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BENEFITS OF FORAGE SPECIES DIVERSITY IN GRAZING SYSTEMS IN PENNSYLVANIA

A Thesis in

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ABSTRACT

Management-intensive rotational grazing has been increasing in the northeast USA because of an increase in net profits as a result of decreasing feeding and harvest costs. However, sustainability of forage production in the region is negatively affected by variability in soils and climate. The use of complex mixtures (mixtures composed by more than three species) is presented as a solution to increase yield and sustain forage production while decreasing weed invasion and ultimately improving farm profitability and economical sustainability. The objectives of the studies presented here were to evaluate: i) weed suppression, ii) forage production, iii) forage nutritive value, and iv) the economic impact of complex forage mixtures compared to simple forage mixtures and pure grass stands commonly used in the Northeast USA, and to develop grazing guidelines for complex mixtures.

This research had three components dealing with weed suppression, grazing management, and economics. In the first component, a series of experiments (two field experiments and a greenhouse experiment) were conducted to evaluate weed suppression during the establishment of complex forage mixtures. The first field experiment was established in late-summer, 2002 and repeated in spring, 2003 to compare weed suppression by complex mixtures and pure stands. The second field experiment was established in late-summer, 2004 to compare weed suppression by complex, simple forage mixtures, and pure grass stands. The third experiment was conducted in the greenhouse to evaluate the use of fast establishing forage species (FEFS; red clover, perennial ryegrass, and chicory) in simple or complex combinations to suppress a broadleaf plant (oil seed rape) and a grass (Japanese millet) during the establishment of an orchardgrass-alfalfa mixture. There were general trends common to the three experiments presented. In the first field experiment mixtures produced on average 65% more forage DM and had less weed content (24%) compared to the pure stands. Similarly in the second field experiment weed proportion decreased and DM increased as mixtures become more complex. Results of the greenhouse experiment also showed a decrease of weed content and increased forage yield for the more complex mixtures. However, FEFS decreased the proportion of the target forage species (alfalfa-orchardgrass). These series of studies have shown that the use of complex mixtures or FEFS is a viable alternative to annual companion crops for weed suppression during forage establishment. Chicory appeared to be the most effective FEFS in all the studies, hence its use in forage mixtures is recommended during pasture renovation. However caution has to be exercised when adding FEFS to slow establishing forage mixtures because they also will decrease the proportion of the target forage species.

In the second component, a grazing experiment was carried out during 2005 and 2006 to evaluate grass in pure stands, simple mixtures, and complex mixtures for their botanical composition, forage nutritive value, and forage production under two grazing management treatments. Among the forages tested, only perennial ryegrass, chicory and red clover were affected by grazing management. Both red clover and chicory produced more under less frequent grazing. On the other hand, perennial ryegrass flourished (increased DM productivity) under more frequent grazing. Legume and weed content decreased as plant diversity increased. Dry matter production was affected by grazing treatment. The “height” grazing treatment (grazing began whenever the canopy reached 25 cm of height) produced 30% more DM (6 777 kg ha^{-1}) compared to the “morphology” grazing treatment (grazing began whenever alfalfa reached bud stage; 5 222 kg ha^{-1}) on average for the 2005 and 2006 growing seasons. For the 2005 growing season the complex mixtures (5- and 7-species) produced more DM compared to the alfalfa-orchardgrass mixture or an orchardgrass pure stand (with or without N). In 2006, a simple alfalfa-orchardgrass mixture produced the greatest yield. More importantly, DM yield of complex mixtures was stable over the diverse climatic conditions experienced in 2005 and 2006. There were differences in nutritive value both by grazing treatment and mixture complexity at first harvest. These differences declined over the growing season. In general, the “height” grazing treatment produced forage of better nutritive value compared to the “morphology” grazing treatment at first harvest in both years. Fewer differences in nutritive value between grazing treatments were found over the growing season. However when differences were significant, the “height” treatment provided forage of better nutritive value. The effect of forage treatments on nutritive value at first harvest was influenced by both plant diversity and the use of N fertilizer on the orchardgrass. In general, as mixture complexity increased the nutritive value improved. The addition of inorganic N to orchardgrass increased CP content both at first harvest and over the growing season.

