centimeter

d: day

g: gram

hr: hour

Hz: Hertz

IVDMD: In-vitro dry matter digestibility

IWG: Intermediate wheatgrass

KBS: W.K. Kellogg Biological Station

L: Liter

LAI: Leaf area index

lb: pound

m: meter

mEq: milliequivalent

mm: millimeter

MSU: Michigan State University

NDF: Neutral detergent fiber

PAR: Photosynthetically active radiation

P-Cut: Perennial cut experiment

PWES: Perennial wheat ecosystem services experiment

Pwheat: Perennial wheat

RCBD: Randomized complete block design

SLA: Specific leaf area

TLI: The Land Institute

v: volt

WSU: Washington State University

CHAPTER ONE

LITERATURE REVIEW

Introduction

The adoption of perennial grain crops would present farmers with many environmental, economic, and agronomic opportunities, as well as risks. If crops such as perennial wheat (*Triticum aestivum* x *Thinopyrum elongatum*; Pwheat) and intermediate wheatgrass (*Thinopyrum intermedium* IWG), two novel perennial grain species, can thrive as dual-purpose forage-grain crops, many of these risks will be alleviated. In particular, if these crops can be used in a dual-purpose fashion, farmers will be better able to dynamically adjust their harvest plans based on specific weather conditions each year. For example, if drought harmed the grain crop one year, a farmer might decide in mid-season that it would be advantageous to harvest a midseason green-chop as a forage, instead of a grain crop during that year. This flexibility is likely to become more and more important, since weather conditions are expected to become more and more erratic and unpredictable as worldwide climate changes.

Annual winter wheat (*Triticum aestivum* L.) is a successful dual-purpose forage-grain crop (Redmon et al., 1995) and IWG is a highly successful perennial forage grass in the Great Plains region of North America (Wagoner, 1995). Breeding programs at Washington State University (WSU), The Land Institute (TLI), and The Rodale Institute have developed lines of Pwheat by crossbreeding these two species and have also bred IWG for improved grain production, while maintaining forage yield (Murphy et al., 2009; DeHaan et al., 2005; Wagoner, 1990).

Growth and Regrowth of Grasses

Plant growth can be described in terms of the growth of components of the plant. Grasses are made up of tillers, which are made up of leaves. For each of these components, growth can be described in terms of appearance rate, expansion rate, and lifespan/rate of senescence. Each growth characteristic of each plant component is affected differently and to different degrees by genetics and various environmental characteristics, such as light quality and quantity, water availability, N availability, and temperature (LeMaire and Agnusdei, 2000). Figures 1.1 and 1.2 schematically present, in the manner of LeMaire and Agnusdei, 2000, the relative effects various factors may have on growth for IWG and Pwheat.

Plant growth is determined by the interactions between genetic factors and management/environmental factors. The range of outcomes these factor combinations are capable of producing determines the degree of plasticity a plant is capable of showing. Because of this, plasticity is an important concept to consider in any investigation of plant growth.

Two basic types of plasticity are genotypic plasticity and phenotypic plasticity. Genotypic plasticity is determined by the range that is present, within an entire population, of variation in genetic makeup. The more genetically variable the population is, the higher its genotypic plasticity will be. The genotypic plasticity of a population plays a major role in determining how effectively the population can adapt to changes in management or environmental factors. Phenotypic plasticity is embodied in the effects that environmental and management factors have on the appearance and development of plants. This includes, but is not limited to, changes in the sizes, density, and growth rates of leaves and tillers due to grazing, or to nutrient, water and light availability (Nelson, 2000).

Many factors, including light quality (i.e. red/far-red ratio), light quantity, plant density, and nutrient availability can affect the phenotypic plasticity of grasses. Although the effects of these conditions are difficult to separate under natural conditions, various experiments have been able to tease out these impacts. Increased plant density has been shown to reduce light quality and quantity, which in turn reduces tillering rate in *Paspalum dilatatum* and *Lolium multiflorum* (Casal et al., 1986). In *P. dilatatum,* increased plant density can also decrease the number of reproductive tillers and expanded leaves present, and increase mortality of young vegetative tillers (Casal et al., 1986). Red light enrichment can increase tillering for moderately dense *P. dilatatum* stands, but not for isolated plants, indicating that natural light has an optimal red/far-red ratio.

Red/far-red ratio can have a number of effects on plant growth. Casal et al. (1985) have shown that a decrease in the red/far-red ratio of the light reaching *L. multiflorum* plants can decrease site filling (i.e., mature bud development) rates and increase the length of time between leaf expansion and appearance of the associated tiller. In addition, a low red/far-red ratio can cause *L. mutiflorum* plants to produce longer shoots, blades, and leaf sheaths and an increased number of reproductive tillers per plant, while overall the number of new tillers may be reduced (Casal et al., 1985).

The ability of plants to grow and regrow after cutting is also highly dependent on access to water and nutrients, especially nitrogen. Access to water and nitrogen is influenced by root distribution, water and nitrogen distribution, and root uptake efficiency. Vertical root distribution has a bigger impact on water uptake than on nitrogen uptake

(Gastal and Durand, 2000). Water deficits can also limit efficiency of nitrogen use. Nutrients are allocated to various parts of a plant, following a specific hierarchy of importance. Senescence can also complicate quantification of partitioning in perennial swards. When nutrient supplies are limited, the highest-priority plant organs are the ones that are affected the most. Limited nitrogen supplies tend to decrease photosynthetic capacity, while drought has a greater impact on light interception, due to processes such as leaf rolling and stomatal function. Drought also negatively affects stomatal function, which decreases photosynthetic capacity (Gastal and Durand, 2000).

Plant growth is a key component in developing pasture management strategies. Growth habits of plants influence the structure of the pasture (e.g., tradeoffs between a sward consisting of many small plants or a few large plants). These plant characteristics lead to different types of pastures, which must each be managed differently. However, despite differences between swards, some principles of management may be generally applied. For example, managing heterogeneity (i.e., "moving heterogeneous patches around") is important for all types of pasture and all forage-management systems (Parsons and Chapman, 1998).

In order to optimize the amount of material harvested from a sward, there are a number of commonly overlooked factors that are crucial to consider. First of all, it is extremely important to distinguish between average growth rate and instantaneous growth rate. Average growth rate is often overlooked, when it is actually more important than instantaneous growth rate in the evaluation of overall forage production. It is also important to assess whether or not potential forage production levels are being met, or if some feature of the system is diminishing the amount of material harvested (Parsons and Penning, 1988).

Perennials

All commercially available grains, including rice, beans, wheat, and corn, currently come from annual plants. Considering that more than 70% of calories consumed by humans worldwide come from these staple grains, it is clear that modern agriculture relies heavily on annuals (Cox et al., 2004).

Perennial cropping systems have the potential to offer many environmental and economic advantages over annuals. For example, perennial crops, such as perennial wheat, can reduce soil erosion (Ewel, 1999; Glover et al., 2010; Jackson, 2002; Bell et al., 2010); increase soil organic matter (Glover et al., 2010); sustain soil fertility (Ewel, 1999); improve soil quality (Franzluebbers et al., 2000; Dalal and Chan, 2001); increase nutrient-cycling efficiency through increased nutrient synchrony (Crews, 2005); conserve soil and water (Glover, 2005); decrease fossil fuel and agrochemical inputs (Jackson, 2002); decrease replanting costs, compared to analogous annual crops, decrease weed pressure, through greater competition, and correct hydrological imbalances, thus decreasing salinization (Bell et al., 2010). Perennial grains may also begin growing earlier in the spring and continue growing later in the fall than analogous annuals (Glover, 2005; Jaikumar et al, 2012), which is a trait that many farmers would find extremely desirable, particularly for a forage crop (Schmitt-Olabisi et al., unpublished data).

However, perennial crops may, in some cases, be associated with increased challenges as compared with annuals, including weed, disease, fertility, yield, and management problems (Glover, 2005). Reduced yields in perennial grains may be caused in part by such negative agronomic traits as shattering, low fertility, indeterminate grain ripening, high awn robustness, small grain size, high glume rigidity, and high abundance of barbs and hairs on the rachis and glumes (Davies and Hillman, 1992). However, it is currently unclear whether several of these potential problems would increase under perennial management, as compared with annual (Glover, 2005). For example, lack of rotation, which is associated with perennial grains, may increase disease pressure, but some perennials, including IWG and Pwheat, have shown higher disease resistance than their annual counterparts (Cox et al., 2005a; Cox et al., 2005b). In addition, currently existing strains of perennial wheat present many challenges to growers, including lower threshability and lower yield than annual wheat (Murphy et al., 2009). However, some of these economic and agronomic difficulties, particularly low grain yield, may be overcome if it is possible to harvest a forage crop from these perennial grasses without negative impacts on the grain crop (Bell et al., 2008).

Dual Use (Grazing/Mowing)

Past research on grain production after grazing or mowing perennial grains is sparse. However, some work has been done on the effect of grazing and mowing on seed production in cool-season perennial grasses. Hopkins et al. (2003) found that in the Southern Great Plains of America, grazing usually resulted in a decrease in seed production in the grasses they studied, including pubescent wheatgrass (*Thinopyrum intermedium* subsp. *barbatulum*).

In grazed or mowed IWG, aspects of regrowth and forage yields have been studied much more thoroughly than seed production. Higher frequency of defoliation events in IWG has been found to decrease overall forage yields in Saskatchewan (Lawrence and Ashford, 1969b) and increasing the extent of defoliation was found to decrease forage IWG yields in North Dakota (Hendrickson and Berdahl, 2002). However, IWG has also been found to produce higher yields when it is cut to a lower height and when the initial cut is made later in the season (Lawrence and Ashford, 1969a). When ranking grazed perennial grasses for regrowth capacity under field conditions in Saskatchewan, Lardner et al. (2002) placed IWG in the medium group. Finally, a study in the Great Plains has shown that tiller replacement ratios are generally highest for IWG grazed in the vegetative or mid-culm elongation stages, but that this can vary across variety (Hendrickson et al., 2005).

In addition, quite a bit of research has been done regarding the effect of grazing and mowing on grain production in annual winter wheat. In an extensive review of the subject, Redmon et al. (1995) found that, when growing conditions are good, grazing tall cultivars before stem elongation occurs can increase grain yields. This is at least partly because grazing under these circumstances can reduce lodging, which would otherwise have a detrimental effect on the grain harvest. Semidwarf wheat cultivars, in contrast, appear to be much more sensitive to grazing. However, depending on factors such as cattle and grain prices, precipitation levels, and soil fertility, grazing may or may not be an advantageous strategy in either type of wheat.

We expect that Pwheat will yield a higher quantity and quality of grain than IWG, but that IWG will be better able to withstand heavier mowing, thus producing a superior forage crop. However, major gaps in past research must be filled in order to fully understand the complexity of the differing interactions between these crops and their environment. As a novel crop, relatively little research has been done concerning the growth habits of Pwheat. In addition, the type of IWG used in this experiment is also a novel genotype. The effect of forage harvest on grain production is particularly poorly understood in these species. Finally, not much research of this sort has been done in Michigan. This project, which will investigate the effects of various management practices on these two genotypes, in an attempt to determine how to maximize the efficiency of a grazed perennial grain crop in Michigan, is a major step toward filling this gap in our current knowledge.

Current breeding research focuses on two complementary strategies: 1) cross-breeding annual grain crops with perennial relatives and 2) selecting perennial relatives of grain crops for increased seed production (Cox et al., 2004).

Objectives

The goal of this research project is to explore the potential to manage perennial grains (Pwheat and IWG) as dual-purpose forage-grain crops. More specifically, we will investigate the effect of genotype, planting date, and cutting regime on initial stand establishment, early growth, regrowth after cutting, total biomass, forage harvest, forage quality, and grain harvest. We will use second-year measurements, especially those regarding post-sexual cycle regrowth, as indicators of the robustness of perenniality.

Hypotheses

We expect that the fall-planted, uncut Pwheat will produce more grain than the other treatments, since Pwheat has a high-yielding grain-producing parent and IWG does not. In addition, the uncut plants will not have to endure the stress of a spring forage cutting and thus may be able to yield more grain than the cut plants.

We expect that the fall-planted, cut IWG will yield more forage than the other plants. This is because IWG has been historically grown as a forage, which Pwheat has not. In addition, the cut IWG will be harvested more times than the uncut IWG and we expect the IWG to be able to recover from spring cutting without effecting later harvests, so overall we expect the cut IWG to produce more forage than the uncut IWG.

Finally, we expect that either the IWG treatments or the spring-planted Pwheat will be the most strongly perennial. IWG has shown itself to be a vigorous perennial, both in trials at our site and elsewhere. However, although Pwheat often regrows sparsely, we expected that spring-planted Pwheat would have higher rates of post-sexual cycle regrowth than fall-planted Pwheat. We hypothesized that, since spring-planted Pwheat would not be harvested for grain or forage until year two, it would have more time to build up its root system and nutrient reserves, and thus would be better able to regrow after grain harvest.

Predictions (Contrasts)

We used contrasts as a way of testing our hypotheses. We used a fall IWG versus fall Pwheat contrast to examine the effect of species, a cut fall Pwheat versus uncut fall Pwheat contrast to examine the effect of cutting in Pwheat, a cut spring Pwheat versus cut fall

Pwheat contrast to examine the effect of planting date in Pwheat, and a cut IWG versus uncut IWG contrast to examine the effect of cutting in IWG.

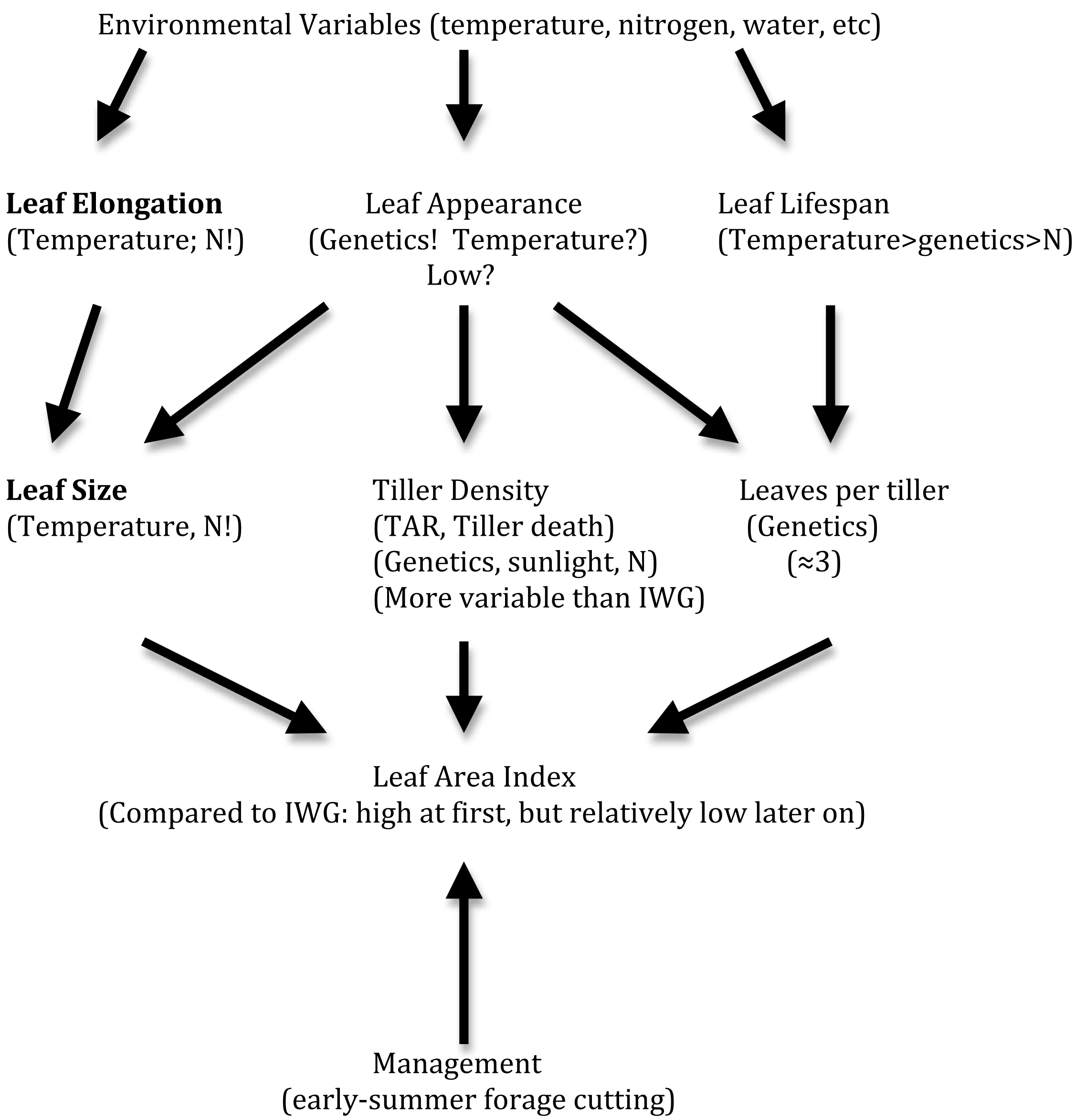
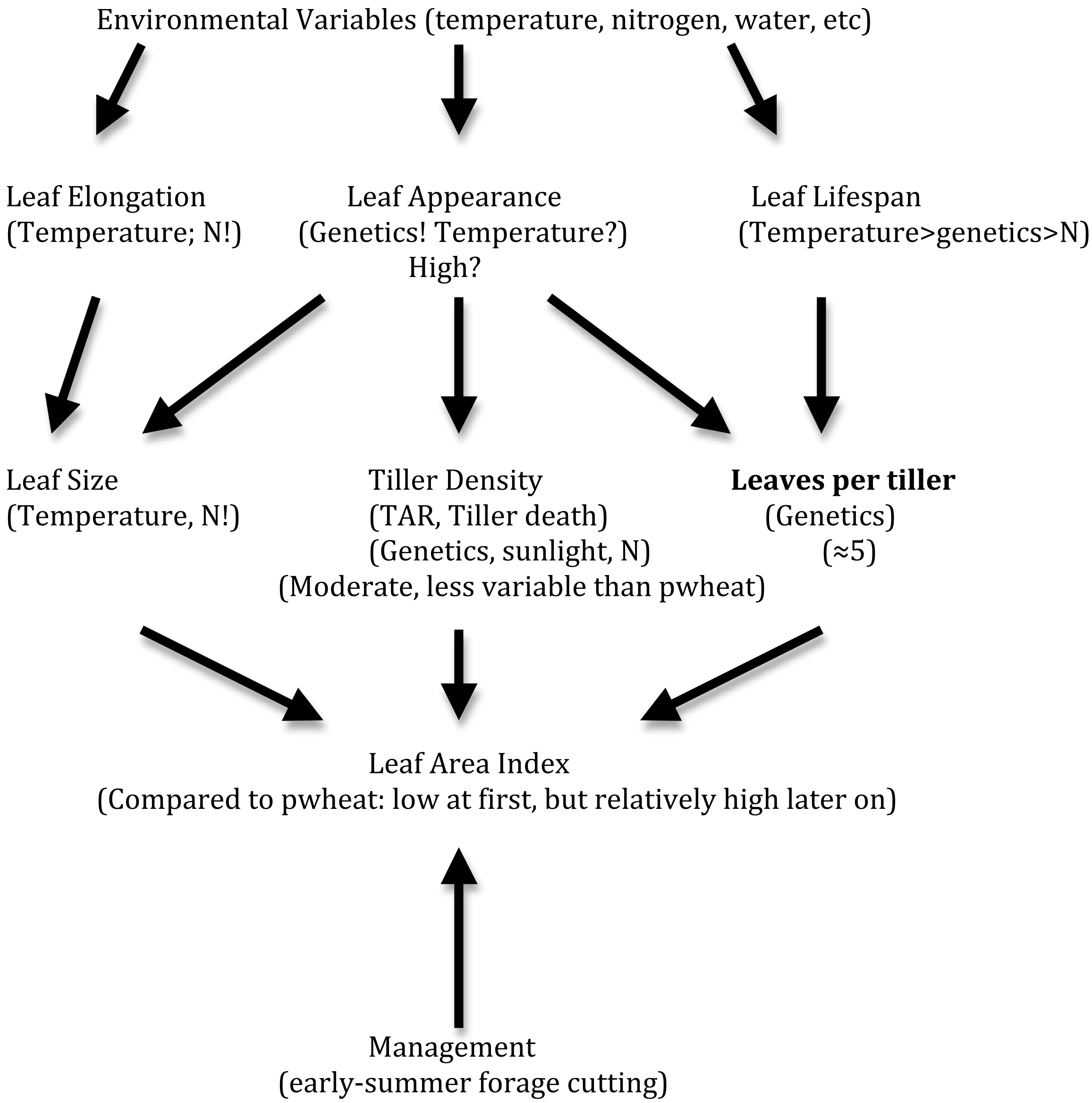


Figure 1.1: Factors influencing growth of perennial wheat
(after LeMaire and Agnusdei, 2000)
*Characteristics in bold font are particular strengths of that species
*Factors followed by an exclamation point have a large effect on the process or characteristic under which they are listed
*Factors followed by a question mark have little influence on the process or characteristic under which they are listed.
*The symbols < and > denote the order of importance of factors regarding their influence on the process or characteristic under which they are listed



<u>Figure 1.2: Factors influencing growth of intermediate wheatgrass</u>
(after LeMaire and Agnusdei, 2000)
*Characteristics in bold font are particular strengths of that species
*Factors followed by an exclamation point have a large effect on the process or characteristic under which they are listed
*Factors followed by a question mark have little influence on the process or characteristic under which they are listed.
*The symbols < and > denote the order of importance of factors regarding their influence on the process or characteristic under which they are listed

CHAPTER TWO

Materials and Methods

Site Description

The experiment was conducted in southwest Michigan at Kellogg Biological Station (KBS) at 42° 24' N, 85° 24' W. The elevation at KBS is 288 m, the mean annual temperature is 9.7 °C, and rainfall averages 890 mm of rainfall per year, including about 445 mm of precipitation in the form of snow. For more detailed weather data, see Table 2.1. KBS soils are underlain by glacial till and consist of a range of well- and poorly-drained alfisols, mollisols, and entisols. Most soils are Typic Hapludalfs, and moderately fertile sandy loams and silty clay loams are common soil textures (LTER website, 2012). A soil test from 2011 found organic matter=1.5%, phosphorus=29 parts per million, potassium=64 parts per million, magnesium=130 parts per million, calcium=700 parts per million, soil pH=5.7, and cation exchange capacity=7.1 mEq/100 g, as well as 2.3% potassium, 15.2% magnesium, 49.0% calcium, and 33.6% hydrogen base saturation for the field where this experiment was conducted. Soil texture data from a nearby field are presented in Table 2.2.

Experimental Design

The perennial-cut (p-cut) experiment (Figure 2.1) was a randomized complete block design (RCBD), with four replications. For both years, management system was the only factor. During the first year, this factor had four levels: 1) fall-planted, cut Pwheat, 2) fall-planted, uncut Pwheat, 3) fall-planted, cut IWG, and 4) fall-planted, uncut IWG. During the second year, a fifth level was added: spring-planted, cut Pwheat.

The fall-planted plots were all sown on October 13, 2010 and the spring-planted plots were sown on May 3, 2011. The entire area was prepared for planting on October 11-12, 2010, when 2000 lb/acre of pelletized poultry manure, providing approximately 80 lb of usable nitrogen per acre, was broadcast, then incorporated with two passes of a soil-finisher. Immediately before planting, plot lines were traced on the ground using twine guidelines and surveyors' paint. All planting was done with a seed drill, at a seeding rate of 1.75 million seeds per acre. Each plot measured approximately 1.5 m by 1.8 m, with a 1.8 m wide alley between each row of plots. Each plot contained six rows, with about 20-30 cm between each row of plants.

Species

Intermediate Wheatgrass (IWG)

Intermediate wheatgrass (*Thinopyrum intermedium* (Host) Barkworth & D.R. Dewey) has traditionally been a valuable perennial, cool-season, forage crop in the central Great Plains region of the United States (Hendrickson et al., 2005; Mitchell et al., 1998). The variety used in this experiment is from a breeding project being conducted at The Land Institute in Salina, KS, where it was selected for increased kernel weight, yield per tiller (Cox et al., 2010), threshability and seed yield per unit area (DeHaan et al., 2005), as well as decreased plant height (Cox et al., 2010). Much of the starting seed at TLI came from a previous breeding program at The Rodale Institute in Kutztown, PA, which had the same goals as the program at TLI (Wagoner, 1990).

Perennial Wheat (Pwheat)

The perennial wheat (*Triticum aestivum* x *Thinopyrum elongatum*) seed used in this experiment (P-15) is a cross between two kinds of annual wheat (*T. aestivum L. cv* Chinese Spring and *T. aestivum L. cv* Madsen) and tall wheatgrass (*Thinopyrum elongatum*) that was bred at Washington State University (WSU) (Murphy et al., 2009). P-15, which we received from WSU in 2005, was selected for this experiment because, when grown at KBS, it has expressed a balanced set of characteristics, including excellent second year regrowth, respectable grain yield, and reasonably high aboveground biomass yield (Jaikumar et al., 2012; N. S. Jaikumar, personal communication, 2010), which is desirable for a dual-purpose crop.

Management

The soybeans that had been growing in this research area were flail mowed on September 14, 2010 and incorporated with a chisel plow on September 29, 2010.

Fertilizer applications were made in the form of pelletized poultry manure (Herbruck's Poultry Ranch, Saranac, MI) that was broadcast at a rate of 2000 lb/acre, which is equivalent to approximately 80 lb of usable nitrogen per acre. This was done shortly before October 12, 2010, as well as on April 5 and October 4, 2011. The first application was incorporated with two passes of a soil finisher on October 12, 2010 and subsequent amendments were applied as top-dressing.

Weeding was conducted by hand and with hand hoes, in order to minimize competition between weeds and research plants. The spring-planted plots were first weeded on May 31, 2011. All plots were weeded on August 14, 2011, March 15, 2012, and between April 26 and May 3, 2012. The aisles between plots were roto-tilled for weed control on June 2, 2011 and July 5, 2011 using a 5-foot wide roto-tiller.

The cutting treatment was imposed on the fall-seeded cut plots on May 11, 2011 and March 22, 2012 for Pwheat and on May 24, 2011 and March 29, 2012 for IWG, and was also the means by which spring forage was harvested (Tables 2.3 and 2.4). The cutting treatment each year took place as soon as possible before stem elongation occurred, while most of the plants were still in the vegetative stage. Cutting was imposed on the Pwheat plots in the first growing season (spring 2011) using a lawn mower set to the highest setting (about 10 cm above the ground). The clippings were caught in a bag attachment for the mower that was emptied after each plot was mowed. IWG was cut by hand, since by the time these plants had reached the appropriate growth stage, they were too tall to be harvested using the mower. Hand clippers were used to cut the IWG to a height of about 20 cm. Immediately after cutting, the forage removed from each plot was weighed, dried at a temperature of 60°C for at least three d, and reweighed. In year two, forage was harvested by hand for all plots. Approximately the top 33% of each plant, estimated based on plant height, was harvested. These samples were weighed and dried following the same procedure that was used in year one.

Plant Monitoring

Emergence Rates

The number of seedlings that had emerged along a randomly chosen, 1-meter length of three inner rows of each plot were counted. Emergence rates were obtained for all fall-seeded plots on November 12, 2010 and during April and May of 2011, until May 9, 2011. Emergence counts took place on June 1, 2011 in the spring-seeded plots (Table 2.5).

Height

Ten plants were randomly selected from inner rows of each plot. The dominant tiller on each plant was measured whenever this distinction was possible. However, when the plants became larger and began growing thickly together, it became impossible to be certain which tiller was dominant, so ten random tillers were measured in each plot. A measuring stick was used to find the height of the tiller from the surface of the ground to the tip of the highest leaf. After seed heads had emerged and grown taller than the highest leaf, plants were measured to the tip of the seed head. Tillers were measured to their highest point, regardless of whether it was on a leaf or a seedhead.

Heights were measured in the fall-planted plots on April 14, 2011, then continued at approximately one-week intervals until July 20, 2011, when they had begun to senesce. Measurements were begun again at one-week intervals on August 11, 2011, in order to monitor postharvest regrowth. On October 22 to November 4, 2011, height was measured at two-week intervals. Heights were measured for the spring-planted plots at approximately one-week intervals from June 3 to October 22, 2011, then at two-week intervals until November 4, 2011. Second-year measurements for all treatments began on March 15, 2012, and continued at approximately one-week intervals until July 6, 2012.

Photosynthetically Active Radiation (PAR) and Leaf Area Index (LAI)

PAR and LAI are important measurements because they provide information about degree of canopy closure at a particular time. The more closed the canopy is, the less sunlight will penetrate the canopy and the fewer weeds will be able to germinate and grow. Since weeds are a primary concern in agriculture, especially in organic systems, it is very important to have this information, since it is an indicator of how able a crop is to compete with weeds at a particular time.

An AccuPAR LP-80 ceptometer (Decagon Devices, Inc., Pullman, WA) was used to measure PAR and LAI between the four center rows at both the northern and southern ends of each plot. The leaf distribution parameter (c) was equal to 1 for all measurements. PAR and LAI were measured as close to noon and when the sky was as clear as possible. When clouds were present, an external PAR sensor (Decagon Devices, Inc., Pullman, WA) was used that enabled the above-canopy and below-canopy readings to be taken simultaneously. This eliminated the error that would otherwise have been present due to variability in cloud cover.

PAR and LAI were first measured on May 4, 2011 in the fall-planted plots and on June 14, 2011 in the spring-planted plots. Measurements were continued about once every week, with additional readings taken before and after cutting, until September 22, 2011. After this date, measurements were taken approximately every two weeks until November 12, 2011. Year-two measurements began for all treatments on March 15, 2012 and continued at approximately one-week intervals until July 5, 2012.

Tiller and Leaf Counts

On May 7, 2011, five plants, one from each of the four inner rows plus a second plant from one of the two center rows, were randomly selected from the northern three-fourths of the plot, in order to avoid the areas that would later be destructively sampled. A colored twist tie was loosely secured around the stem of each selected plant, in order to mark it for future reference. This same procedure was repeated for the spring-seeded plots on June 18, 2011. Individual plants were designated using twist ties while the plants were young enough and thus far enough apart to estimate where one plant ended and another began. The number of tillers and leaves on each plant bearing a twist tie marker was periodically counted throughout the growing season. A new leaf was only counted after it was >1/2 the length of the next-newest leaf.

Beginning on the day of twist-tie placement, counts were tiller and leaf counts were recorded every two weeks until November 3, 2011. The first set of second-year measurements was made on March 18 and 19, 2012. These measurements continued at approximately two-week intervals, until July 10, 2012.

Growth Stage

Plant development was monitored throughout the growing season using Moore's modification (Moore et al., 1991) of Zadoks' Scale (Zadoks et al., 1974). The characteristics of plants at each growth stage are presented in Table 2.6. Ten tillers per plot were randomly selected from the four inner rows for each growth stage measurement. During the first year, once seed-fill stage was reached (June 21, 2011 for perennial wheat and July 13, 2011 for IWG), five random tillers in the two outer rows were evaluated, in order to minimize the effect of growth stage measurements on grain harvest. During the second year, growth stage measurements were halted once seed-fill stage was reached, because the expectation of a poor harvest that year meant it was essential that no grain be sacrificed to destructive measurements.

Growth stage of fall-seeded plants was first measured on May 10, 2011 and continued at approximately one-week intervals until July 27, 2011. Growth stage of spring-planted Pwheat was first measured on June 2, 2011 and continued at approximately one-week intervals until October 22, 2011. Second-year measurements for all treatments began on March 21 and 22, 2012 and continued at approximately one-week intervals until June 26, 2012.

Biomass Sampling

During each growing season, each fall-seeded plot was sampled twice by cutting all plants within a 0.5 m by 0.25 m quadrat at ground level in the southern ends of the plots. Each year, the first sample was taken just before stem elongation and the second sample was taken when about 40% of plants had headed. The sampling areas were marked with flags and thereafter avoided when making all further measurements. Stover from grain harvest was used as a third biomass sample. Dates of biomass sampling are presented in Tables 2.5 and 2.7. Biomass samples were fresh-weighed, oven-dried for at least 3 d at 60°C, and then dry-weighed.

Specific Leaf Area (SLA)

Ten fresh leaves from each sample were randomly selected for surface area measurements using a LI-COR model #3100 Area Meter (LI-COR Biosciences, Lincoln, NE). They were then placed into individually labeled envelopes, oven-dried as described above, and weighed individually. Specific leaf area was calculated as follows: specific leaf area=surface area of a leaf/weight of that leaf.

In the first year, leaf area was measured for uncut, fall-seeded Pwheat on May 11 and June 13, 2011, for cut, fall-seeded Pwheat on May 11 and June 14, 2011, for uncut, fall-seeded IWG on May 24 and June 16, 2011, and for cut, fall-seeded IWG on May 24 and June 17, 2011. First-year leaves were weighed for uncut, fall-seeded Pwheat on May 17 and June 18, 2011, for cut, fall-seeded Pwheat on May 17 and June 19, 2011, for uncut, fall-seeded IWG on May 28 and June 21, 2011, and for cut, fall-seeded IWG on May 28 and June 22, 2011. In the second year, leaf area was measured for cut and uncut, fall-seeded IWG on June 6, 2012. Leaf weight was measured for these samples on June 11, 2012.

Spring Forage Harvest

Spring forage was harvested by imposing the cutting treatment on the cut plots. For a complete description of this process, see the section on management, above. Dates of spring forage harvests are presented in Tables 2.3 and 2.4.

Stover Harvest

Stover was harvested by hand as part of grain harvest. Two 0.5 m by 0.5 m quadrats were harvested from each plot as described in the grain harvest section below. All biomass that remained after removal of grain, either by threshing or by clipping seedheads, was considered stover. Dates of stover harvests are presented in Tables 2.3 and 2.4.

Grain Harvest

Pwheat grain was harvested after the kernals were hard and dry, and the rest of the plant was completely senesced. IWG grain is ripe when the grain is hard and dry, but not so dry that shattering is excessive. Shattering is a major problem for IWG and should be minimized to the greatest extent possible. Dates of grain harvest are presented in Tables 2.3 and 2.4.

To harvest each plot in year one, a 0.5 m by 0.5 m quadrat was placed over a representative portion of the westerly three rows of plants. An identical quadrat was placed in a similar fashion over the easterly three rows. Plants within each quadrat were cut and bagged by hand. Biomass samples were also taken using a 0.5 m by 0.25 m quadrat from the first two blocks for determining moisture content. The unsampled areas were cut with a pair of gas-powered clippers, leaving behind stubble that was about 15 cm tall, to encourage root survival and regrowth. This material was threshed in the field and residues were discarded away from the plot. The plants from the harvested quadrats were fresh-weighed, dried at 60°C for at least three d, and reweighed. Before weighing the 0.5 m by 0.25 m quadrat samples, the seed heads were cut off the plants. Seed heads and straw were separated, weighed, dried, and reweighed, then seed heads were threshed, and threshed grain weighed.

In year one, all perennial wheat samples harvested using a 0.5 m by 0.5 m quadrat were threshed in an ALMACO LPR portable wheat thresher (ALMACO, Nevada, IA). All

Pwheat mini-samples harvested from a 0.5 m by 0.25 m area were threshed in tabletop threshers. After threshing, all grain and straw samples were weighed. IWG grain is too small and light to be threshed on the larger thresher. However, the tabletop threshers are too small and time-consuming to use for large samples of IWG. Instead, the seed heads from the 0.5 m by 0.25 m samples were threshed on the tabletop threshers. Subsamples were taken from two of the blocks from randomly chosen quadrats (eastern and western side of the plots) and used to determine the percent threshibility by weighing seed heads before and after threshing, using a high-precision, tabletop thresher.

In year two, harvest was conducted as described above, except for the changes stated here. In year two, 0.5 m by 0.25 m quadrat samples were not harvested. Instead, the 0.5 m by 0.5 m samples were used to determine moisture content. After the samples were cut, they were fresh-weighed and the seed heads were cut off. These seed heads were counted and weighed. As in year one, seed heads and biomass were dried at 60°C for at least three d, and reweighed. Finally, in year two, the easterly 0.5 m by 0.5 m sample from each plot was threshed using a tabletop threshed, weighed, dried in a soil tin at 60°C for at least three d, and reweighed.

Late Season Heading

After harvest, many of the plants sent out new shoots (late season regrowth), some of which eventually grew into reproductive tillers (late season heading). The prevalence of this circumstance was evaluated on October 21, 2011, by randomly placing a meter stick beside one of the center rows in each plot and counting the number of reproductive tillers that were in that section of the row. This procedure was repeated three times in each plot. Late season heading was not measured in 2012.

Post-Sexual Cycle Regrowth (Survival Rates)

In 2011 post-sexual cycle regrowth, which is also the rate of perennial plant survival, was evaluated by comparing the number of plants being monitored for tiller and leaf growth that had died, compared with the number that had survived on November 3, 2011, which was the last day these measurements were taken in 2011. In 2012, too few of the monitored perennial wheat plants survived to provide a representative estimate for post-sexual cycle regrowth. Instead, the plants in three random one-meter segments of inner row were measured in each plot. A visual estimate was made of the number of plants that were dead and the number that were alive on September 8, 2012. This was only done for the Pwheat plots because none of the IWG plants appeared to be dead. For all plants in all years, dead plants were defined as any plant that had not put out any new green shoots at least a month after grain harvest. Plants that survived were plants that did regrow (i.e., put out green shoots after harvest). Regrowth measurement dates are presented in Table 2.8.

Forage Quality Analyses

Three types of forage quality analyses were conducted for each plot, on plant samples collected at intervals throughout the plants' lives (Tables 2.9 and 2.10) in order to determine the range of forage qualities through which these species pass at different growth stages. The early, middle and late biomass samples and the material harvested as forage, all of which are described above in greater detail, are the samples on which these analyses were conducted. All experimental samples were oven-dried at 60°C for at least 3 d, and then ground in a blue Christy mill with a 1 mm screen. The standard used was a new internal reference, consisting of dried, ground alfalfa. Two previously established standards, one internal and one external, were used to verify this new standard.

Neutral Detergent Fiber (NDF)

For each sample 0.450 g-0.550 g of dried, ground plant matter was weighed out and sealed into an F57 filter bag (ANKOM Technology, Macedon, NY) using a 120v 50/60 Hz heat sealer (ANKOM Technology, Macedon, NY). This procedure was replicated for each sample. Twenty-four sample bags at a time were processed in an ANKOM 200 Fiber Analyzer, 120v domestic model (ANKOM Technology, Macedon, NY). A blank bag and at least two bags containing a standard were included in each run (Ankom Technology, Method 6, 13 Apr., 2011).

Acid Detergent Fiber (ADF)

After NDF analyses were completed, the same bagged samples were used for ADF analyses. These analyses were completed using the same procedure and the same ANKOM 200 Fiber Analyzer as for the NDF analyses. The only difference was that for the ADF procedure, the incubation time is only 1 hr and the alpha-amylase was not required (Ankom Technology, Method 5, 13 Apr., 2011).

In-Vitro Dry Matter Digestibility (IVDMD)

A second set of bagged samples was prepared for IVDMD analysis, which was performed using a Daisy II Incubator, 120v domestic model (ANKOM Technology, Macedon, NY). On each day during which an incubation would begin, 1-2L of rumen fluid was collected from a cannulated cow at the KBS dairy (Ankom Technology, Method 3, Aug. 2005).

Statistical Analyses

All statistical analyses were conducted using SAS statistical software, version 9.2 (SAS Institute, Cary, NC). Growth measurements (height, LAI, and whole-plant dried biomass) and forage quality measurements (NDF, ADF, and IVDMD) from early (shortly before spring forage cutting), middle (at about 40% heading), and late (shortly before harvest) dates, regrowth, emergence, grain harvest, and stover harvest data were analyzed as RCBD with four levels (fall-planted, cut and uncut Pwheat and fall-planted, cut and uncut IWG) in year one, and five levels (same as year one, with the addition of spring-planted, cut Pwheat) in year two. Cumulative totals over both years were analyzed in the same manner as the year two data sets. Mass and quality of spring forage were analyzed in the same manner as the data sets listed above, but using only the systems with a cut treatment (fall-planted, cut Pwheat and IWG in year one, with the addition of spring-planted, cut Pwheat in year two).

For all measurement types, assumptions were checked using proc mixed and proc univariate. First, the residuals were calculated using proc mixed and their normality was checked by graphing a normal plot and a QQ plot, both using proc univariate. Next, homogeneity of the residuals was checked in two ways: 1) plotting residuals versus predicted values using proc plot and proc gplot; 2) generating side-by-side box plots using proc sort and proc univariate. Studentized residuals were used for the plots in proc gplot. Assumptions were generally met, although for the year one, LAI, repeated measures data set, a log transformation was required to meet the normality assumption and some of the RCBD data sets (year one early LAI, year two middle biomass, year two late LAI, year one spring forage yield, year two spring forage yield, year one early NDF for forage cuttings, year one early ADF for forage cuttings, year one early IVDMD for forage cuttings, year one middle IVDMD, year two early ADF for forage cuttings, year two early NDF for whole-plant biomass, and year two late NDF) had to be analyzed assuming heterogeneous variances. Bonferroni adjustments were required for first-year ADF from the middle sampling date, first-year stover, and first year total harvestable forage. None of the adjustments yielded significant results.

Height and LAI over the entire growing season were analyzed using repeated measures methods. For these data sets, the next step after checking assumptions was to select an appropriate variance-covariance structure. Each data set was fitted in proc mixed with the following variance-covariance structures: compound symmetry, compound symmetry with heterogeneous variances, unstructured, unstructured with scoring, spatial power with unequal spacing, auto-regressive of order one, auto-regressive of order one with heterogeneous variances, toeplitz, toeplitz with heterogeneous variances, and variance components. The variance-covariance structure that generated the lowest Akaike's Information Criterion (AIC) value was selected for use with that data set. The following variance-covariance structures were selected: toeplitz with heterogeneous variances for first-year height, auto-regressive of order one with heterogeneous variances for second-year height and first- and second-year LAI. In addition, a simple log transformation was performed on the first-year LAI data set, in order to ensure normality of the residuals.

All data sets except height and LAI over an entire growing season were analyzed as RCBD data sets. After checking assumptions for these data sets, AIC values were generated for analysis with homogeneous variances and for analysis with heterogeneous variances. Whichever type of analysis produced a lower AIC was chosen for use with that particular data set.

For RCBD data sets, an analysis of variance (ANOVA) test and a number of pre-planned contrasts were run, and least squares means and differences between least squares means were generated in proc mixed. The differences between least squares means were used to perform mean separation for all RCBD data sets. The contrasts generally used for year one RCBD data sets were: cut versus uncut, IWG versus Pwheat, cut IWG versus uncut IWG, and cut Pwheat versus uncut Pwheat. Recall that all treatments in year one were fall-planted. The contrasts generally used for year two RCBD data sets were: fall-planted cut versus fall-planted uncut, fall-planted IWG versus fall-planted Pwheat, fall-planted cut Pwheat versus fall-planted uncut Pwheat, spring-planted cut Pwheat versus fall-planted cut Pwheat, and fall-planted cut IWG versus fall-planted uncut IWG. The exceptions to this were the forage harvest dry weight data sets. Because forage harvest data are only available for cut plots, any contrasts involving uncut treatments could not be run with this data set. Thus, the only contrast run for year one forage harvest dry weight is fall-planted cut IWG versus fall-planted cut Pwheat and the contrasts run for year two forage harvest dry weight are fall-planted cut IWG versus fall-planted cut Pwheat and spring-planted cut Pwheat versus fall-planted cut Pwheat. For repeated measures data sets, confidence limits were generated, for use as error bars in line graphs. For all data sets, block was treated as a random variable.