In the third component, the short- and long-term economic impact of the forage and grazing treatments were evaluated using results from the previous experiment. These alternative forage and grazing management scenarios were evaluated by computer simulations using the Integrated Farm System Model (IFSM). The short-term analysis showed that differences between the two grazing managements were mainly due to a smaller pasture production in the "morphology" grazing treatment which led to a decrease in net return of 8% compared to the "height" grazing treatment. Similarly, forage treatment mainly affected pasture production, seed, and fertilizer cost and subsequently the amount of excess forage for sale and the income generated by those sales. Nevertheless, complex mixtures generated greater net returns compared to either the simple mixtures or pure grass stands. Complex forage mixtures presented more consistent net return as a consequence of their consistency in DM production.

The long-term economic analysis showed that the "height" grazing treatment produced greater net return compared to the morphology-based grazing due to greater income from feed and bedding sales and lower feed costs. Additionally, production risk was smaller for the "height" grazing treatment compared to the "morphology" grazing treatment. Comparing the simple mixtures to the complex forage mixtures, differences in feed produced, production costs, and net returns were small. More importantly, when comparing the difference in net return obtained by a particular forage treatment in dry and wet years, the net return using complex mixtures was reduced only by 25 to 27%. On the other hand, net return reductions ranged from 36% for a three species mixture up to 55% for pure grass stands. This gives supporting evidence to the increased consistency both in DM yield and net return of the complex mixtures.

These studies demonstrated that the addition of chicory or a combination of all three FEFS studied (chicory, red clover, and perennial ryegrass) in a low proportion (≤12.5%) of the seeding mixture helps decrease weed invasion and increase forage yield at the first harvest. Additionally forage nutritive value, DM yield, and overall net return are optimized by grazing forages based on canopy height. The use of complex mixtures can be an alternative to drought prone environments where consistency in DM production is more important than top forage productivity. Complex mixtures are a useful alternative for pastures in dairy farms to manage forage production risks in dry years and thereby increase and stabilize annual net returns.

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CHAPTER 1

INTRODUCTION

Pastures are plant communities (generally composed of introduced species) that typically receive inputs (i.e. fertilizers); they are mainly used for grazing and cutting by humans for fodder conservation (Tow and Lazenby, 2001). Pastures represent 5.6 % of the total non-federal land use of the northeast region of the USA (USDA, 2003). The use of pastureland through management-intensive rotational grazing has been increasing in the USA (Casler and Undersander, 2005). This trend is mainly driven by an increase in net profits as a result of decreasing feeding and harvest costs associated with pasture systems (Dart et al., 1999). Management-intensive rotational grazing systems have been shown to improve the net profit of dairies in the north central USA (Rudstorm, 2004). In the northeast USA, management-intensive rotational grazing has been shown to increase net profit from $40 up to $300 per cow (Aiello, 2004).

The components of a pasture plant community may differ in phenotypic plasticity, adaptation to grazing, and therefore persistence. Early in its settlement, the climax forest vegetation of the northeast USA was cleared and replaced by pastures that require management techniques to maintain species mixtures in order to expand agriculture (Fales et al., 1996).The cool-season grasses and legumes that dominate pastures in the northeast USA are almost entirely non-native species (Tracy and Sanderson, 2000). Over time there were differences in the optimum number of species that were considered best for pasture establishment (Harris, 2001). In New Zealand, early in the 20th century, mixtures with up to 20 species were recommended, but by the 1970’s the number of species was reduced to about seven (Harris, 2001). Presently, simple mixtures (two or three species) are recommended for establishing a pasture in Pennsylvania (Hall, 2004). The reason for using simple mixtures or pure stands resides not only in that simple mixtures are easier to manage, but there is also a large amount of information on how to manage them (Harris, 2001). Moreover producers perceive that species-rich pastures are an obstacle to livestock productivity because they associate plant diversity with semi-natural pastures that have low dry matter (DM) production (Isselstein, 2005). Nevertheless, some ecology literature suggests that increased biodiversity increases and stabilizes total community biomass in natural ecosystems (Tilman, 2001).