Table 2.1: Temperature and rainfall daily averages from the W.K. Kellogg Biological Station (KBS) in southwest Michigan for each month during 2010, 2011, and 2012, as well as historical averages from 1988-2011.

	2010		2011		2012		1988-2011*	
Month	**Mean Air Temp. (C°)**	**Mean Daily Precipitation (mm)**	**Mean Air Temp. (C°)**	**Mean Daily Precipitation (mm)**	**Mean Air Temp. (C°)**	**Mean Daily Precipitation (mm)**	**Mean Air Temp. (C°)**	**Mean Daily Precipitation (mm)**
Jan.	-4.77	0.83	-6.25	0.68	-1.59	2.20	-4.72	1.49
Feb.	-3.29	1.73	-3.46	2.70	-0.38	1.80	-2.97	1.33
March	4.43	0.48	0.95	2.15	9.96	2.52	1.77	1.78
April	11.90	2.38	7.60	4.87	8.78	3.63	8.47	2.62
May	16.06	4.35	15.10	4.59	17.19	0.98	14.47	3.09
June	20.25	6.14	20.24	1.58	21.05	0.76	19.78	2.87
July	23.55	4.80	24.11	6.02	25.28	1.47	22.00	2.94
Aug.	22.53	1.10	20.75	3.10	20.66	2.26	20.67	3.17
Sept.	16.52	2.22	15.56	2.76	16.45	1.94	16.32	3.13
Oct.	11.59	1.55	10.55	2.90	9.82	4.61	10.08	2.74
Nov.	4.80	2.15	6.17	3.63	N/A	N/A	4.14	2.78
Dec.	-3.67	1.45	0.97	2.02	N/A	N/A	-2.18	1.50

***Note that temperature data from 2006 to 2009, inclusive, are not available, and thus are not included in the historical averages for monthly mean air temperature.**

Table 2.2: Means and standard errors of soil textures in perennial grains ecosystem services trial

Depth (cm)	pH	SOC (g kg^{-1})	TSN (g kg^{-1})	Sand (%)	Clay (%)	BD (g cm^{-2})
0 – 10	5.46 +/- 0.05	9.47 +/- 0.53	0.94 +/- 0.03	55.81 +/- 1.82	7.36 +/- 0.46	1.38 +/- 0.02
10 – 20	5.61 +/- 0.06	7.26 +/- 0.41	0.81 +/- 0.03	53.89 +/- 1.89	7.13 +/- 0.46	1.57 +/- 0.02
20 – 40	5.91 +/- 0.07	3.20 +/- 0.35	0.49 +/- 0.03	55.80 +/- 2.38	13.19 +/- 1.09	1.64 +/- 0.02

*SOC = soil organic carbon; TSN = total soil nitrogen; BD = bulk density.

Table 2.3: Dates of first-year yield measurements are presented, including spring forage, stover, cumulative forage, grain yield, and % regrowth from 2011. Field experiment conducted in southwest Michigan at the W.K. Kellogg Biological Station (KBS) on four systems: two species, IWG and Pwheat, planted in the fall and subjected to two cutting regimes (uncut or cut for spring forage).

System	Spring Forage	Stover	Total Harvestable Forage	Grain Yield
Uncut IWG	N/A	August 10	August 10	August 10
Uncut Pwheat	N/A	August 2	August 2	August 2
Cut IWG	May 24	August 10	May 24 and August 10	August 10
Cut Pwheat	May 11	August 2	May 11 and August 2	August 2

Table 2.4: Dates of second-year yield measurements are presented, including spring forage, stover, cumulative forage, grain yield, and % regrowth from 2012. Field experiment conducted in southwest Michigan at the W.K. Kellogg Biological Station (KBS) on five systems: two species, IWG and Pwheat, planted in the fall and subjected to two cutting regimes (uncut or cut for spring forage), and Pwheat planted in the spring and cut for spring forage in year two as a comparison.

System	Spring Forage	Stover	Total Harvestable Forage	Grain Yield
Uncut IWG	N/A	July 25	July 25	July 25
Uncut Pwheat	N/A	July 16	July 16	July 16
Cut IWG	March 29	July 25	March 29 and July 25	July 25
Cut Pwheat	March 22	July 16	March 22 and July 16	July 16
Spring-Planted, Cut Pwheat	March 22	July 16	March 22 and July 16	July 16

Table 2.5: Dates of first-year growth measurements, including height, LAI, and biomass (aboveground dry weight) at early, middle, and late growth periods and emergence from 2011. Field experiment conducted in southwest Michigan at the W.K. Kellogg Biological Station (KBS) on four systems: two species, IWG and Pwheat, planted in the fall and subjected to two cutting regimes (uncut or cut for spring forage).

		Early (Pre-Stem Elongation)			Middle (40% Heading)			Late (Harvest)		
System	**Emergence Rate**	**Height**	**Leaf Area Index (LAI)**	**Biomass**	**Height**	**Leaf Area Index (LAI)**	**Biomass**	**Height**	**Leaf Area Index (LAI)**	**Biomass**
Uncut IWG	April 14	May 9	May 9	May 24	June 15	June 21	June 16	July 20	July 29	August 10
Uncut Pwheat	April 14	May 9	May 9	May 11	June 15	June 21	June 13	July 20	July 29	August 2
Cut IWG	April 14	May 9	May 9	May 24	June 15	June 21	June 17	July 20	July 29	August 10
Cut Pwheat	April 14	May 9	May 9	May 11	June 15	June 21	June 14	July 20	July 29	August 2

Table 2.6: Perennial wheat and intermediate wheatgrass growth stages (modified Moore stages (Moore et al., 1991) after Zadoks' scale (Zadoks et al., 1974))

Vegetative Stages (V_x)	**Characteristics**
V_0	Zero collared leaves on the main stem.
V_1	One collared leaf on the main stem.
V_2	Two collared leaves on the main stem.
V_3	Three collared leaves on the main stem.
V_4	Four collared leaves on the main stem.
V_5	Five collared leaves on the main stem.
Elongation Stages (E_x)	
E_0	Stem elongated. No detectable nodes.
E_1	Stem elongated. One detectable node.
E_2	Stem elongated. Two detectable nodes.
E_3	Stem elongated. Three detectable nodes.
E_4	Stem elongated. Four detectable nodes.
E_5	Stem elongated. Five detectable nodes.
Reproductive Stages (R_x)	
R_0	Boot stage: flag leaf emerged.
R_1	Inflorescence emergence begins.
R_2	Inflorescence emerged. Peduncle not elongated.
R_3	Inflorescence emerged. Peduncle elongated.
R_4	Anther emergence (anthesis). Anthers are yellow.
R_5	Post-anthesis (fertilization). Anthers are white.
Seed Development Stages (S_x)	
S_0	Caryopsis visible.
S_1	Milk stage: grain is green and filled with milky fluid
S_2	Soft dough stage: grain is very soft when squeezed
S_3	Hard dough stage: grain is pasty in texture when squeezed
S_4	Endosperm hard
S_5	Endosperm dry (ripe)

Table 2.7: Dates of second-year growth measurements, including height, LAI, and biomass (aboveground dry weight) at early, middle, and late growth periods from 2012. Field experiment conducted in southwest Michigan at the W.K. Kellogg Biological Station (KBS) on five systems: two species, IWG and Pwheat, planted in the fall and subjected to two cutting regimes (uncut or cut for spring forage), and Pwheat planted in the spring and cut for spring forage in year two as a comparison.

	Early (Pre-Stem Elongation)			Middle (40% Heading)			Late (Harvest)		
System	Height	Leaf Area Index (LAI)	Biomass	Height	Leaf Area Index (LAI)	Biomass	Height	Leaf Area Index (LAI)	Biomass
Uncut IWG	March 21	March 21	March 29	May 31	June 2	June 6	July 6	July 5	July 25
Uncut Pwheat	March 21	March 21	March 22	May 31	June 2	May 29	July 6	July 5	July 16
Cut IWG	March 21	March 21	March 29	May 31	June 2	June 6	July 6	July 5	July 25
Cut Pwheat	March 21	March 21	March 22	May 31	June 2	May 27	July 6	July 5	July 16
Spring-Planted, Cut Pwheat	March 21	March 21	March 22	May 31	June 2	May 24	July 6	July 5	July 16

Table 2.8: Dates of regrowth and yield measurements over two years are presented, including regrowth in 2011 and 2012, and cumulative total forage (spring forage plus stover) and cumulative grain yield from 2011 and 2012. Field experiment conducted in southwest Michigan at the W.K. Kellogg Biological Station (KBS) on five systems: two species, IWG and Pwheat, planted in the fall and subjected to two cutting regimes (uncut or cut for spring forage), and Pwheat planted in the spring and cut for spring forage in year two as a comparison.

System	% Regrowth (Year 1)	% Regrowth (Year 2)	Cumulative % Regrowth Over Two Years	Cumulative Total Forage Yield	Cumulative Grain Yield
Uncut IWG	November 3, 2011	September 8, 2012	November 3, 2011 and September 8, 2012	August 10, 2011 and July 25, 2012	August 10, 2011 and July 25, 2012
Uncut Pwheat	November 3, 2011	September 8, 2012	November 3, 2011 and September 8, 2012	August 2, 2011 and July 16, 2012	August 2, 2011 and July 16, 2012
Cut IWG	November 3, 2011	September 8, 2012	November 3, 2011 and September 8, 2012	May 24, 2011, August 10, 2011, March 29, 2012, and July 25, 2012	August 10, 2011 and July 25, 2012
Cut Pwheat	November 3, 2011	September 8, 2012	November 3, 2011 and September 8, 2012	May 11, 2011, August 2, 2011, March 22, 2012, and July 16, 2012	August 2, 2011 and July 16, 2012
Spring-Planted, Cut Pwheat	November 3, 2011	September 8, 2012	November 3, 2011 and September 8, 2012	March 22, 2012 and July 16, 2012	July 16, 2012

Table 2.9: Dates of first-year forage quality measurements are presented, including whole-plant ADF, NDF, and IVDMD from early, middle, and late time periods and spring forage cutting ADF, NDF, and IVDMD from the early time period in 2011. Field experiment conducted in southwest Michigan at the W.K. Kellogg Biological Station (KBS) on four systems: two species, IWG and Pwheat, planted in the fall and subjected to two cutting regimes (uncut or cut for spring forage).

	Early (Pre-Stem Elongation)			Middle (40% Heading)			Late (Harvest)			Early (Pre-Stem Elongation)		
	Forage Cuttings			Whole Plant			Whole Plant			Stover		
System	NDF	ADF	IVDMD	NDF	ADF	IVDMD	NDF	ADF	IVDMD	NDF	ADF	IVDMD
Uncut IWG	N/A	N/A	N/A	May 24	May 24	May 24	June 16	June 16	June 16	August 10	August 10	August 10
Uncut Pwheat	N/A	N/A	N/A	May 11	May 11	May 11	June 13	June 13	June 13	August 2	August 2	August 2
Cut IWG	May 24	May 24	May 24	May 24	May 24	May 24	June 17	June 17	June 17	August 10	August 10	August 10
Cut Pwheat	May 11	May 11	May 11	May 11	May 11	May 11	June 14	June 14	June 14	August 2	August 2	August 2

Table 2.10: Dates of second-year forage quality measurements are presented, including whole-plant ADF, NDF, and IVDMD from early, middle, and late time periods and spring forage cutting ADF, NDF, and IVDMD from the early time period in 2012. Field experiment conducted in southwest Michigan at the W.K. Kellogg Biological Station (KBS) on five systems: two species, IWG and Pwheat, planted in the fall and subjected to two cutting regimes (uncut or cut for spring forage), and Pwheat planted in the spring and cut for spring forage in year two as a comparison.

	Early (Pre-Stem Elongation)			Middle (40% Heading)			Late (Harvest)			Early (Pre-Stem Elongation)		
	Forage Cuttings			Whole Plant			Whole Plant			Stover		
System	**NDF**	**ADF**	**IVDMD**	**NDF**	**ADF**	**IVDMD**	**NDF**	**ADF**	**IVDMD**	**NDF**	**ADF**	**IVDMD**
Uncut IWG	N/A	N/A	N/A	March 29	March 29	March 29	June 6	June 6	June 6	July 25	July 25	July 25
Uncut Pwheat	N/A	N/A	N/A	March 22	March 22	March 22	May 29	May 29	May 29	July 16	July 16	July 16
Cut IWG	March 29	March 29	March 29	March 29	March 29	March 29	June 6	June 6	June 6	July 25	July 25	July 25
Cut Pwheat	March 22	March 22	March 22	March 22	March 22	March 22	May 27	May 27	May 27	July 16	July 16	July 16
Spring-Planted, Cut Pwheat	March 22	March 22	March 22	March 22	March 22	March 22	May 24	May 24	May 24	July 16	July 16	July 16

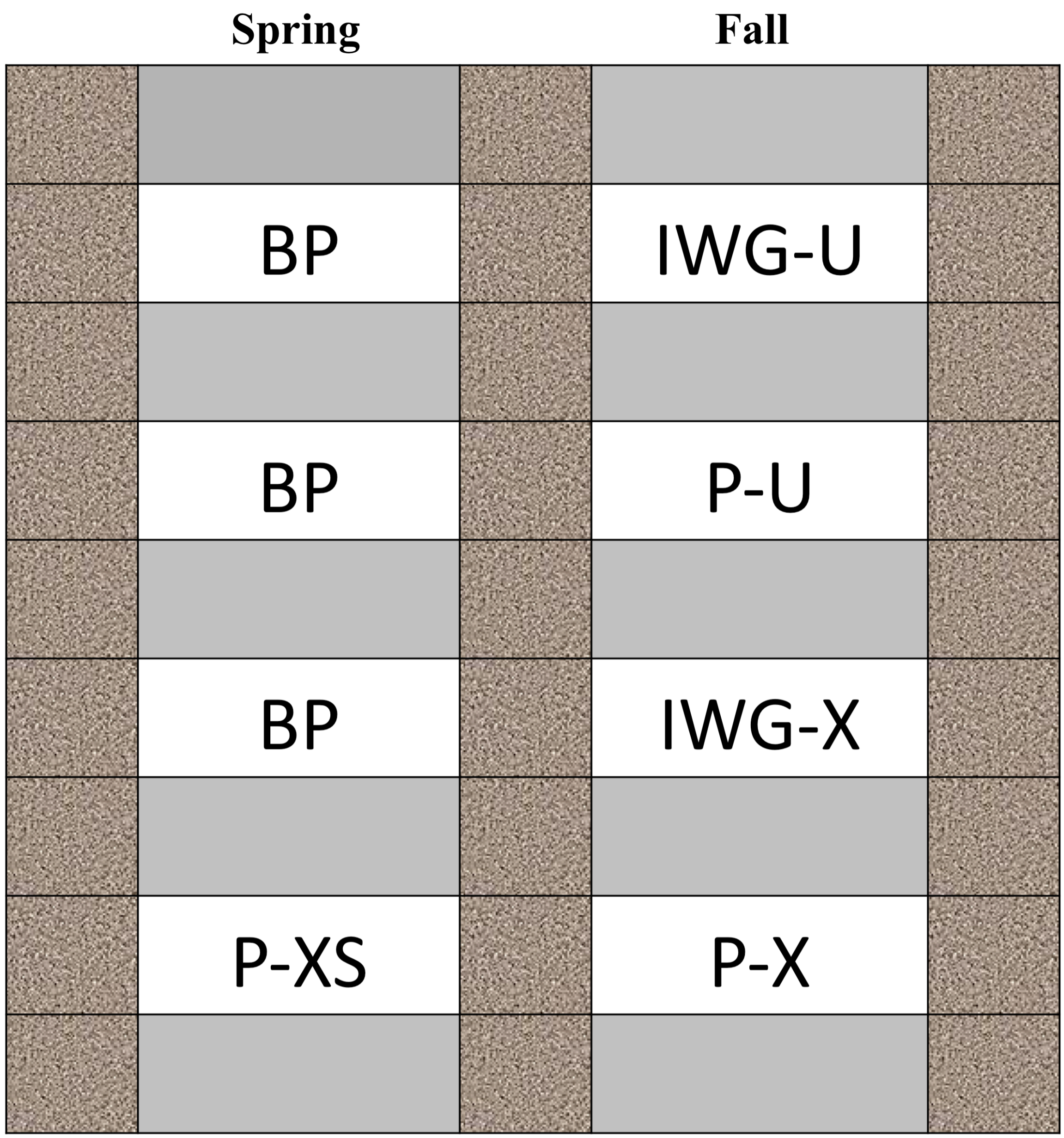


Figure 2.1: P-cut planting map. Block 1 only. Not to scale.
Key: BP=Border Plot
IWG-N=Intermediate Wheatgrass, Fall-Planted, Uncut
IWG-X=Intermediate Wheatgrass, Fall-Planted, Cut
P-N=Perennial Wheat, Fall-Planted, Uncut
P-X=Perennial Wheat, Fall-Planted, Cut
P-XS=Perennial Wheat, Spring-Planted, Cut

CHAPTER THREE

Results, Discussion, and Conclusions

Weather

As shown in Table 2.1, the spring and summer of 2010 were hotter than the 24-year average. The spring and fall were fairly dry that year, but the summer was wetter than average. This was followed by a cold winter after the fall-planted plots were seeded. The summer of 2011 was warm and wet, followed by a fairly typical autumn. The winter spanning late 2011 and early 2012 was exceedingly warm. March 2012 was particularly warm, with an average temperature of 9.96˚C, as compared with the 24-year average of 1.77˚C. This caused the spring forage cutting to take place much earlier than it otherwise would have. The warm spring was followed by a very hot, dry summer, especially May, June, and July, which were each about 1-3˚C above the 24-year average, while delivering only 30-50% the usual amount of rainfall.

Results

Year 1 Growth

Emergence

Emergence rates differed across treatments, with fall-planted Pwheat having the highest emergence rates (228.00 plants/m^2), followed by the cut IWG (188.50 plants/m^2), then the spring-planted Pwheat (124.32 plants/m^2 on June 1, 2011) and the uncut IWG (151.50 plants/m^2) (Table 3.1). Large differences were observed due to planting time ($p=<0.0001$) and species ($p=0.0003$; Table 3.2). Emergence rates were higher in the fall than in the spring, reflecting favorable soil moisture conditions in the fall compared to excessively wet soil in the spring (Table 2.1).

Early

Means for first-year growth measurements are shown in Table 3.1. Species effects explained the growth differences observed at the early measurement date. This time period corresponded with vegetative stage, soon before stem elongation, and the cutting treatments had not yet been imposed. Early rapid growth was observed in Pwheat relative to IWG, as shown by height measurements (Figure 3.1). A planned contrast was conducted for Pwheat and IWG, where a species effect was found to be highly significant for height and leaf area (Table 3.1). On average, Pwheat was taller (20.5 cm) and had a higher LAI (0.96), relative to IWG, with an average height=11.95 cm and average LAI=0.17 (Table 3.2). There were no differences observed at the early growth period among any of the treatments for above-ground net primary productivity, as indicated by biomass measurements at the early sampling time (Table 3.1).

Middle

In year one, the biomass at the middle measurement date was sampled one day later for each cut treatment as compared to the corresponding uncut treatment, due to differences in development rates caused by cutting (Table 2.5). At the middle measurement date, species remained the most important factor influencing plant growth (Table 3.2). At the time of these measurements, approximately 40% of plants had headed, and thus most plants were in early reproductive stages. As shown in Figure 3.1, Pwheat was taller than IWG throughout the early and middle growth periods. In fact, relative to IWG, Pwheat was much taller (Pwheat=90.6 cm, IWG=65.3 cm) and had a much higher LAI (Pwheat=2.74, IWG=1.82; Table 3.1). Year 1 LAI for all measurement times is shown in Figure 3.2. In addition, Pwheat produced more biomass than IWG (Pwheat=845.64 g/m^2, IWG=449.15 g/m^2) at the middle sampling date (Table 3.1). However, cutting regime also impacted plant size, especially height (Table 3.2), causing small but significant differences. For each species, the uncut plants were taller than the cut plants (uncut plants=81.9 cm, cut plants=73.9 cm; Table 3.1). Cutting also decreased LAI for IWG (cut IWG=1.67, uncut LAI= 1.96), but not for Pwheat (Tables 3.1 and 3.2). Cutting regime did not influence biomass accumulated by either species at this time.

Late

At the late growth period, which lasted until harvest, height was significantly influenced by species but not by cutting regime (Table 3.2). Interestingly, species effects were reversed, with IWG surpassing Pwheat in height (Pwheat=101.6 cm, IWG=108.2 cm; Table 3.1). As shown in Figure 3.1, Pwheat has a faster initial growth rate and reached a plateau at a lower height than that of IWG. There was no difference in LAI between the two species (Pwheat=1.93, IWG=1.91; Tables 3.1 and 3.2) and, despite being taller, IWG produced less biomass than Pwheat (Pwheat=1180.55 g/m^2, IWG=736.15 g/m^2; Table 3.1). During this late growth period, there were no differences observed between cut and uncut plants for either species; apparently mid-season regrowth compensated for the reduction in height caused by the cutting treatment (Table 3.2).

Post-Sexual Cycle Regrowth

The regrowth of the treatments was monitored on November 3, 2011 to assess perennial vigor (Table 3.3). The one treatment associated with poor regrowth in the first year was fall-planted, cut Pwheat (≈50% regrowth), compared to all other treatments, which were associated with 85-100% regrowth (Table 3.3 and 3.4). On average, Pwheat plants that had never been cut (regardless of planting time) and all IWG plants (regardless of cutting regime) were 1.9 times more likely to regrow than fall-planted, cut Pwheat plants (Tables 3.3 and 3.4).

Year 2 Growth

Early

Similarly to year one, species effects were more important than cutting regime for growth parameters in year two (Tables 3.5 and 3.6). Pwheat was taller than IWG (Pwheat=29.7 cm, IWG=24.9 cm; Table 3.5) at the early measurement time, which was the same direction of response observed in year one. Note the similarity in growth curves for height between years one and two (Figures 3.1 and 3.3). However, in contrast to plant height, IWG was associated with greater LAI (Pwheat=1.30, IWG=4.16) and biomass (Pwheat=389.46 g/m^2, IWG=1276.12 g/m^2), relative to Pwheat (Table 3.5). Cutting in year one did not affect height, LAI, or biomass at the early measurement time in year two (Table 3.6). Planting time only had an effect on LAI, at this time. This resulted in spring-planted Pwheat having an LAI that was much higher than fall-planted Pwheat, and much more comparable to that of IWG than of the fall-planted Pwheat (fall-planted Pwheat LAI=1.30, spring-planted Pwheat LAI=3.73, IWG LAI=4.16; Tables 3.5 and 3.6).

Middle

In year two, the biomass at the middle measurement date was sampled on different days for each Pwheat treatment, due to differences in development rates caused by cutting and planting times (Table 2.7). At the middle measurement date, there was no longer any difference in height between the two species (Tables 3.5 and 3.6). However, IWG still had much more canopy closure than Pwheat, as shown by LAI (Pwheat LAI=1.67, IWG LAI=5.99; Figure 3.4, Tables 3.5 and 3.6), as well as more biomass (Pwheat=889.5 g/m^2, IWG=2191.75 g/m^2; Tables 3.5 and 3.6). At this middle measurement time, there were no growth differences observed due to cut treatment, which was imposed between the early and middle measurements. As at the early measurement time, planting time only affected canopy closure (fall-planted Pwheat LAI=1.67, spring-planted Pwheat LAI=2.97, IWG LAI=5.99; Tables 3.5 and 3.6).

Late

At the late measurement date in year two, species was still the most important factor influencing plant growth (Table 3.6). IWG had much greater height (Pwheat=97.8 cm, IWG=127.2 cm), LAI (Pwheat LAI=0.88, IWG LAI=4.27), and biomass (Pwheat=669.71 g/m^2, IWG=1171.05 g/m^2) than Pwheat (Table 3.5). At the late measurement time, there were no differences due to cut treatments (Table 3.6). As was the case throughout the year, planting time only affected canopy closure (fall-planted Pwheat LAI=0.88, spring-planted Pwheat LAI=1.67, IWG LAI=4.27; Tables 3.5 and 3.6).

Post-Sexual Cycle Regrowth

In the second year, species had the greatest effect on post-sexual cycle regrowth (Table 3.4). IWG was far more likely to regrow than Pwheat in year two (Pwheat=51.0% regrowth, IWG=100.0% regrowth; Tables 3.3 and 3.4). The cut treatment had no effect on regrowth of either species. The planting time did have a modest effect, with the fall-planted Pwheat being more likely to regrow than the spring-planted (fall Pwheat=51.0% regrowth, spring Pwheat=34.8% regrowth; Tables 3.3 and 3.4), but it did not have as big an influence as species.

Cumulative Post-Sexual Cycle Regrowth

After two years of growth, all IWG plants remained alive (100% regrowth; Table 3.3), which was higher then the percentage of plants surviving for any Pwheat treatment. A greater percentage of uncut Pwheat plants (41.45%) were alive after two years, as compared with cut Pwheat plants (25.21%; Tables 3.3 and 3.4). However, there was no difference between survival rates of the spring-planted Pwheat (33.28%) and the fall-planted Pwheat treatments (33.33%; Tables 3.3 and 3.4).

Year 1 Forage Quality

Early (Forage Cuttings)

At the early measurement date in year one, IWG forage had lower NDF (Pwheat forage=64.43%, IWG forage=46.27%) and ADF (Pwheat forage=49.49%, IWG forage=21.06%) values and a higher IVDMD value (Pwheat forage=32.16%, IWG forage=65.30%) than Pwheat forage (Tables 3.7 and 3.8).

Early (Whole Plant)

On the early measurement date in year one, species was the only factor that was observed to influence the biochemical quality of plant biomass (Table 3.8). Relative to Pwheat, IWG had high NDF (Pwheat=47.01%, IWG=50.83%) and ADF (Pwheat=21.74%, IWG=24.06%) values and a low IVDMD value (Pwheat=65.84%, IWG=63.45%; Table 3.7).

Middle (Whole Plant)

On the middle measurement date in year one, species was, once again, the only factor that was observed to affect forage quality (Table 3.8). IWG had a higher IVDMD value (Pwheat=50.29%, IWG=53.92%) than Pwheat (Table 3.7). The two species had equivalent NDF (63.51%) and ADF values (34.59%; Table 3.7). Although the ADF of IWG versus Pwheat contrast seems significant at first (p=0.0430; Table 3.8), a Bonferroni Adjustment is necessary since the ANOVA is not significant. After the adjustment, the p-value must be below 0.0167 to be significant, which is not the case (0.0430>0.0167), so there is no species difference for ADF at the middle time period.

Late (Stover)

On the late measurement date in year one, species was again the only factor studied that had an observed effect on forage quality (Table 3.8). IWG had lower NDF (Pwheat=79.19%, IWG=69.79%) and ADF (Pwheat=49.44%, IWG=41.24%) values and a higher IVDMD value (Pwheat=29.14%, IWG=41.60%) than Pwheat (Table 3.7). Quality of stover is presented in Figures 3.5, 3.6, and 3.7.

Year 2 Forage Quality

Early (Forage Cuttings)

On the early measurement date in year two, species and planting time both affected the quality of forage cuttings, with IWG forage having lower NDF (Pwheat forage=65.80%, IWG forage=50.19%) and ADF (Pwheat forage=34.96%, IWG forage=25.90%) values and a higher IVDMD value (Pwheat=50.96%, IWG=64.04%) than Pwheat forage (Tables 3.9 and 3.10). Spring-planted, Pwheat forage had lower NDF (spring Pwheat=53.84%, fall pwheat=65.80%) and ADF (spring Pwheat=25.72%, fall Pwheat=34.96%) values and a higher IVDMD value (spring Pwheat=63.95%, fall Pwheat=50.96%) than fall-planted, Pwheat forage (Tables 3.9 and 3.10).

Early (Whole Plant)

On the early measurement date in year two, species and planting time both affected whole-plant forage quality (Table 3.10). IWG had lower NDF (Pwheat=70.65%, IWG=65.73%) and ADF (Pwheat=42.70%, IWG=36.65%) values and a higher IVDMD value (Pwheat=38.35%, IWG=51.61%) than Pwheat (Table 3.9). Spring-planted Pwheat had lower NDF (spring Pwheat=63.39%, fall pwheat=70.65%) and ADF (spring Pwheat=33.56%, fall Pwheat=42.70%) values and a higher IVDMD value (spring Pwheat=47.46%, fall Pwheat=38.35%) than fall-planted Pwheat (Table 3.9). There was no effect of cutting (Table 3.10).

Middle (Whole Plant)

On the middle measurement date in year two, planting time affected NDF and ADF, while species and cutting affected IVDMD (Table 3.10). Spring-planted Pwheat had lower NDF (spring Pwheat=63.95%, fall Pwheat=69.17%) and ADF (spring Pwheat=35.63%, fall Pwheat=41.25%) values than fall-planted Pwheat (Table 3.9). There was no effect of species or cutting for NDF (69.96%) or ADF (41.05%). IWG had a higher IVDMD value than Pwheat (Pwheat=40.84%, IWG=44.35%). Cut Pwheat had a higher IVDMD value than uncut Pwheat (cut Pwheat=43.06%, uncut Pwheat=38.62%). Planting time had no effect on IVDMD (42.60%) and cutting had no effect on IVDMD for IWG alone (IWG=44.35%; Tables 3.9 and 3.10).

Late (Stover)

On the late measurement date in year two, species had the biggest effect on forage quality of whole-plant biomass (Table 3.10). IWG had lower NDF (Pwheat=80.06%, IWG=73.44%) and ADF (Pwheat=48.94%, IWG=42.41%) values and a higher IVDMD value (Pwheat=30.77%, IWG=38.26%) than Pwheat (Tables 3.9 and 3.10). Planting time also had a small effect, but only on NDF. Spring-planted, cut Pwheat had a lower NDF value than fall-planted, cut Pwheat (Spring Pwheat=79.28%, fall Pwheat=80.60%; Tables 3.9 and 3.10). Quality of stover is presented in Figures 3.5, 3.6, and 3.7.

Overall Quality

In general, biochemical quality tended to decline over time. This trend can be seen in Tables 3.7 and 3.9. In addition, IWG biomass tended to be of higher quality than Pwheat, especially late in the season when stover was harvested, although there were some exceptions to this (Tables 3.7 and 3.9, Figures 3.5, 3.6, and 3.7). Spring-planted Pwheat was much higher in quality than fall-planted Pwheat at the beginning of the season, but the difference between them became less pronounced by the time stover was harvested (Table 3.10). The effects of cutting appear to have been negligible (Tables 3.8 and 3.10).

Yield (Years 1 and 2)

Spring Forage

Forage produced by the spring cutting treatment is presented in Figure 3.8. In year one, the spring forage biomass produced in the cut Pwheat treatment was higher than in the cut IWG treatment (Pwheat=34.77 g/m^2, IWG=10.34 g/m^2; Tables 3.11 and 3.12).

A species effect for spring forage was also observed in year two. However, the pattern was the reverse of what occurred in year one, with IWG yielding more spring forage than Pwheat did (Pwheat=23.21 g/m^2, IWG=33.75 g/m^2; Tables 3.13 and 3.14). There was also an effect of planting time, with spring Pwheat producing more forage than fall Pwheat (spring Pwheat=45.20 g/m^2, fall Pwheat=23.21 g/m^2; Tables 3.13 and 3.14).

Overall, forage produced in the spring was a very small proportion of the total forage harvested, which was dominated by the stover produced at grain harvest (Figure 3.9). However, it is still interesting to note that all cut treatments produced about the same cumulative amount of spring forage in the first two years of growth (51.04 g/m^2; Tables 3.11 and 3.13, Figure 3.8). Neither species nor planting date had any observed effect on two-year spring forage production.

Stover

Overall stover production is presented in Figure 3.10. In year one, there were no differences in harvested stover dry weight due to species or cutting (Table 3.12). At first glance, there seems to be a difference between cut and uncut IWG (cut IWG=507.24 g/m^2, uncut IWG=760.93 g/m^2; Tables 3.11 and 3.12). However, a Bonferroni adjustment is required since the ANOVA is not significant. In this case, this adjustment means that only contrasts with p-values below 0.0167 are significant. Since 0.0262>0.0167, the difference between the cut and uncut IWG was not actually significant (Table 3.12).

In year two, species had a large effect on stover production, with IWG producing more stover than Pwheat (Pwheat=379.62 g/m^2, IWG=939.32 g/m^2; Tables 3.13 and 3.14). There was a difference between spring Pwheat (498.90 g/m^2) and fall cut Pwheat (302.37 g/m^2), although there was no difference between fall uncut Pwheat (456.87 g/m^2) and either of the other Pwheat treatments (Tables 3.13 and 3.14).

Species, cutting, and planting time affected two-year cumulative totals of stover dry weights (Tables 3.12 and 3.14, Figure 3.10). Overall, IWG produced more stover than Pwheat (Pwheat=1092.4 g/m^2, IWG=1573.4 g/m^2), uncut Pwheat produced more stover than cut Pwheat (uncut Pwheat=1221.8 g/m^2, cut Pwheat=963.10 g/m^2), and fall-planted Pwheat produced more stover than spring-planted Pwheat (spring Pwheat=485.42 g/m^2, fall Pwheat=1092.4 g/m^2), while cutting had no effect on IWG (IWG stover=1573.4 g/m^2; Tables 3.11 and 3.13; Figure 3.10).

Total Forage (Spring Plus Fall)

As with stover in year one, dry weight of total harvestable forage was about the same for all species and cutting regimes (684.72 g/m^2; Table 3.11), after a required Bonferroni adjustment had been applied, due to the ANOVA not being significant. The Bonferroni-adjusted alpha was again 0.0167, and the lowest p-value for any of the contrasts was 0.0325 for cut IWG versus uncut IWG (Table 3.12).

In year two, species and planting time both had an effect on the total amount of dried forage (spring plus fall forage) that was harvested (Table 3.14). Over the course of the year, IWG produced more forage than Pwheat (Pwheat=391.23 g/m^2, IWG=956.20 g/m^2) and spring-planted Pwheat produced more forage than fall-planted Pwheat (spring Pwheat=543.60 g/m^2, fall Pwheat=391.23 g/m^2; Table 3.13). There was no effect of cutting (673.72 g/m^2; Tables 3.13 and 3.14).

Species and planting time both affected the two-year cumulative totals for spring and fall forage dry weights (Table 3.4). Overall, IWG produced almost 50% more forage than Pwheat (Pwheat=1121.4 g/m^2, IWG=1595.5 g/m^2) and fall-planted Pwheat produced more than twice as much forage as spring-planted Pwheat (spring Pwheat=530.32 g/m^2, fall Pwheat=1121.4 g/m^2; Table 3.3). Cutting had no effect on Pwheat or IWG (1358.4 g/m^2; Tables 3.3 and 3.4). Although spring forage was produced in extremely limited quantities by all systems, it was of very high quality (low NDF and NDF, high IVDMD; Figure 3.9, Tables 3.7 and 3.9). Stover quantities were much greater, but they were of only moderate quality (Figures 3.5, 3.6, 3.7, and 3.9). This is one of the key trade-offs inherent in this system.

Grain

Overall grain yield is presented in Figure 3.11. In the first year, Pwheat yielded much more grain than IWG (Pwheat=318.02 g/m^2, IWG=126.35 g/m^2; Tables 3.11 and 3.12). There was no difference in grain harvest between cut plants and uncut plants for either species (222.19 g/m^2; Tables 3.11 and 3.12).

In year two, species was again the only variable that was observed to affect grain harvest, with Pwheat once again producing more grain than IWG (Pwheat=159.37 g/m^2, IWG=80.75 g/m^2; Tables 3.13 and 3.14). There was no difference in grain harvest due to cutting (120.06 g/m^2) or planting date (160.60 g/m^2; Tables 3.13 and 3.14).

Species and planting time both affected the two-year cumulative grain yield dry weight totals (Table 3.4). Overall, Pwheat produced more than twice as much grain as IWG (Pwheat=477.39 g/m^2, IWG=207.10 g/m^2), and fall-planted Pwheat produced much more grain than spring-planted Pwheat (spring Pwheat=161.76 g/m^2, fall Pwheat=477.39 g/m^2), while cutting had no observed effect on Pwheat or IWG (342.25 g/m^2; Tables 3.3 and 3.2, Figure 3.11).

Discussion

Emergence, Growth, and Regrowth

Emergence

While uniformity in emergence rates is desirable, it is very difficult to achieve, due to differences in seed characteristics between species and in temperature and soil moisture at spring and fall planting times. These factors likely account for most of the differences among emergence rates seen here (Table 3.1). Overall, varying emergence rates among treatments can be largely compensated for in grasses, as they can fill out sparsely populated areas by putting out new tillers.

Growth

Each year, Pwheat got off to a faster start than IWG in terms of plant height, but IWG always caught up by the end of the year. Early in the first year of growth, Pwheat was taller than IWG, but by the end of that growing season, IWG was taller than Pwheat (Tables 3.1 and 3.2). In year two, the pattern was the same, but to a lesser degree; Pwheat started out only slightly taller than IWG in year two and it was surpassed by IWG earlier (Tables 3.5 and 3.6). IWG was able to surpass Pwheat in height not by growing faster, but by continuing its growth longer. In year one, both species had similar growth rates, but Pwheat growth leveled off as it approached harvest, while IWG height continued to increase (Figure 3.1). The two species followed a similar pattern in year two (Figure 3.3).

The relationship between LAI of Pwheat and IWG closely mimicked change in heights for the two species in the first year, but not in the second year. In the first year, Pwheat had greater canopy closure than IWG early in the season, but by harvest, both species had the same amount of canopy closure (Tables 3.1 and 3.2). In the second year, IWG started the season with much greater canopy closure than Pwheat, and this relationship did not change for the entire season (Tables 3.5 and 3.6). Pwheat clearly had higher canopy closure relative to IWG early in year one, but as the season progressed, the gap became smaller until, finally, IWG had surpassed Pwheat in canopy closure by early September (Figure 3.2). In year two, the pattern was different, with IWG consistently having a higher LAI than Pwheat (Figure 3.4). Interestingly, the LAI of spring-planted Pwheat followed a trajectory similar to that of first-year, fall-planted Pwheat; spring-planted Pwheat LAI started out high (comparable to that of IWG), but steadily decreased over time until it was eventually the same as the LAI of fall-planted Pwheat (Figure 3.4). Since greater canopy closure is associated with being better able to outcompete weeds, this pattern suggests that early in the first season, Pwheat is less susceptible than IWG to being overrun by weeds early in the first growing season. However, IWG is much more weed-competitive than Pwheat late in the first year and throughout the second year of growth.

Mitchell et al. (1998) found that IWG planted in the spring of 1991 had a maximum LAI of 4.7 in 1992 and a maximum LAI of 9.5 in 1993. These are higher than the maximum LAIs we found for IWG (3.90 in year one and 6.68 in year two; Figures 4 and 5). This may be due to IWG being planted in the spring in the Mitchell et al. study, thus the plants were about 6 months older than the plants in our study. Mitchell et al. mention that rainfall was key in determining IWG LAI, so the drought we experienced in the summer of year two (Table 2.1) may also have negatively impacted IWG LAI.

In a study by Xiao et al. (2012) investigating the relationship between grain yield and LAI for a number of annual wheat cultivars, LAIs of wheat ranged from 4.40 to 6.63 between plant heading (approximately the same as our middle sample date) and grain filling (shortly before our late sample date). This was much higher than the LAIs of our Pwheat, which ranged from 1.80 to 2.75 in year one and from 0.80 to 1.95 in year two between the middle and late sample dates. This may have been due to the low fertility of our soil and the fact that our site is fairly marginal for wheat production, whereas Xiao et al.'s study took place in Shandong, the second-largest wheat-producing province in China. Further, Pwheat demonstrates slow initial growth relative to annual wheat, as indicated by an earlier study at our site (Jaikumar et al., 2012).

The relationship between biomass of Pwheat and LAI was different from that for either height or LAI, although there was the same overall pattern of Pwheat showing more vigorous growth early on, only to be eventually surpassed by IWG. In this case, however, the progression spans both years, with Pwheat producing more biomass than IWG at the middle and late sampling dates in year one (Tables 3.1 and 3.2), followed by IWG producing substantially more biomass than Pwheat at every sampling date in year two (Tables 3.5 and 3.6).

Post-Sexual Cycle Regrowth

Regrowth is a key trait for a perennial grain, because it is the characteristic that distinguishes perennials from annuals. In the first year IWG, as a true perennial, consistently regrew after grain harvest (Table 3.3). Sometimes Pwheat regrew after grain harvest (Table 3.3), but because it did not always do so, it is important to understand the factors that influence Pwheat regrowth. Year one provided ideal conditions for Pwheat regrowth: a cool summer with sufficient rainfall (Table 2.1). Under these conditions, cut Pwheat regrew poorly. However, uncut Pwheat (including spring-planted Pwheat, which was not cut until year two) regrew very well (Table 3.3).

As in year one, second-year IWG regrew consistently, showing its reliably perennial nature (Table 3.3). However, unlike in year one, none of the Pwheat regrew well (Table 3.3). This lack of Pwheat regrowth may have been due to the unusually hot, dry summer southwest Michigan experienced in 2012 (Table 2.1). It is important that under every treatment, at least some Pwheat survived, even though higher regrowth levels would be desirable before putting this crop into commercial production. It is also encouraging to note that in the second year, regrowth was not diminished for either species by harvesting a spring forage crop.

Overall, we found perennial wheat to regrow each year about 30-95% of the time, with most treatments in most years showing at least 50% regrowth (Table 3.3). After two years of growth, IWG had 100% regrowth and Pwheat had about 25-40% regrowth (Table

3.3). This is comparable to the findings of Murphy et al. (2009) who report 42.9% regrowth of Pwheat line P-15. Jaikumar et al. (2012) report a very wide range of regrowth for Pwheat line P-15 (4.0-80.9% regrowth). Stand age and weather conditions both seem to impact regrowth strongly, with older plants and those grown under hot, dry conditions tending to regrow more poorly. However, more research is needed under a variety of weather conditions to draw definite conclusions.

Summary

In the first two years, species was the factor that affected growth and regrowth the most strongly. The differences in growth and regrowth between species are probably related to degree of perennial traits exhibited. Perennials tend to grow slowly at first, but they grow for such a long time, that eventually they surpass shorter-lived plants in size (Van Tassel et al., 2010). This is exactly what we see with Pwheat and IWG. Since IWG has a greater tendency to behave as a perennial than Pwheat, it makes sense for it to grow slowly during the early time period of year one, as confirmed by mean height and LAI values (Table 3.1), but to eventually surpass Pwheat in size, as shown by year two mean values, especially for LAI and biomass (Table 3.5).