The overall objective of any intensively managed pasture-based operation is to optimize herbage production and utilization. If more diverse mixtures increase and stabilize forage production thereby improving net return, it would be advantageous for livestock producers to increase pasture diversity to optimize herbage production.

REVIEWED LITERATURE

PLANT DIVERSITY and PASTURE PRODUCTIVITY

How does diversity work?

Before analyzing diversity effects on pasture productivity, it is important to clarify some terms such as diversity, competition, and competitive ability. Diversity is usually considered to be only the number and distribution of plants in a habitat. More important however, is the diversity of traits (e.g. nitrogen fixation, drought tolerance, differences in growth patterns, cold and heat tolerance, disease and low oxygen tolerance, etc.) encompassed in the species pool than number of species (Tilman, 2001; White et al., 2004). Competition is defined as "an interaction between individuals, brought about by a shared requirement for a resource in limited supply, and leading to a reduction in the survivorship, growth and/or reproduction of at least some of the competing individuals concerned" (Begon, et al., 1996). Competitive ability is the capacity of a species to grow, reproduce, and survive under competition.

Environmental factors, such as temperature, moisture, and day length in addition to soil chemical and physical properties affect the competitive ability of plant species and varieties (Nurjaya and Tow, 2001). Among plant morphological and physiological traits, relative growth rate, height, leaf area ratio, specific leaf area, root mass, and rapid or prolonged root growth are associated with competitive ability (Zannone et al., 1983;

Piano and Annicchiarico, 1995; Zannone, 1985; Nurjaya and Tow, 2001). All these traits are associated with the capacity of plants to pre-empt limiting resources. Ultimately the interaction of environmental factors with plant traits determines the outcome of competition (Nurjaya and Tow, 2001).

Grazing is a major disturbance event that affects competition in diverse plant communities. Grazing-induced species replacement can occur due to selective grazing or to unequal growth capability of the species (Briske, 1996). Grazing affects plant growth, mortality, and reproduction (Bullock, 1996). Plants have differential ability to resist grazing (Briske, 1996). Grazing resistance can be divided into avoidance (reduce the probability and severity of grazing) and tolerance (plant possess traits that allow it to grow after grazing) (Briske, 1996). Thus, it is necessary to know the avoidance/tolerance strategies of the targeted species within a grassland to successfully manage the grassland (Briske, 1996). Residual leaf area after grazing and rapid regrowth are the most important traits in conferring competitive ability to plants in grazed communities (Nurjaya and Tow, 2001; Briske, 1996; Carrere et al., 1997; Cuomo et al., 1999; Belesky et al., 2002a). Plant competition under grazing is also altered by dung and urine deposition, treading, and the effect of animals lying on plants and leaving open gaps (Bullock, 1996; Davies, 2001; Kemp and King, 2001).

In total, competitive ability depends on several plant traits and environmental factors, some of which change with time, and others that can be managed. Therefore, it is difficult to draw conclusions about the competitive outcome of diverse plant communities. Then how is it possible that in nature a large number of plant species can coexist? Diverse plant communities can coexist due to a spatial and temporal heterogeneity in resource supply rate (Tilman, 1999). Since plant species differ in their requirements (both physical and chemical) temporal or spatial variation of such factors allows for the coexistence of multiple plant species (Tilman, 2001).

Diversity effects can be divided into four main categories: sampling effect, niche differentiation effects, interspecific facilitation, and insurance effect.