Degree of perenniality also affected growth in year two in that Pwheat's lack of robust perennial regrowth (Table 3.3) drastically reduced Pwheat's second year LAI and biomass/m^2 (Table 3.5). Height trends were similar for Pwheat during both years because those Pwheat plants that did regrow were perfectly healthy (Tables 3.1 and 3.5). However, because many did not survive into the second year, the Pwheat plants grew much more sparsely in year two than in year one, thus causing the low LAI and biomass/m^2 values, relative to those in year one.

Forage Quality

We found that, for most measurement dates in both years, IWG produced higher quality (lower NDF and ADF, higher IVDMD) forage than Pwheat (Tables 3.7, 3.8, 3.9, and 3.10). The major exceptions to this were the whole-plant samples from the early and middle measurement dates in year one (Table 3.7) and the whole-plant samples from the middle measurement dates in year two (Table 3.9). On the early date IWG had higher NDF and ADF values and a lower IVDMD value than Pwheat and at the middle dates in both years Pwheat and IWG had equal NDF and ADF values. Other than these exceptions, IWG forage quality was always higher than that of Pwheat (Tables 3.7, 3.8, 3.9, and 3.10).

In year two, the forage quality of spring-planted Pwheat followed a pattern similar to the LAI of spring-planted Pwheat (Table 3.9). Spring-planted Pwheat started off with relatively high-quality forage; it was generally equal to (early forage cuttings, IVDMD of early and middle whole-plant samples) or even surpassing (NDF and ADF of early and middle whole-plant samples) IWG in quality at the same measurement times. However, by the end of the season, senescence decreased the quality of spring-planted Pwheat forage until it was the same as that of fall-planted Pwheat for every metric except NDF, which was still worse than the NDF of IWG at that date (Table 3.9).

For all treatments, forage quality generally decreased, often markedly, throughout the year (Tables 3.7 and 3.9). This is a common pattern with forages. Edmisten et al. (1998) found a similar pattern in a study of forage quality of four small-grain species over the course of a growing season. They noted that IVDMD generally decreased and that NDF and ADF generally increased (i.e., forage quality decreased) for all four species between vegetative stage (equivalent to our early measurement time) and milk stage (between our middle and late measurement times).

In general, the forage quality values we found were about the same as, or slightly worse than, those of the wheat tested by Edmisten et al. (1998), which they describe as an "excellent" and "nutritious" forage late in the season (i.e., at soft dough stage). Edmisten et al. reported the following values for wheat: 24.5-67.0% for NDF, 20.1-76.0% for ADF, and 52.6-80.4% for IVDMD. Our NDF values were slightly higher (Pwheat=46.39-80.60%, IWG=46.27-73.83%), but our ADF values (Pwheat=21.36-49.99%, IWG=21.06-43.22%; Tables 3.7 and 3.9) were lower than many of Edmisten's. However, our IVDMD values (Pwheat=26.68-66.60%, IWG=37.81-65.30%; Tables 3.7 and 3.9) were also lower than Edmisten's.

Our forage was generally relatively low in quality when compared with perennial cool-season forage grasses. For example, Burner and Belesky found IVDMD values with a mean of 65.5% in their unshaded control plots of orchardgrass (*Dactylis glomerata* L.), with traces of tall fescue (*Festuca arundinacea* Schreb.), in an experiment conducted in Booneville, AR in 2000-2002 (Burner and Belesky, 2004). This is higher, and thus higher quality, than most of the IVDMD values we found (Pwheat=26.68-66.60%, IWG=37.81-65.30%; Tables 3.7 and 3.9). In addition, Scarbrough et al. (2004) found NDF values of 64.0% and ADF values of 32.6% in their orchardgrass control sample, which was a second cutting harvested on June 20, 2001 in Fayetteville, AR. Both of these values fall within the ranges of NDF and ADF values we found. However, about half of our NDF values

(Pwheat=46.39-80.60%, IWG=46.27-73.83%) were higher (and thus of lower quality) and most of our ADF values (Pwheat=21.36-49.99%, IWG=21.06-43.22%) were higher (and thus of lower quality) than those reported by Scarbrough. Our first-year NDF values (Pwheat=46.39-79.46%, IWG=46.27-71.04%; Table 3.7) were comparable to or better than Scarbrough's orchardgrass, but our second-year values (Pwheat=53.84-80.60%, IWG=50.19-73.83%; Table 3.9) were almost all higher (i.e., of lower quality).

Productivity/Yield

Grain Yield

In both years one and two, Pwheat grain yields were substantially higher than IWG grain yields (Tables 3.11, 3.12, 3.13 and 3.14; Figure 3.11). Additionally, in year two, spring-planted Pwheat yielded as much grain as fall-planted Pwheat (Table 3.14). The difference in grain yield between Pwheat and IWG is due to the difference in genetic background between the two species. Specifically, Pwheat was bred from an annual grain crop and a perennial forage crop, while this IWG was selectively bred from a perennial forage crop for increased seed mass. Perhaps with investments in plant breeding, IWG could produce as much grain as Pwheat but, as our harvest results show, this is not yet the case.

Unsurprisingly, cumulative grain yields from both years are also higher for fall-planted Pwheat than for IWG. Because spring-planted Pwheat only produced a grain crop in the second year, its cumulative yield is about the same as that of IWG (Tables 3.3 and 3.4; Figure 3.11).

The same line of Pwheat (P-15) used in this experiment was also used in a number of other field trials in various locations. Our Pwheat yields averaged about 235 g/m^2 (310-320 g/m^2 in year one, 140-170 g/m^2 in year two). Murphy et al. (2009), who first developed this line, reported yields of about 160 g/m^2 in eastern Washington State, which were lower than the yields we found. Jaikumar et al. (2012) reported similar yields to Murphy et al. from a site near our trial at the W.K. Kellogg Biological Station (140 g/m^2 for first- and second-year plants). Hayes et al., (2012) found yields for line P-15 to be around 180 g/m^2 in New South Wales, Australia. Overall, our grain yield was higher than the previously reported values for Pwheat germplasm, but lower than for annual wheat grown at a site adjacent to our trial (≈300 g/m^2; S. Snapp personal communication, 2012).

Many of the studies on Pwheat line P-15 also included one or more varieties of annual wheat as a comparison. Murphy et al. (2009) reported annual wheat yields of about 380-420 g/m^2, or about 2.4-2.6 times their yields for Pwheat line P-15. Jaikumar et al. (2012) reported annual wheat yields of 270 g/m^2, or about 1.9 times their yields for Pwheat line P-15. Clearly, Pwheat cannot compete with annual wheat when it comes to simple amount of grain yield. However, other characteristics, such as its potential for regrowth, and for dual-purpose use may still make Pwheat a viable cropping option. For example, Bell et al. (2008) determined that, based on their modeling, Pwheat may be a viable dual-purpose cropping option in dryland, mixed crop/livestock systems in Australia, especially if it can thrive with fewer fertilizer and herbicide inputs than annual wheat.

Little research has been done on grain yields for IWG, but Hopkins et al. (2003) did a study in the southern Great Plains on seed production of grazed pubescent wheatgrass (*Thinopyrum intermedium* subsp. *barbulatum* (Shur) Barkw. & D.R. Dewey), which is very closely related to IWG. However, this wheatgrass had not been selected for increased grain production, as that in our study had, and the yields were very low in comparison to ours (0.3-15.7 g/m^2 under no grazing, 0.1-10.9 g/m^2 under limited grazing, and 0.1-8.2 g/m^2 under extended grazing, compared to our yields of 86.9-140.0 g/m^2 for uncut IWG and 74.6-112.7 g/m^2 for cut IWG; Tables 3.11 and 3.13).

Varieties of IWG that had not been bred for high grain yield have been reported to produce 6-45g/m^2 of seed each year in Colorado and North Dakota, in commercial seed-production fields that had been maintained for 5-25 years (Soil Conservation Service, 1985). This is much lower than our yields from the improved IWG varieties, yet still much higher than the yields reported by Hopkins et al. (2003).

The IWG plants which were first selected for grain-production breeding at The Rodale Institute yielded anywhere from about 2 to 60 g/m^2 of seed (Wagoner and Schauer, 1989). This is lower than our yields, which is what we would expect from the distant parents of our plants. The parent plants for our IWG seed have been reported to produce up to 41-320 g/100 spikes of grain at TLI, although their median yields were much lower (6 g/100 spikes) (Cox et al., 2010). Our per-spike IWG yields were generally slightly higher than that in year two, the only year for which such data are available. Our yield for each plot varied from about 5 to 12 g/100 spikes. On average, our cut IWG plants yielded nearly 8 g/100 spikes, while the average yield for uncut IWG plants was over 10 g/100 spikes.

Finally, a study in a field near ours found IWG grain yields of about 11-16 g/m^2 in the first year of growth and about 140-170 g/m^2 in the second year (Culman and Snapp, unpublished data, 2012). Our IWG produced much more grain than theirs in the first year (110-140 g/m^2; Table 3.11), but much less in the second year (75-90 g/m^2; Table 3.13). This discrepancy is probably due, at least in part, to varying weather conditions. In particular, 2011 (their year two and our year one), was an exceptionally good year for wheat in our area, while 2012 (our year two) had a very hot, dry summer (Table 2.1).

Spring Forage

Pwheat produced more spring forage than IWG in year one (Tables 3.11 and 3.12). However, in year two, both IWG and spring-planted Pwheat produced more spring forage than fall-planted Pwheat (Tables 3.13 and 3.14; Figure 3.8). This was probably due to degree of perenniality and characteristics associated with this (i.e., it is due to the fact that IWG starts growing very slowly in year one and to the fact that fall-planted Pwheat regrew poorly after grain harvest in year one).

Cumulatively, over two years of growth, IWG, fall-planted Pwheat, and spring-planted Pwheat all yielded about the same amount of spring forage (Figure 3.3). This is one of the very few cases when, in one year, spring-planted Pwheat can produce about as much the other treatments do in two years.

Little previous work has been done to study spring forage harvest and its effect on grain production in Pwheat and these improved varieties of IWG. However, many studies have been done on forage harvest in annual winter wheat. Redmon et al. (1994) conducted an excellent review of winter wheat forage harvest, from which they concluded that taller wheat cultivars are much better adapted to grazing than newer semidwarf cultivars because grain yield of semidwarf varieties tends to be extremely sensitive to grazing. This indicates that Pwheat, which is indeed fairly tall, might be a good choice for forage harvest. Redmon et al. also mention that grazing before jointing occurs may, under good growing conditions, increase grain harvest by decreasing lodging. We did not observe lodging to be a problem for Pwheat, but it was often a slight problem for IWG. Perhaps this can be alleviated through forage harvest.

Stover

In year one, all treatments (cut IWG, uncut IWG, cut Pwheat, uncut Pwheat) produced about the same amount of stover (Tables 3.11 and 3.12). In year two, IWG produced the most stover, followed by spring-planted Pwheat, and then fall-planted Pwheat (Tables 3.13 and 3.14). This is mainly due to poor Pwheat regrowth in year one, and to vigorous year two IWG growth, in spite of the drought (Table 2.1).

When stover produced over both years is totaled (Tables 3.11 and 3.13), we can see that, overall, both IWG treatments produced the most stover, followed by fall-planted, uncut Pwheat, then fall-planted, cut Pwheat, and, finally, spring-planted Pwheat (Figure 3.10). High IWG cumulative yields are mainly due to their high yield in the second year. The difference between cut and uncut pwheat is likely due to poor post-sexual cycle regrowth of cut Pwheat in year one. However, it is notable that this is one of very few measurements, besides first year regrowth, for which there is a difference between cut and uncut Pwheat. The low cumulative yield of spring-planted Pwheat is due to the fact that stover was only harvested from those plots in year two, whereas all other plots were harvested for stover in both years one and two.

From a study in an adjacent field, Jaikumar et al. (2012) reported stover yields from Pwheat line P-15 around 440 g/m^2, averaged over two years. This is a bit lower than the stover yields we found (≈480-610 g/m^2 averaged over two years; Tables 3.11 and 3.13).

Not much research has been done on the improved varieties of IWG, which we used, as a forage crop, nor has much research been done on any sort of IWG in the Great Lakes region. However, other cool-season forage grasses that are comparable to IWG have been studied in this area. For example, Hudson et al. (2010) reported about 50-300 g/m^2 of dry matter offered from pastures consisting of mixtures of cool-season grasses and legumes (including perennial ryegrass (*Lolium perenne* L.), quackgrass [*Agropyron repens* (L.) Beauv.], alfalfa (*Medicago sativa* L.), white clover (*Trifolium repens* L.), red clover (*Trifolium pretense* L.), orchardgrass (*Dactylis glomerata* L.), and tall fescue (*Festuca arundinacea* Schreb.)) at KBS in southwest Michigan at any given time over the growing season. This is not directly comparable to our results, since we harvested at discrete time points and Hudson et al. intended their pastures for grazing. However, it is encouraging to note that our IWG generally had whole-plant weights (year one: 80-810 g/m^2, year two: 1150-2450 g/m^2; Tables 3.1 and 3.5) and stover yields (500-1000 g/m^2; Tables 3.11 and 3.13) that were multiple times higher than the dry matter availability of pasture grasses on any given day, indicating that it is not outside the realm of possibility for IWG to be integrated as a useful part of this system.

A study was done in a field close to ours from 2010 to 2011, which found IWG to produce about 390-500 g/m^2 of biomass at harvest in the first year of growth and about 1200-1700 g/m^2 of biomass at harvest in the second year of growth (Culman and Snapp, Unpublished data, 2012). As with grain yield, our stover yields were lower than those of Culman and Snapp in the first year of growth (500-760 g/m^2), but higher than those of Culman and Snapp in the second year of growth (910-960 g/m^2). This is likely due to the excellent weather we experienced in 2011 and the poor weather in 2012 (Table 2.1), as discussed in the section on grain yield, above.

Yield Summary

Overall, we found that Pwheat produced more grain than IWG, while IWG tended to produce more stover than Pwheat, especially after the first year (Figures 3.10 and 3.11). Both species produce about the same amount of spring forage (Figure 3.8). IWG forage, especially stover, tends to be of higher quality than Pwheat forage (Tables 3.7, 3.8, and 3.9, and 3.10), but all of our forage tends to be comparable or lower in quality (Tables 3.7 and 3.9) than reported values for comparable species.

Our grain and stover yields were generally higher than other reported yields for similar species, but our Pwheat regrowth was similar to what has been previously reported for line P-15. Our higher yields may have been at least partially due to excellent weather conditions from fall 2010 through summer 2011 (Table 2.1).

Based on data from the literature, our IWG produced more seed than unimproved forage lines, but neither our IWG nor our Pwheat produced as much grain as annual wheat can. However, the benefits of perenniality and strong potential for dual-purpose use may render either or both of these species viable cropping options, despite lower grain yields (Bell et al., 2008).

Discussion Summary

Overall, we have seen that Pwheat grew faster than IWG early in the first year, while IWG maintained its growth longer than Pwheat. IWG has greater regrowth potential and generally produced more, higher-quality forage than Pwheat. However, Pwheat generally produced more grain, and this grain is more similar to a current crop, thus making it more recognizable to consumers and probably more easily marketed, than IWG. Therefore we can see that, although these crops may appear similar at first, they are actually quite different, and that evaluating them requires careful consideration of many potential tradeoffs.

In general, our grain yields were high compared with those reported in the literature for similar species. However, none of our yields equaled those of annual wheat grown under similar conditions. Our stover yields were comparable to stover yields of similar species, as reported in the literature. However, spring forage yield was extremely low as compared to stover yield.

Revisting our hypotheses, we see that our data support some, but not others. We were correct that IWG would produce the most forage and Pwheat would produce the most grain. However, there was no difference between cut and uncut cumulative grain production in Pwheat, or between cut and uncut cumulative forage production in IWG, as we expected. In addition, IWG exhibited excellent post-sexual cycle regrowth, as we expected. However, a spring planting date did not improve regrowth rates of Pwheat at the end of two years, as we thought it would.

Conclusions

Overall, It is impossible to say which cropping or management option examined in this study is the best. There are tradeoffs inherent in any of the choices presented, so decisions must be made on a case-by-case basis, depending on the goals of individual farms. For example, if grain yield is a primary goal of a farm and forage production is secondary, especially if only two years of production are required, Pwheat may be a very good option. However, if high forage production, especially in the second year of growth, maximizing forage quality, and multiple years of vigorous regrowth are more important than grain production or early forage production, IWG would be a better option. In addition, early forage harvest is best if quality is most important, but later forage harvest can provide a larger yield, although of lower quality. Planting time is the only studied characteristic where one option fairly consistently outperformed the other (in this case fall-planted generally outperformed spring-planted). However, even in this case, planting Pwheat in the spring may be beneficial for certain cropping systems. For example, if thick second-year growth and moderate to high second-year forage and grain yields are desired, and nonexistent first year yields are acceptable, this is in excellent cropping option.

It is encouraging that, in most cases, spring forage harvest does not affect later grain and forage production, especially for IWG. This implies that both crops could be used for dual-use production, which would allow these crops to fit into a variety of cropping systems. In addition, dual-use can be extremely beneficial, as it lends flexibility to a system. For example, if weather conditions are not favorable for grain production in one year, one can simply harvest all plants early as a forage crop instead. This type of flexibility is particularly important and practical for small, diversified famers, and the need for flexibility will only increase as weather variability due to climate change increases.

We do not expect these perennial grain crops to replace annual grains currently in production, even on a small-scale, anytime soon. The greatest barriers to large-scale, mainstream production of perennial grains include low grain yields (especially for IWG), lack of consistant regrowth in Pwheat, and lack of an appropriate market currently in place (especially for IWG). However, these novel crops may be appropriate for niche uses, especially on small, diversified farms, in the near future. Farmers that we interviewed about their opinions and beliefs regarding perennial grains had diverse and unique ideas for ways such crops might be incorporated into their farms (Schmitt-Olabisi et al., Unpublished interview data, 2012). For example, one farmer talked at length about how he might use Pwheat or IWG as buffer strips for his organic fields. These areas are difficult for him to till or plant, since organic regulations require him to clean his equipment after using it in the buffer areas, in order to prevent contamination of the organic fields. If he could plant a crop that would require less frequent management, such as a perennial grain crop, it would save many hours of labor that would otherwise be spent cleaning machinery. However, in order for a perennial grain to be used in this manner, it would have to regrow consistently for a number of years. In addition, the harvest equipment would have to be relatively easy to clean, or else the number of hours spent cleaning harvest equipment may render this use impractical.

Timing of harvest is also important when considering how these crops might fit into farming systems. For example, farmers stated in interviews (Schmitt-Olabisi et al., Unpublished interview data, 2012) that they would find perennial grains desirable if they could provide a forage crop earlier or later in the season than the forages they currently use. Extending the season during which forage is available for their animals to graze is critical. In addition, the timing of grain harvest is also important to consider. Pwheat generally ripens a few weeks after annual wheat and IWG tends to ripen a few weeks after Pwheat. If mid-June to mid-July, when annual wheat generally ripens, is a particularly busy time for a particular farmer, he might choose to grow a crop, such as Pwheat or IWG, that ripens later, in order to spread out the work that must be done over time.

Clearly, more consideration is needed regarding exactly how and when these crops may profitably fit into existing farming systems. Additional farmer interviews and focus groups, as well as on-farm trials, can help shed light on this question. However, additional selective plant breeding is also needed, to maximize desirable plant traits (e.g., high grain yield, high forage yield, high regrowth rates), which will increase the number of situations in which these plants will be able to contribute to whole-farm productivity and profitability.

Table 3.1: Analysis of variance (ANOVA) results from four systems: two species, IWG and Pwheat, planted in the fall and subjected to two cutting regimes (uncut or cut for spring forage). First-year growth measurements are presented, including height, LAI, and biomass (aboveground dry weight) at early, middle, and late growth periods and emergence from 2011. Least squares means presented with ANOVA F-Values. Field experiment conducted in southwest Michigan at the W.K. Kellogg Biological Station (KBS). Numbers in the same column followed by different letters, are significantly different at the alpha=0.05 level.

		Early (Pre-Stem Elongation)			Middle (40% Heading)			Late (Harvest)		
System	**Emergence Rate (seedlings/m²)**	**Height (cm)**	**Leaf Area Index (LAI)**	**Biomass (g/m²)**	**Height (cm)**	**Leaf Area Index (LAI)**	**Biomass (g/m²)**	**Height (cm)**	**Leaf Area Index (LAI)**	**Biomass (g/m²)**
Uncut IWG	151.50c	11.2b	0.16b	77.40a	68.6c	1.96b	462.02b	108.6a	1.93a	814.4b
Uncut Pwheat	228.50a	20.1a	0.95a	70.90a	95.2a	2.72a	929.56a	101.5b	2.05a	1199.4a
Cut IWG	188.50b	12.7b	0.18b	99.82a	61.9d	1.67c	436.28b	107.8a	1.88a	657.9b
Cut Pwheat	227.50a	20.8a	0.96a	103.64a	85.9b	2.75a	761.72ab	101.6b	1.80a	1161.7a
ANOVA Results (F-Values)										
System	17.01^	33.53^	53.11^	1.71	79.14^	69.91^	4.09*	5.05*	1.09	12.76**

*=treatment effects are significant at $p \leq 0.05$
**= treatment effects are significant at $p \leq 0.01$
***= treatment effects are significant at $p \leq 0.001$
^= treatment effects are significant at $p \leq 0.0001$

Table 3.2: Results of planned contrasts between four systems: two species, IWG and Pwheat, planted in the fall and subjected to two cutting regimes (uncut or cut for spring forage). First-year growth measurements are presented, including height, LAI, and biomass (aboveground dry weight) at early, middle, and late growth periods and emergence from 2011. Field experiment conducted in southwest Michigan at the W.K. Kellogg Biological Station (KBS). P-values are presented for alpha=0.05.

		Early (Pre-Stem Elongation)			Middle (40% Heading)			Late (Harvest)		
Contrast	Emergence Rate (seedlings/m^2)	Height (cm)	Leaf Area Index (LAI)	Biomass (g/m^2)	Height (cm)	Leaf Area Index (LAI)	Biomass (g/m^2)	Height (cm)	Leaf Area Index (LAI)	Biomass (g/m^2)
IWG vs Pwheat	0.0003	<0.0001	<0.0001	0.9162	<0.0001	<0.0001	0.0085	0.0037	0.8972	0.0002
Cut Pwheat vs Uncut Pwheat	0.9527	0.5633	0.9568	0.0945	0.0042	0.7323	0.3418	0.9681	0.1293	0.7275
Cut IWG vs Uncut IWG	0.0435	0.2458	0.7247	0.2327	0.0228	0.0113	0.8811	0.7420	0.7666	0.1699

Table 3.3: Analysis of variance (ANOVA) results from five systems: two species, IWG and Pwheat, planted in the fall and subjected to two cutting regimes (uncut or cut for spring forage), and Pwheat planted in the spring and cut for spring forage in year two as a comparison. First- and second-year regrowth measurements and two-year cumulative yield measurements are presented, including regrowth in 2011 and 2012, and cumulative total forage (spring forage plus stover) and cumulative grain yield from 2011 and 2012. Least squares means presented with ANOVA F-Values. Field experiment conducted in southwest Michigan at the W.K. Kellogg Biological Station (KBS). Numbers in the same column followed by different letters, are significantly different at the alpha=0.05 level.

System	% Regrowth (Year 1)	% Regrowth (Year 2)	Cumulative % Regrowth Over Two Years	Cumulative Total Forage Yield (g/m^2)	Cumulative Grain Yield (g/m^2)
Uncut IWG	100.00a	100.00a	100.00a	1675.64a	226.97b
Uncut Pwheat	85.00a	50.90b	41.45b	1221.76b	488.12a
Cut IWG	100.00a	100.00a	100.00a	1515.25a	187.22b
Cut Pwheat	50.00b	51.01b	25.21c	1021.08b	466.66a
Spring-Planted, Cut Pwheat	92.00a	34.81c	33.28bc	530.32c	161.76b
ANOVA Results (F-Values)					
System	9.98***	47.32^	81.46^	42.18^	48.49^

*=treatment effects are significant at p≤0.05
**= treatment effects are significant at p≤0.01
***= treatment effects are significant at p≤0.001
^= treatment effects are significant at p≤0.0001

Table 3.4: Results of planned contrasts between five systems: two species, IWG and Pwheat, planted in the fall and subjected to two cutting regimes (uncut or cut for spring forage), and Pwheat planted in the spring and cut for spring forage in year two as a comparison. First- and second-year yield measurements are presented, including regrowth in 2011 and 2012, and cumulative total forage (spring forage plus stover) and cumulative grain yield from 2011 and 2012. Field experiment conducted in southwest Michigan at the W.K. Kellogg Biological Station (KBS). P-values are presented for alpha=0.05.

Contrast	Year 1 Regrowth (% Survival)	Year 2 Regrowth (% Survival)	Cumulative Regrowth (% Survival After Two Years)	Cumulative Total Forage Yield (g/m^2)	Cumulative Grain Yield (g/m^2)
Fall IWG vs Fall Pwheat	0.0003	<0.0001	<0.0001	<0.0001	<0.0001
Cut, Fall Pwheat vs Uncut, Fall Pwheat	0.0024	0.9867	0.0161	0.0739	0.5251
Spring, Cut Pwheat vs Fall, Cut Pwheat	0.0004	0.0208	0.1727	0.0002	<0.0001
Cut IWG vs Uncut IWG	1.0000	1.0000	1.0000	0.1443	0.2480

Table 3.5: Analysis of variance (ANOVA) results from five systems: two species, IWG and Pwheat, planted in the fall and subjected to two cutting regimes (uncut or cut for spring forage), and Pwheat planted in the spring and cut for spring forage in year two as a comparison. Second-year growth measurements are presented, including height, LAI, and biomass (aboveground dry weight) at early, middle, and late growth periods from 2012. Least squares means presented with ANOVA F-Values. Field experiment conducted in southwest Michigan at the W.K. Kellogg Biological Station (KBS). Numbers in the same column followed by different letters, are significantly different at the alpha=0.05 level.

	Early (Pre-Stem Elongation)			**Middle (40% Heading)**			**Late (Harvest)**		
System	**Height (cm)**	**Leaf Area Index (LAI)**	**Biomass (g/m^2)**	**Height (cm)**	**Leaf Area Index (LAI)**	**Biomass (g/m^2)**	**Height (cm)**	**Leaf Area Index (LAI)**	**Biomass (g/m^2)**
Uncut IWG	24.1c	4.03a	1288.78a	92.0a	6.10a	2453.82a	126.8a	4.18a	1145.78a
Uncut Pwheat	30.8a	1.33b	422.00b	87.0a	1.95bc	948.62b	99.7b	0.96c	789.36b
Cut IWG	25.6bc	4.29a	1263.46a	87.0a	5.88a	1929.68a	127.6a	4.35a	1196.32a
Cut Pwheat	28.6ab	1.27b	356.92b	82.7b	1.38c	830.38b	95.8b	0.80c	550.05b
Spring-Planted, Cut Pwheat	29.0a	3.73a	596.47b	89.3a	2.97b	1098.57b	98.9b	1.67b	780.00b
ANOVA Results (F-Values)									
System	7.50**	15.88^	21.24^	1.34	25.01^	8.83**	23.65^	33.24^	11.70***

*=treatment effects are significant at p≤0.05
**= treatment effects are significant at p≤0.01
***= treatment effects are significant at p≤0.001
^= treatment effects are significant at p≤0.0001

Table 3.6: Results of planned contrasts between five systems: two species, IWG and Pwheat, planted in the fall and subjected to two cutting regimes (uncut or cut for spring forage), and Pwheat planted in the spring and cut for spring forage in year two as a comparison. Second-year growth measurements are presented, including height, LAI, and biomass (aboveground dry weight) at early, middle, and late growth periods and emergence from 2012. Field experiment conducted in southwest Michigan at the W.K. Kellogg Biological Station (KBS). P-values are presented for alpha=0.05.

	Early (Pre-Stem Elongation)			Middle (40% Heading)			Late (Harvest)		
Contrast	**Height (cm)**	**Leaf Area Index (LAI)**	**Biomass (g/m^2)**	**Height (cm)**	**Leaf Area Index (LAI)**	**Biomass (g/m^2)**	**Height (cm)**	**Leaf Area Index (LAI)**	**Biomass (g/m^2)**
Fall IWG vs Fall Pwheat	0.0003	<0.0001	<0.0001	0.1463	<0.0001	0.0001	<0.0001	<0.0001	<0.0001
Cut, Fall Pwheat vs Uncut, Fall Pwheat	0.1459	0.9127	0.6514	0.3256	0.3784	0.4445	0.4217	0.3616	0.0544
Spring, Cut Pwheat vs Fall, Cut Pwheat	0.7705	0.0003	0.0970	0.1223	0.0189	0.0555	0.4948	0.0047	0.0525
Cut IWG vs Uncut IWG	0.2829	0.6361	0.8600	0.2565	0.7364	0.2737	0.8716	0.7920	0.6626

Table 3.7: Analysis of variance (ANOVA) results from four systems: two species, IWG and Pwheat, planted in the fall and subjected to two cutting regimes (uncut or cut for spring forage). First-year forage quality measurements are presented, including whole-plant ADF, NDF, and IVDMD from early, middle, and late time periods and spring forage cutting ADF, NDF, and IVDMD from the early time period in 2011. Least squares means presented with ANOVA F-Values. Field experiment conducted in southwest Michigan at the W.K. Kellogg Biological Station (KBS). Numbers in the same column followed by different letters, are significantly different at the alpha=0.05 level.

	Early (Pre-Stem Elongation)			Middle (40% Heading)			Late (Harvest)			Early (Pre-Stem Elongation)		
	Forage Cuttings			Whole Plant			Whole Plant			Stover		
System	NDF	ADF	IVDMD	NDF	ADF	IVDMD	NDF	ADF	IVDMD	NDF	ADF	IVDMD
	----%----											
Uncut IWG	N/A	N/A	N/A	49.54 ab	23.32 ab	63.64b	63.06 a	33.10 b	53.90ab	68.53b	40.31b	42.58a
Uncut Pwheat	N/A	N/A	N/A	46.39 c	22.11 b	65.08ab	63.64 a	36.06 a	49.09c	78.92a	48.88a	29.59b
Cut IWG	46.27b	21.06b	65.30a	52.11 a	24.79 a	63.25b	64.93 a	34.18 ab	53.93a	71.04b	42.17b	40.62a
Cut Pwheat	64.43a	49.49a	32.16b	47.62 bc	21.36 b	66.60a	62.40 a	34.99 ab	51.48bc	79.46a	49.99a	28.68b
ANOVA Results (F-Values)												
System	75.02**	68.91**	49.78**	7.08**	4.85*	5.98*	1.37	2.45	18.53***	30.13^	35.72^	39.61^

*=treatment effects are significant at p≤0.05
**= treatment effects are significant at p≤0.01
***= treatment effects are significant at p≤0.001
^= treatment effects are significant at p≤0.0001

Table 3.8: Results of planned contrasts between four systems: two species, IWG and Pwheat, planted in the fall and subjected to two cutting regimes (uncut or cut for spring forage). First-year yield measurements are presented, including whole-plant ADF, NDF, and IVDMD from early, middle, and late time periods and spring forage cutting ADF, NDF, and IVDMD from the early time period in 2011. Field experiment conducted in southwest Michigan at the W.K. Kellogg Biological Station (KBS). P-values are presented for alpha=0.05.

	Early (Pre-Stem Elongation)			Middle (40% Heading)			Late (Harvest)			Early (Pre-Stem Elongation)		
	Forage Cuttings			Whole Plant			Whole Plant			Stover		
Contrast	**NDF**	**ADF**	**IVDMD**	**NDF**	**ADF**	**IVDMD**	**NDF**	**ADF**	**IVDMD**	**NDF**	**ADF**	**IVDMD**
	----%----											
IWG vs Pwheat	0.0032	0.0037	0.0059	0.0028	0.0077	0.0040	0.3172	0.0430	0.0012	<0.0001	<0.0001	<0.0001
Cut Pwheat vs Uncut Pwheat	N/A	N/A	N/A	0.3751	0.4591	0.1178	0.3646	0.3715	0.0699	0.7106	0.3587	0.5872
Cut IWG vs Uncut IWG	N/A	N/A	N/A	0.0847	0.1617	0.6678	0.1826	0.3661	0.9766	0.1113	0.1370	0.2604

Table 3.9: Analysis of variance (ANOVA) results from five systems: two species, IWG and Pwheat, planted in the fall and subjected to two cutting regimes (uncut or cut for spring forage), and Pwheat planted in the spring and cut for spring forage in year two as a comparison. Second-year forage quality measurements are presented, including whole-plant ADF, NDF, and IVDMD from early, middle, and late time periods and spring forage cutting ADF, NDF, and IVDMD from the early time period in 2012. Least squares means presented with ANOVA F-Values. Field experiment conducted in southwest Michigan at the W.K. Kellogg Biological Station (KBS). Numbers in the same column followed by different letters, are significantly different at the alpha=0.05 level.

	Early (Pre-Stem Elongation)			Middle (40% Heading)			Late (Harvest)			Early (Pre-Stem Elongation)		
	Forage Cuttings			Whole Plant			Whole Plant			Stover		
System	NDF	ADF	IVDMD	NDF	ADF	IVDMD	NDF	ADF	IVDMD	NDF	ADF	IVDMD
	----%----											
Uncut IWG	N/A	N/A	N/A	66.13bc	36.94b	51.67a	70.52a	41.03a	43.92a	73.83c	43.22b	37.81a
Uncut Pwheat	N/A	N/A	N/A	70.18ab	42.11a	39.33b	69.91a	41.47a	38.62b	79.52ab	48.33a	30.98b
Cut IWG	50.19b	25.90b	64.04a	65.33c	36.35bc	51.54a	70.95a	40.66a	44.78a	73.04c	41.60b	38.71a
Cut Pwheat	65.80a	34.96a	50.96b	71.12a	43.28a	37.37b	68.42a	41.03a	43.06a	80.60a	49.54a	30.56b
Spring-Planted, Cut Pwheat	53.84b	25.72b	63.95a	63.28d	33.09c	48.69a	63.95b	35.63b	45.50a	79.28b	48.09a	30.86b
ANOVA Results (F-Values)												
System	28.75***	14.52**	22.06***	9.69***	13.24***	18.86^	10.60***	9.14***	5.53**	100.77^	38.25^	62.36^

*=treatment effects are significant at p≤0.05
**= treatment effects are significant at p≤0.01
***= treatment effects are significant at p≤0.001
^= treatment effects are significant at p≤0.0001

Table 3.10: Results of planned contrasts between five systems: two species, IWG and Pwheat, planted in the fall and subjected to two cutting regimes (uncut or cut for spring forage), and Pwheat planted in the spring and cut for spring forage in year two as a comparison. Second-year yield measurements are presented, including whole-plant ADF, NDF, and IVDMD from early, middle, and late time periods and spring forage cutting ADF, NDF, and IVDMD from the early time period in 2012. Field experiment conducted in southwest Michigan at the W.K. Kellogg Biological Station (KBS). P-values are presented for alpha=0.05.

	Early (Pre-Stem Elongation)			Middle (40% Heading)			Late (Harvest)			Early (Pre-Stem Elongation)		
	Forage Cuttings			Whole Plant			Whole Plant			Stover		
Contrast	**NDF**	**ADF**	**IVDMD**	**NDF**	**ADF**	**IVDMD**	**NDF**	**ADF**	**IVDMD**	**NDF**	**ADF**	**IVDMD**
	----%----											
Fall IWG vs Fall Pwheat	0.0002	0.0074	0.0008	0.0062	0.0003	<0.0001	0.1215	0.6519	0.0106	<0.0001	<0.0001	<0.0001
Cut, Fall Pwheat vs Uncut, Fall Pwheat	N/A	N/A	N/A	0.7443	0.5085	0.3969	0.2842	0.7260	0.0192	0.4890	0.1615	0.5795
Spring, Cut Pwheat vs Fall, Cut Pwheat	0.0007	0.0010	0.0006	0.0016	<0.0001	0.0001	0.0038	0.0005	0.1458	0.0049	0.0823	0.6776
Cut IWG vs Uncut IWG	N/A	N/A	N/A	0.4631	0.7366	0.9547	0.7539	0.7710	0.6131	0.6147	0.0672	0.2498

Table 3.11: Analysis of variance (ANOVA) results from four systems: two species, IWG and Pwheat, planted in the fall and subjected to two cutting regimes (uncut or cut for spring forage). First-year yield measurements are presented, including spring forage, stover, total harvestable forage (spring forage plus stover), and grain yield from 2011. Least squares means presented with ANOVA F-Values. Field experiment conducted in southwest Michigan at the W.K. Kellogg Biological Station (KBS). Numbers in the same column followed by different letters are significantly different at the alpha=0.05 level.

System	Spring Forage	Stover	Total Harvestable Forage	Grain Yield
	----g m^{-2}----			
Uncut IWG	N/A	760.93a	760.93a	140.04b
Uncut Pwheat	N/A	764.88a	764.88a	313.23a
Cut IWG	10.34b	507.24b	517.58b	112.66b
Cut Pwheat	34.77a	660.73ab	695.50ab	322.81a
ANOVA Results (F-Values)				
System	38.76**	3.20	2.89	37.70^

*=treatment effects are significant at p≤0.05
**= treatment effects are significant at p≤0.01
***= treatment effects are significant at p≤0.001
^= treatment effects are significant at p≤0.0001

Table 3.12: Results of planned contrasts between four systems: two species, IWG and Pwheat, planted in the fall and subjected to two cutting regimes (uncut or cut for spring forage). First-year yield measurements are presented, including spring forage, stover, total harvestable forage (spring forage plus stover), and grain yield from 2011. Field experiment conducted in southwest Michigan at the W.K. Kellogg Biological Station (KBS). P-values are presented for alpha=0.05.

Contrast	Spring Forage	Stover	Total Harvestable Forage	Grain Yield
	----g m^{-2}----			
IWG vs Pwheat	0.0084	0.2739	0.2148	<0.0001
Cut Pwheat vs Uncut Pwheat	N/A	0.3040	0.4898	0.7173
Cut IWG vs Uncut IWG	N/A	0.0262	0.0325	0.3133

Table 3.13: Analysis of variance (ANOVA) results from five systems: two species, IWG and Pwheat, planted in the fall and subjected to two cutting regimes (uncut or cut for spring forage), and Pwheat planted in the spring and cut for spring forage in year two as a comparison. Second-year yield measurements are presented, including spring forage, stover, total harvestable forage (spring forage plus stover), and grain yield from 2012. Least squares means presented with ANOVA F-Values. Field experiment conducted in southwest Michigan at the W.K. Kellogg Biological Station (KBS). Numbers in the same column followed by different letters, are significantly different at the alpha=0.05 level.

System	Spring Forage	Stover	Total Harvestable Forage	Grain Yield
	----g m^{-2}----			
Uncut IWG	N/A	914.72a	914.72a	86.93b
Uncut Pwheat	N/A	456.87bc	456.87bc	174.89a
Cut IWG	33.75a	963.92a	997.67a	74.56b
Cut Pwheat	23.21b	302.37c	325.58c	143.85a
Spring-Planted, Cut Pwheat	45.20a	498.90b	543.60b	161.82a
ANOVA Results (F-Values)				
System	31.87***	22.70^	20.97^	6.38**

*=treatment effects are significant at p≤0.05
**= treatment effects are significant at p≤0.01
***= treatment effects are significant at p≤0.001
^= treatment effects are significant at p≤0.0001

Table 3.14: Results of planned contrasts between five systems: two species, IWG and Pwheat, planted in the fall and subjected to two cutting regimes (uncut or cut for spring forage), and Pwheat planted in the spring and cut for spring forage in year two as a comparison. Second-year yield measurements are presented, including spring forage, stover, total harvestable forage (spring forage plus stover), and grain yield from 2012. Field experiment conducted in southwest Michigan at the W.K. Kellogg Biological Station (KBS). P-values are presented for alpha=0.05.

Contrast	Spring Forage	Stover	Total Harvestable Forage	Grain Yield
	----g m^{-2}----			
Fall IWG vs Fall Pwheat	0.0001	<0.0001	<0.0001	0.0008
Cut Fall Pwheat vs Uncut Fall Pwheat	N/A	0.1022	0.1726	0.2471
Spring, Cut Pwheat vs Fall, Cut Pwheat	0.0265	0.0354	0.0258	0.4749
Cut IWG vs Uncut IWG	N/A	0.5851	0.3785	0.6372

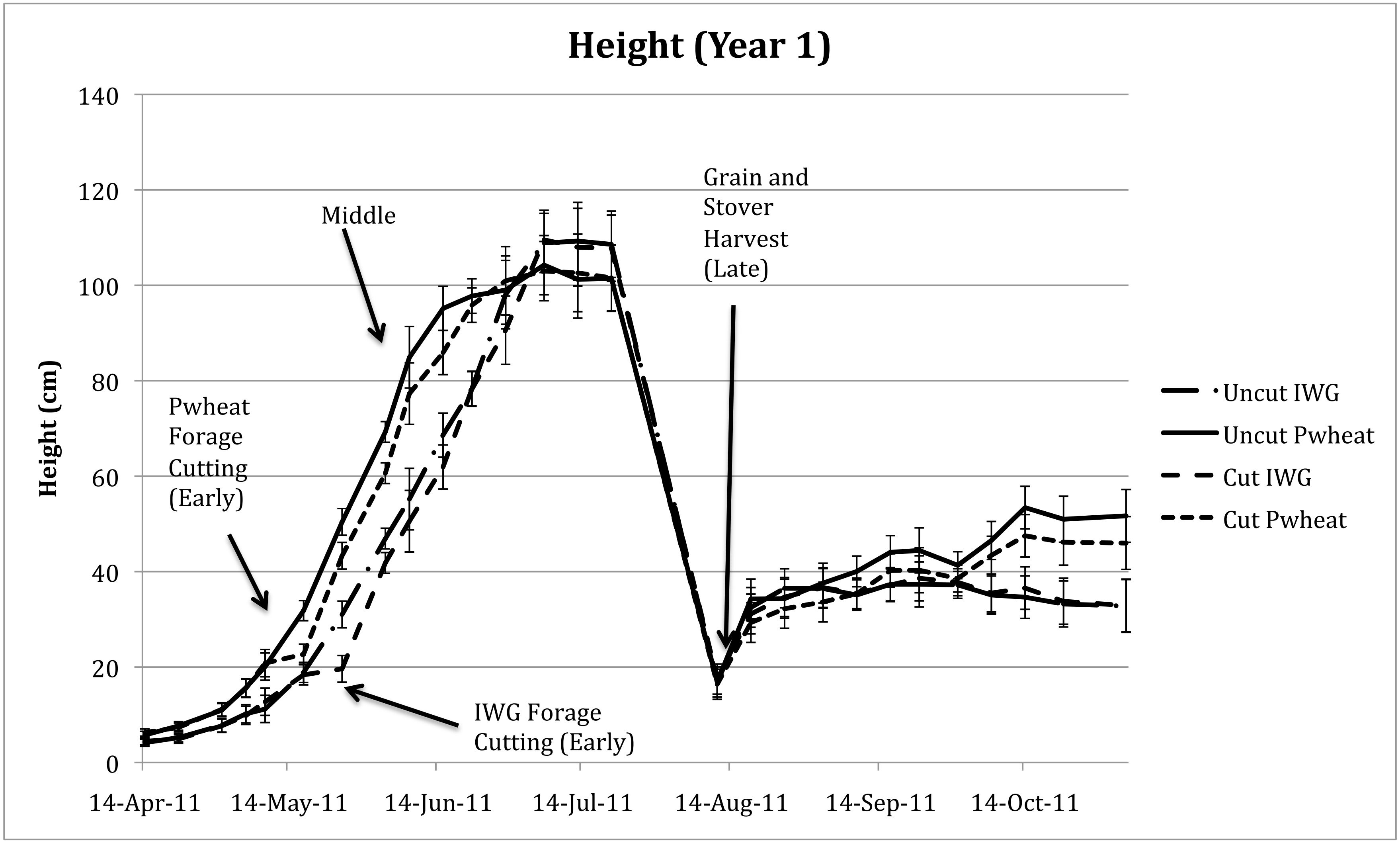


Figure 3.1: First-year (2011) height measurements taken over the course of the growing season for four systems: two species, IWG and Pwheat, planted in the fall and subjected to two cutting regimes (uncut or cut for spring forage). Field experiment conducted in southwest Michigan at the W.K. Kellogg Biological Station (KBS). Confidence intervals are at the 95% level.

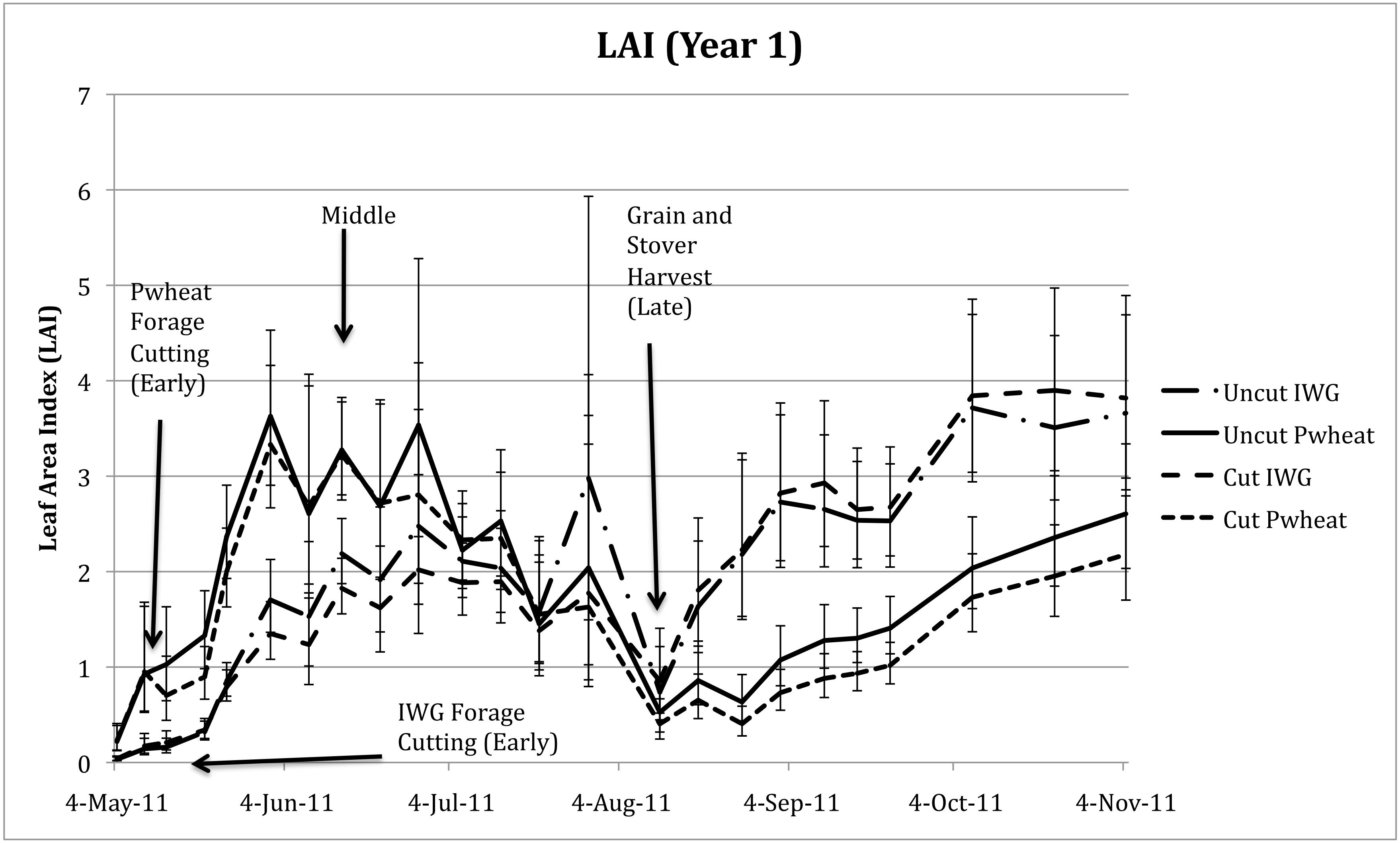


Figure 3.2: First-year (2011) leaf area index (LAI) measurements taken over the course of the growing season for four systems: two species, IWG and Pwheat, planted in the fall and subjected to two cutting regimes (uncut or cut for spring forage). Field experiment conducted in southwest Michigan at the W.K. Kellogg Biological Station (KBS). Confidence intervals are at the 95% level.

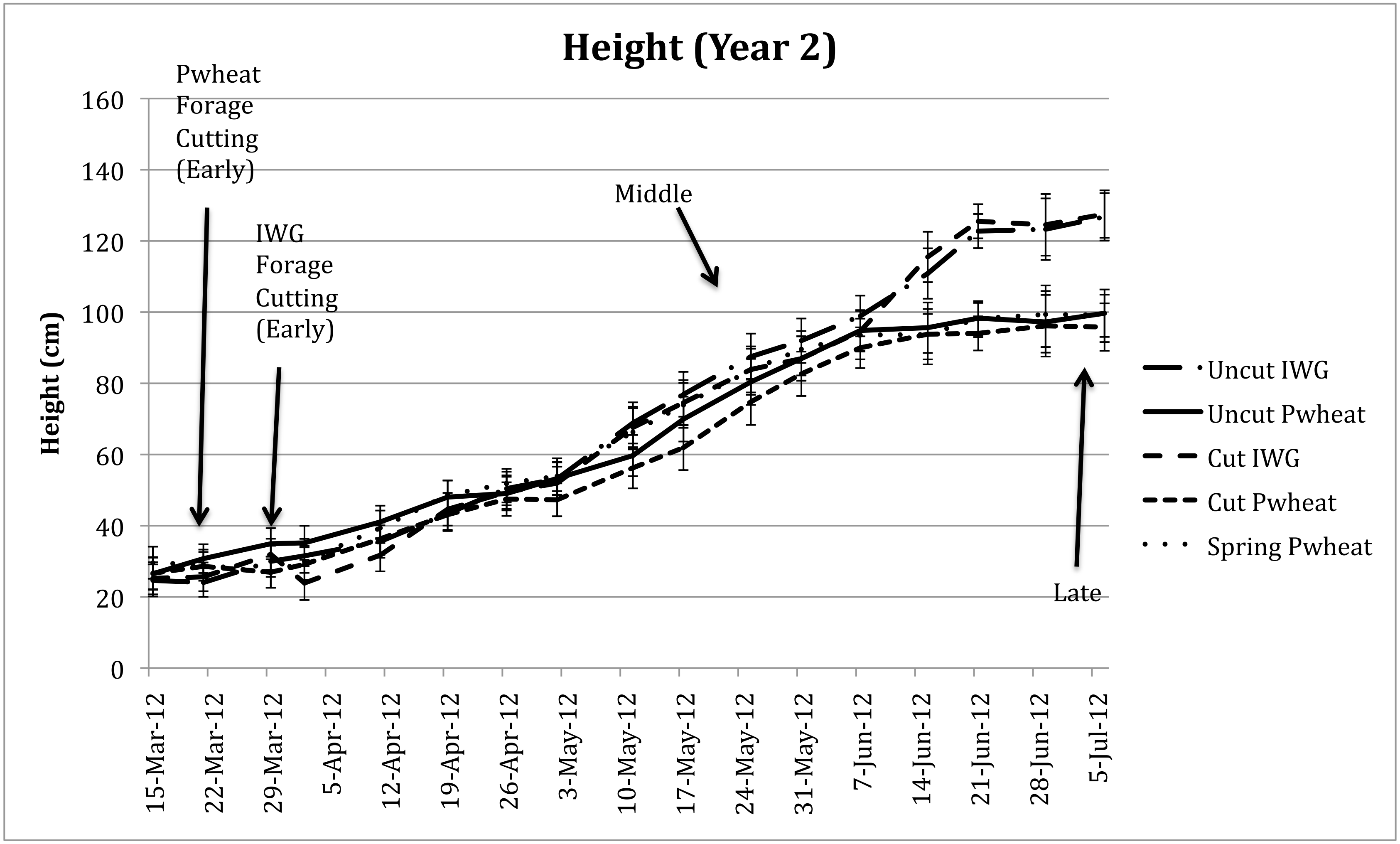


Figure 3.3: Second-year (2012) height measurements taken at intervals until the middle of the growing season for five systems: two species, IWG and Pwheat, planted in the fall and subjected to two cutting regimes (uncut or cut for spring forage), and Pwheat planted in the spring and cut for spring forage in year two as a comparison. Field experiment conducted in southwest Michigan at the W.K. Kellogg Biological Station (KBS). Confidence intervals are at the 95% level.

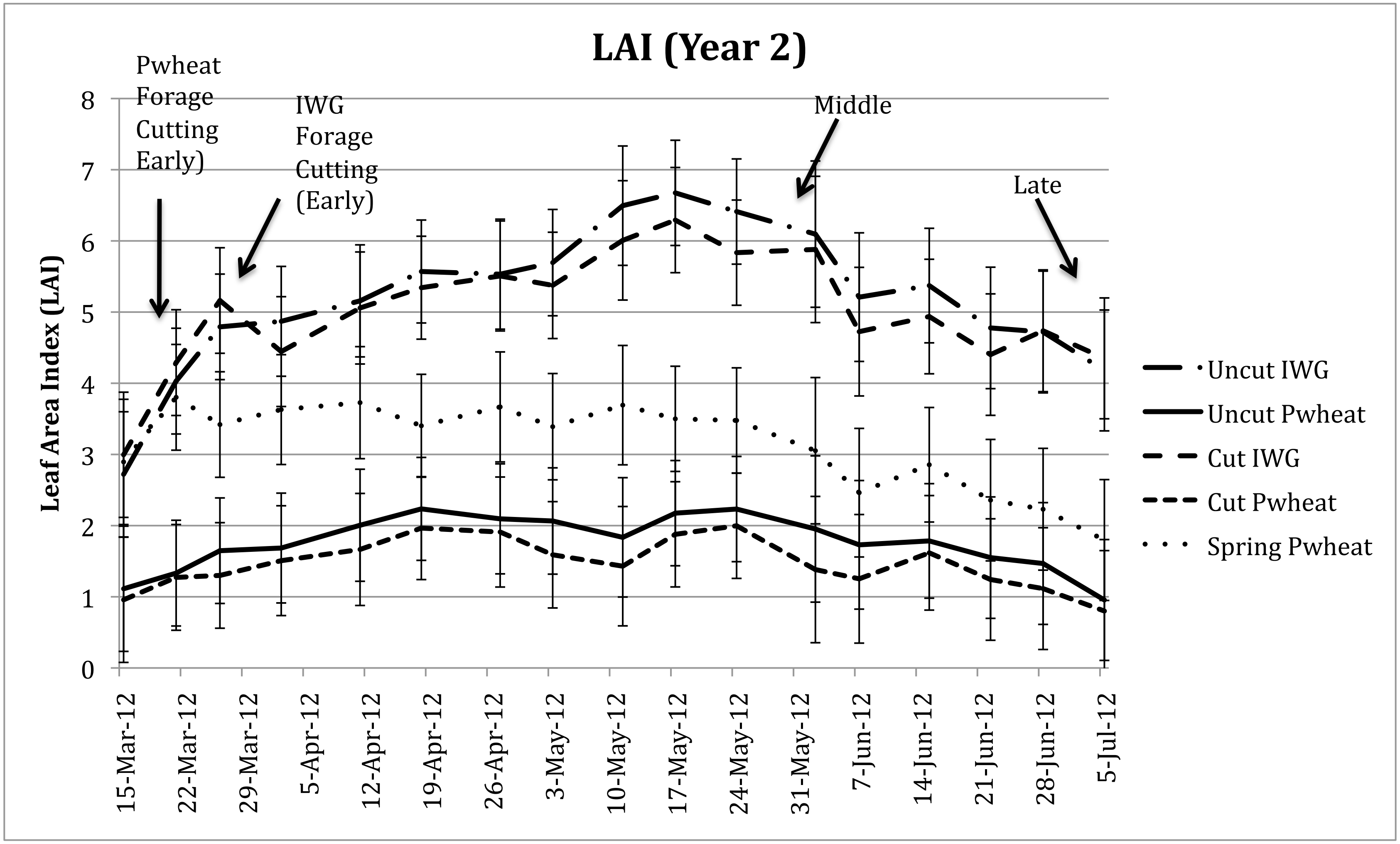


Figure 3.4: Second-year (2012) leaf area index (LAI) measurements taken at intervals until the middle of the growing season for five systems: two species, IWG and Pwheat, planted in the fall and subjected to two cutting regimes (uncut or cut for spring forage), and Pwheat planted in the spring and cut for spring forage in year two as a comparison. Field experiment conducted in southwest Michigan at the W.K. Kellogg Biological Station (KBS). Confidence intervals are at the 95% level.

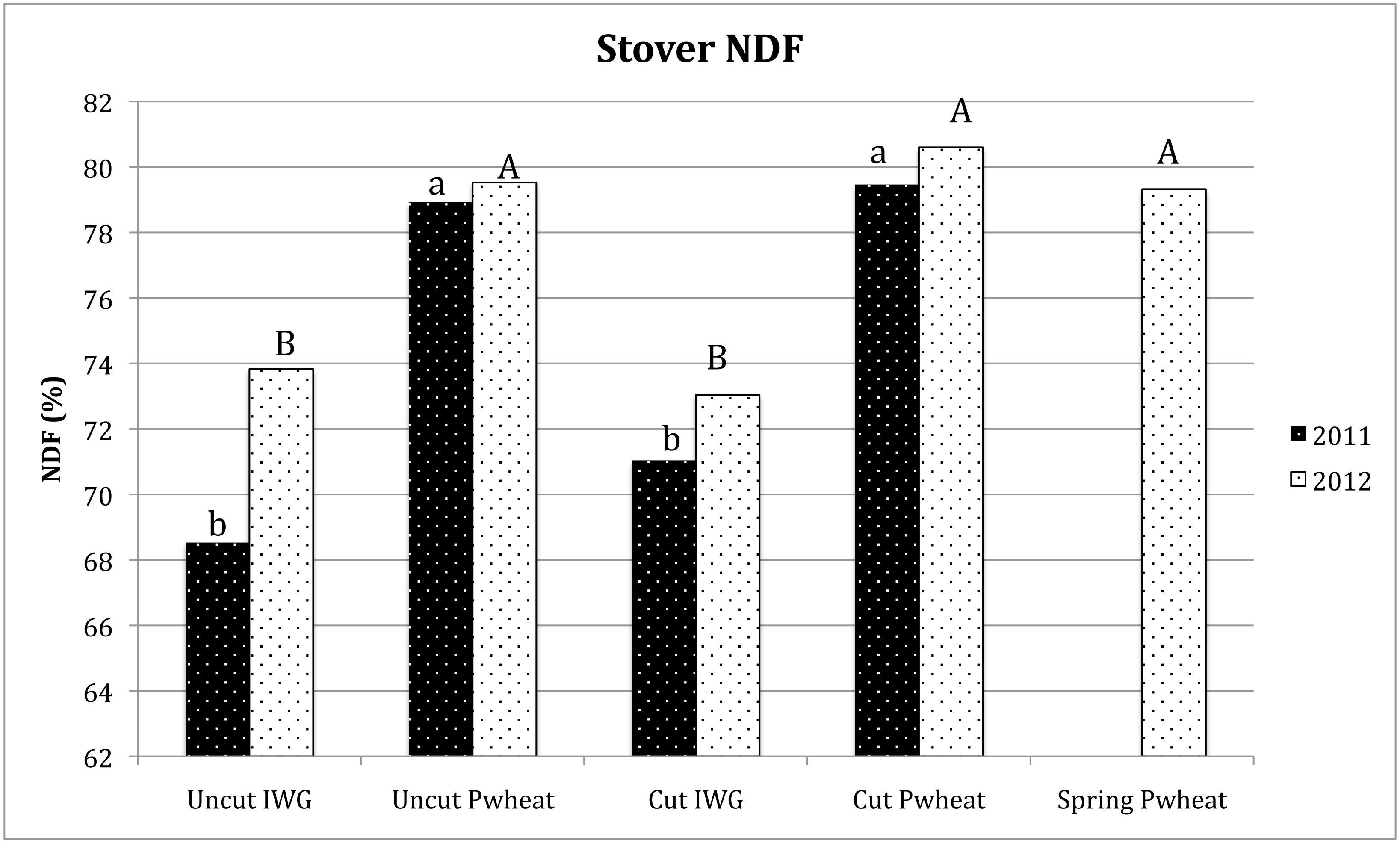


Figure 3.5: First- and second-year (2011 and 2012) neutral detergent fiber (NDF) of stover for four systems: two species, IWG and Pwheat, planted in the fall and subjected to two cutting regimes (uncut or cut for spring forage), and second-year NDF of stover for a fifth system: Pwheat planted in the spring and cut for spring forage in year two as a comparison. Field experiment conducted in southwest Michigan at the W.K. Kellogg Biological Station (KBS). Columns labeled with different lowercase letters are significantly different from each other. Columns labeled with different capital letters are significantly different from each other. Alpha=0.05.

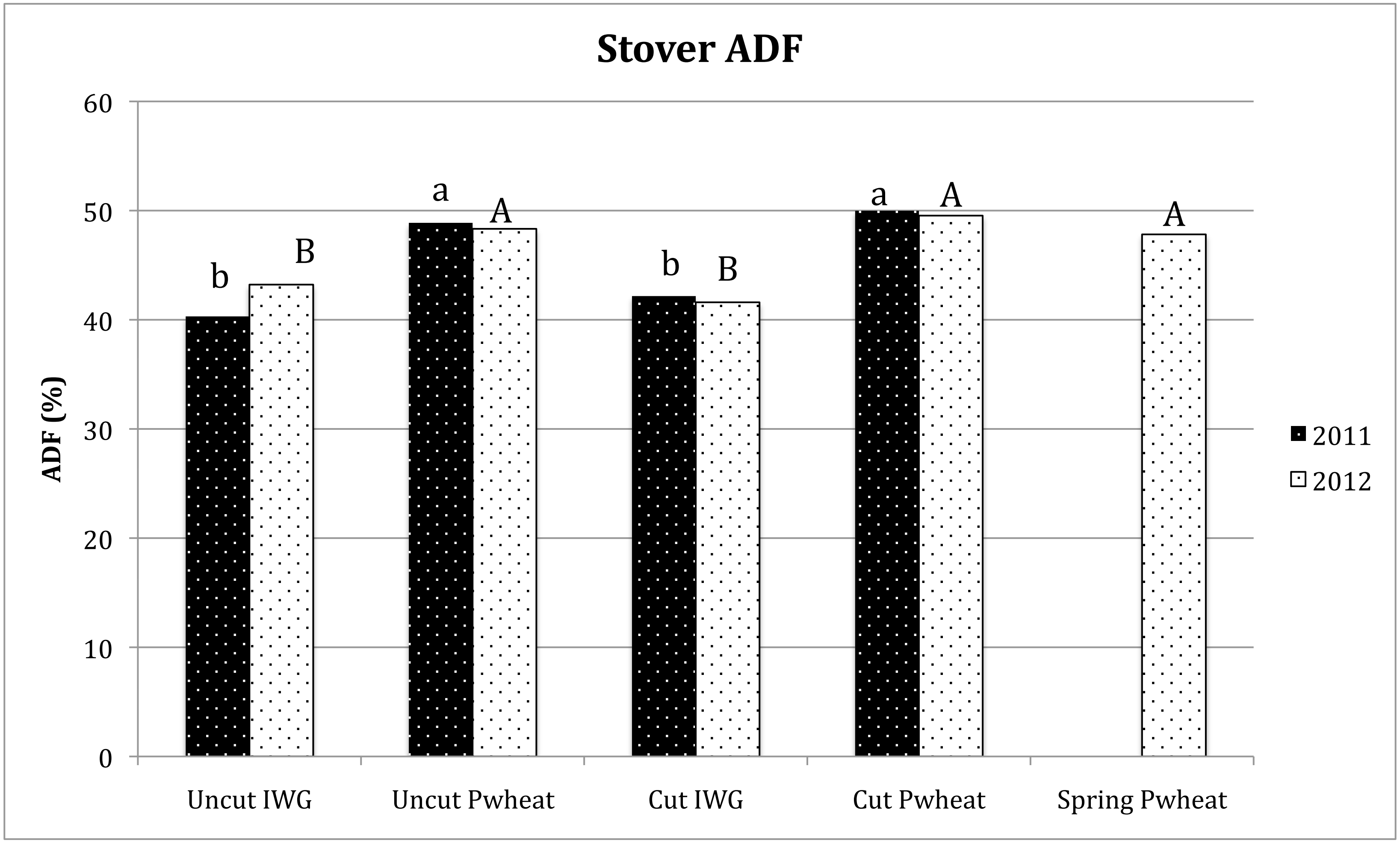


Figure 3.6: First- and second-year (2011 and 2012) acid detergent fiber (ADF) of stover for four systems: two species, IWG and Pwheat, planted in the fall and subjected to two cutting regimes (uncut or cut for spring forage), and second-year ADF of stover for a fifth system: Pwheat planted in the spring and cut for spring forage in year two as a comparison. Field experiment conducted in southwest Michigan at the W.K. Kellogg Biological Station (KBS). Columns labeled with different lowercase letters are significantly different from each other. Columns labeled with different capital letters are significantly different from each other. Alpha=0.05.

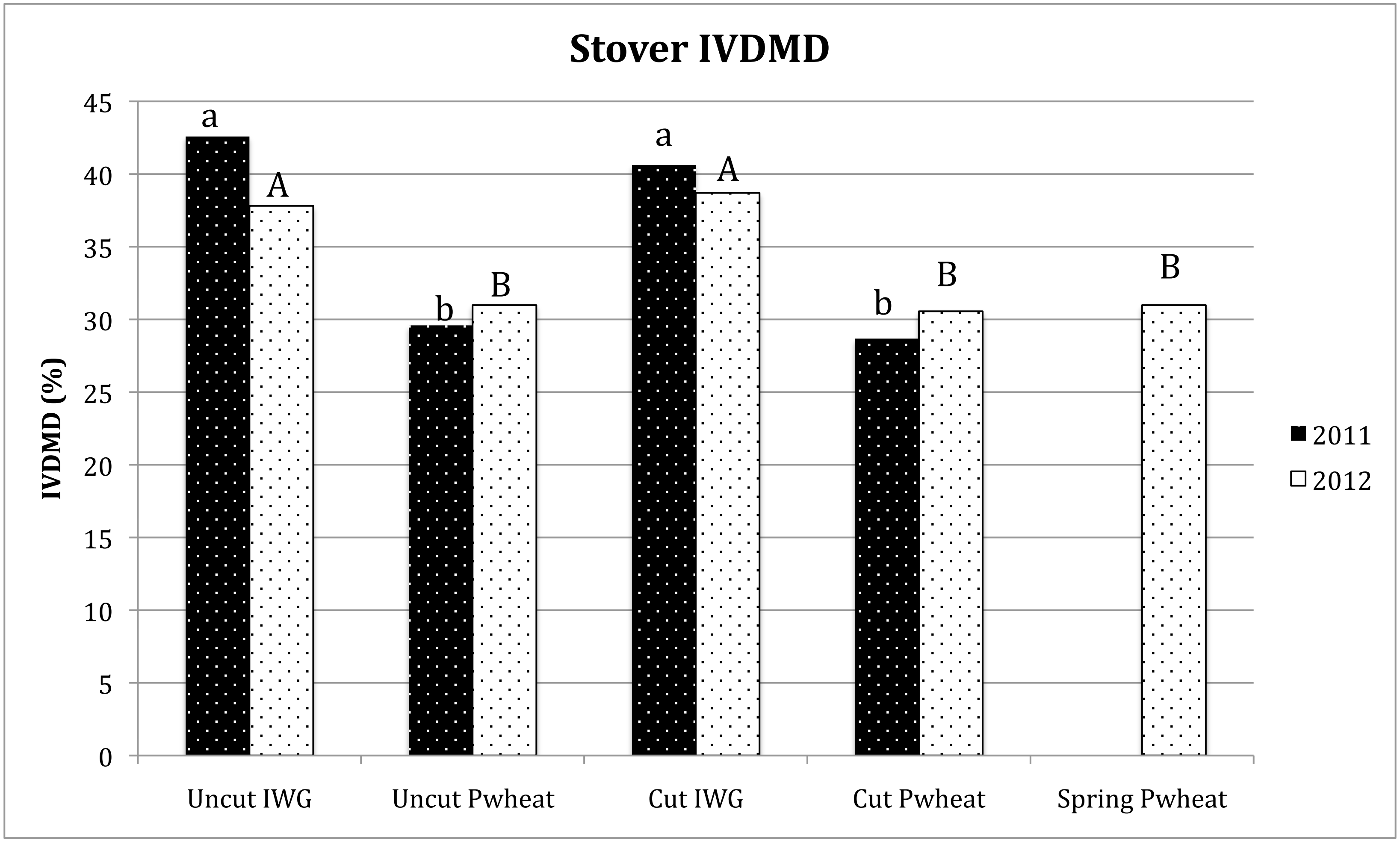


Figure 3.7: First- and second-year (2011 and 2012) in-vitro dry matter digestibility (IVDMD) of stover for four systems: two species, IWG and Pwheat, planted in the fall and subjected to two cutting regimes (uncut or cut for spring forage), and second-year IVDMD of stover for a fifth system: Pwheat planted in the spring and cut for spring forage in year two as a comparison. Field experiment conducted in southwest Michigan at the W.K. Kellogg Biological Station (KBS). Columns labeled with different lowercase letters are significantly different from each other. Columns labeled with different capital letters are significantly different from each other. Alpha=0.05.

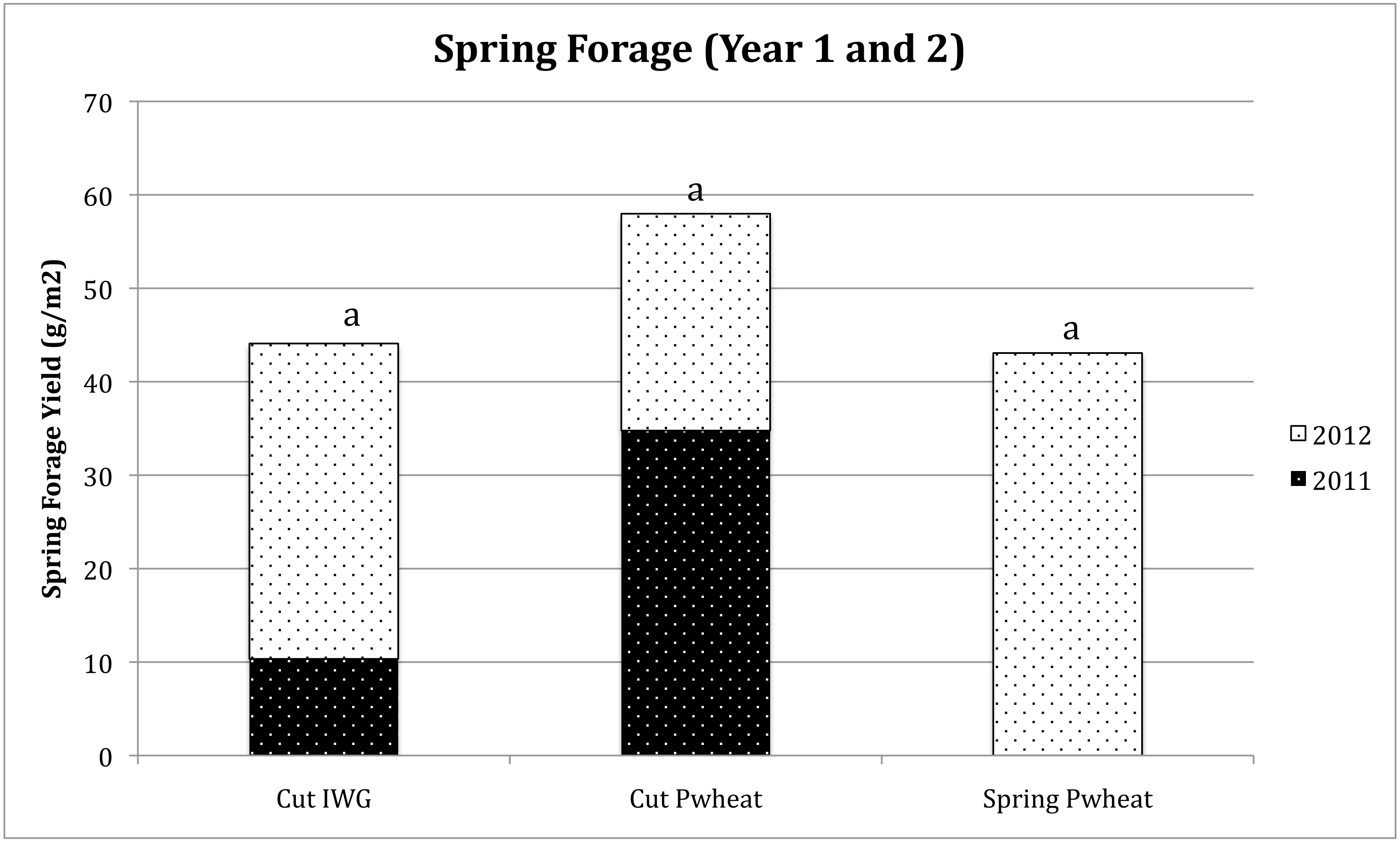


Figure 3.8: First- and second-year (2011 and 2012) cumulative spring forage dry weights for four systems: two species, IWG and Pwheat, planted in the fall and subjected to two cutting regimes (uncut or cut for spring forage), and second-year spring forage dry weight for a fifth system: Pwheat planted in the spring and cut for spring forage in year two as a comparison. Field experiment conducted in southwest Michigan at the W.K. Kellogg Biological Station (KBS). Columns labeled with different letters are significantly different. Alpha=0.05.

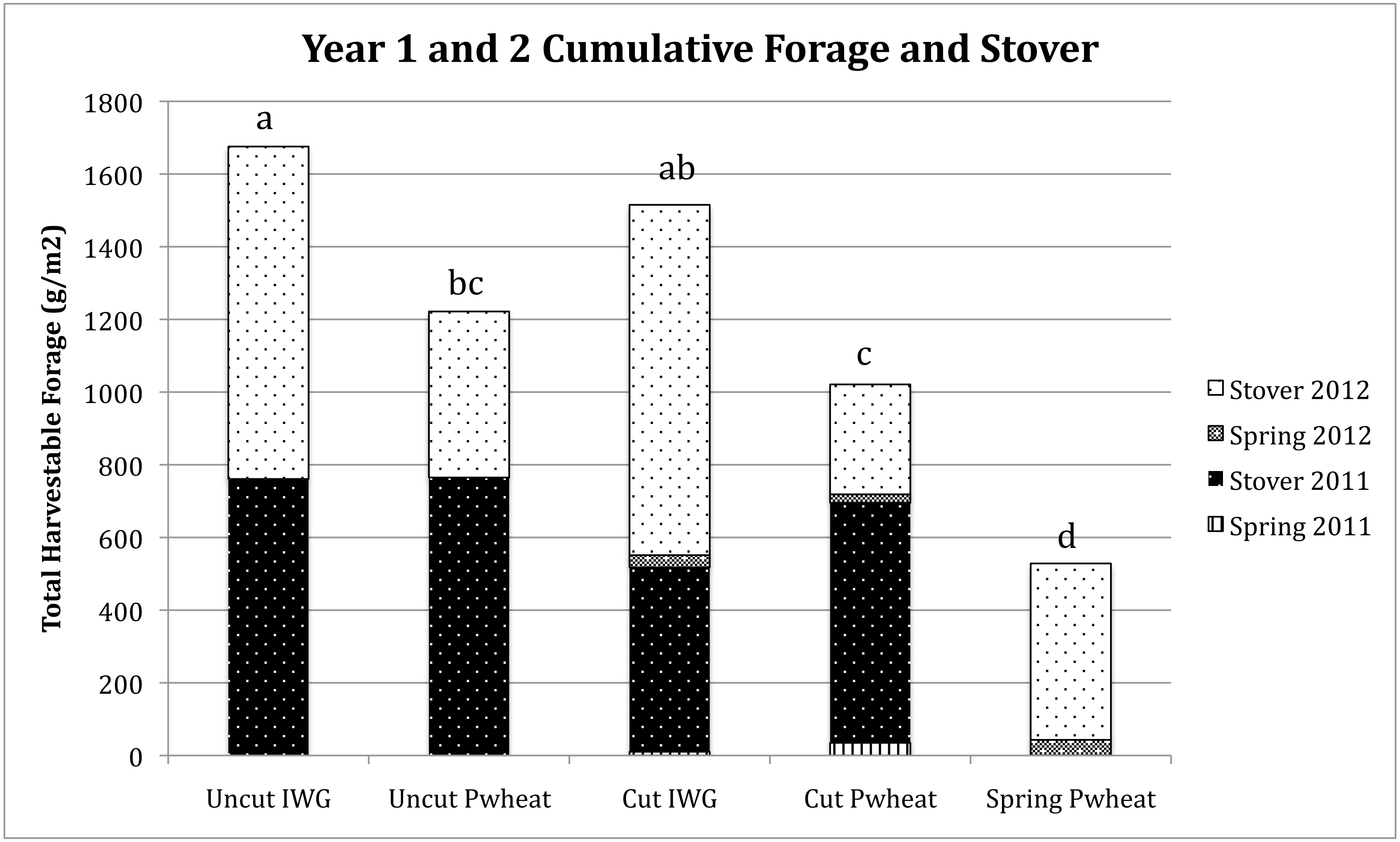


Figure 3.9: First- and second-year (2011 and 2012) cumulative spring forage and stover (total harvestable forage) for four systems: two species, IWG and Pwheat, planted in the fall and subjected to two cutting regimes (uncut or cut for spring forage), and second-year spring forage and stover (total harvestable forage) for a fifth system: Pwheat planted in the spring and cut for spring forage in year two as a comparison. Field experiment conducted in southwest Michigan at the W.K. Kellogg Biological Station (KBS). Columns labeled with different letters are significantly different. Alpha=0.05.

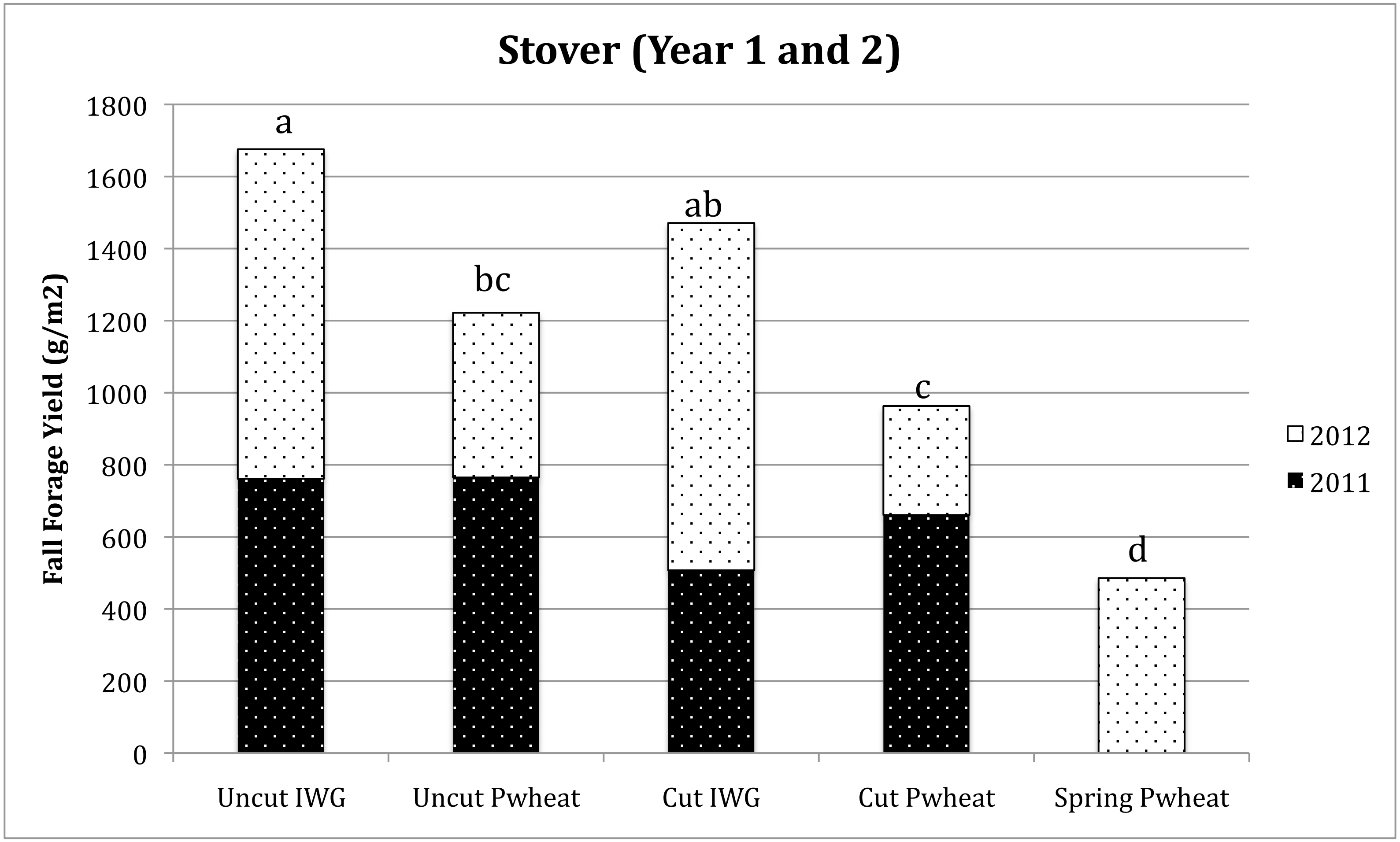


Figure 3.10: First- and second-year (2011 and 2012) cumulative stover for four systems: two species, IWG and Pwheat, planted in the fall and subjected to two cutting regimes (uncut or cut for spring forage), and second-year stover dry weight for a fifth system: Pwheat planted in the spring and cut for spring forage in year two as a comparison. Field experiment conducted in southwest Michigan at the W.K. Kellogg Biological Station (KBS). Columns labeled with different letters are significantly different. Alpha=0.05.

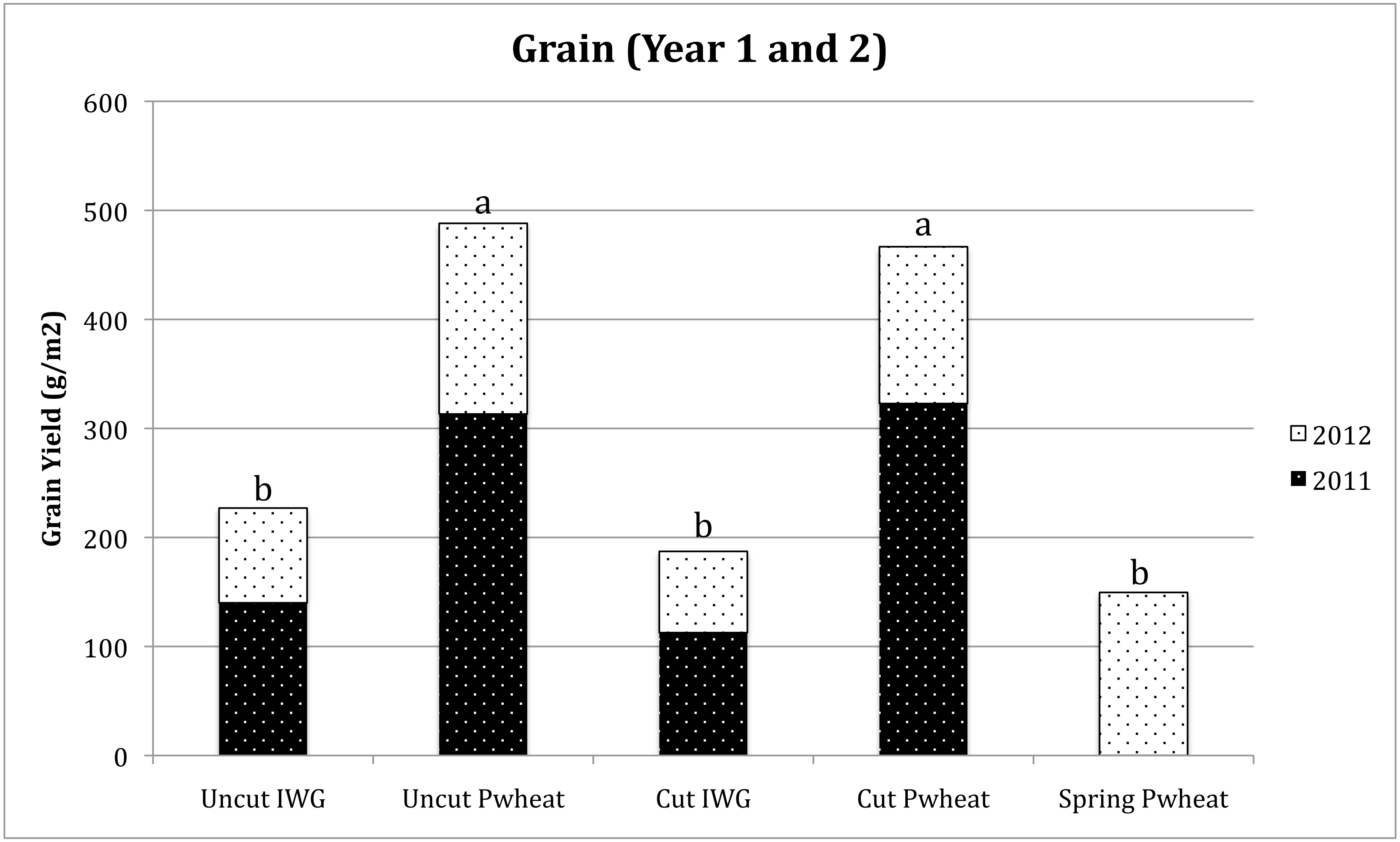


Figure 3.11: First- and second-year (2011 and 2012) cumulative grain yield for four systems: two species, IWG and Pwheat, planted in the fall and subjected to two cutting regimes (uncut or cut for spring forage), and second-year grain yield for a fifth system: Pwheat planted in the spring and cut for spring forage in year two as a comparison. Field experiment conducted in southwest Michigan at the W.K. Kellogg Biological Station (KBS). Columns labeled with different letters are significantly different. Alpha=0.05.

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