Sampling effect:

This is defined as the likelihood of the presence of a single species which dominates the ecosystem increases with greater diversity. In this case, it is assumed that the dominant species is a superior competitor, hence it would increase total community biomass (Tilman 2001). In other words, by including many species in a mixture there is a greater chance that one or more of the species will be highly productive. For instance the inclusion of alfalfa was the major reason for improved yield of complex mixtures compared to simple mixtures in an on-farm grazing experiment (Skinner et al., 2006).

Niche differentiation:

In heterogeneous environments (heterogeneity both in space and time), diverse species with differential competitive ability perform the best and dominate part of the habitat where conditions are closer to the species optimal growth factors, but no species can fully exploit the entire range of conditions (Tilman, 2001). For instance the recommendation of seeding complex mixtures (seven species mixtures) in New Zealand in the 1970s aimed to cover the different ecological niches in a pasture (Harris, 2001).

Interspecific facilitation:

The presence of a species increases the growth and survival of other species thorough the facilitation of resource capture (Bertness, 1998). For instance, nitrogen fixing plants (legumes) can provide nitrogen to non-fixing plants, such as grasses (Harris, 2001).

Insurance effect:

In this instance, higher plant diversity buffers ("insures") community biomass production against environmental fluctuations due to differential capacity of the species to respond to stress (Loreau et al., 2001). For instance, the use of drought tolerant species (e.g. chicory) in complex mixtures improved forage productivity and stability under drought stress (Skinner et al., 2004).

In nature, some or all of the above mentioned effects may operate simultaneously and at different scales. Niche differentiation and insurance effects predominate at a larger scale (farm level or greater); the sampling effect and interspecific facilitation predominate at the smaller scale (paddock level). The plant diversity required to optimize DM production increases in highly heterogeneous environments such as grasslands (Tilman, 1999). It has been suggested that 10-15 plant species are required at a small-scale (1 m^2) to cause near saturation of relationship between diversity and ecosystem functioning (Tilman, 1999).

Potential use and benefits of forage diversity in grazing systems

Forage research has been focused mainly on simple mixtures or pure stands of forages managed as agricultural crops (Harris, 2001; Kemp and King, 2001). There is a large amount of evidence that shows the advantages of simple mixtures composed of a grass and legume compared to their pure stand. However, there is a wide range of different grass-legume mixtures, and there are differences among them regarding DM yield and forage quality (Chamblee and Lovvorn, 1953; Osman and Nersoyan, 1986).

The addition of legumes to pure cool-season grass stands improves forage nutritive value by reducing neutral detergent fiber (NDF) and acid detergent fiber (ADF) content (Zemenchik et al., 2002) yet increasing crude protein (CP) and in vitro true dry matter digestibility (IVTDMD; Malhi et al., 2002; Sleugh 2000). Moreover, legumes can reduce the need for N fertilizer, which is energy intensive and costly to produce (Mouriño et al., 2003, Malhi et al., 2002). The needs for N fertilizer may increase in the future as well as its cost. Thus, properly selected and managed grass-legume mixtures are an environmentally sound solution to reduce N fertilizer needs while at the same time improving forage and livestock production.

Lately there has been a revived interest in increasing the number of plant species in forage mixtures. The potential advantages of complex forage mixtures (mixtures containing more than three forage species) for pasture use are based on the ecological theory explained in the previous section. Complex mixtures have been suggested to improve DM yield, DM seasonal distribution, and adapt to heterogeneous environments (Belesky et al., 2002a; Belesky et al. 2002b). Diverse communities may lead to a more complete use of the resources and therefore decrease the possibility of weed invasion (Kemp and Michalk, 2005; Tracy and Sanderson, 2004a; Tilman, 1997). Additionally, increased diversity may improve soil and water quality and increase wildlife (Kephart et al., 1995). On the downside, botanical shifts within highly diverse pastures may affect forage quality, complicating the estimation of nutritional value of a pasture (Skinner et al., 2004; Crosthwaite et al., 1996; Wilson and Clark, 1960; Belesky et al., 1999).

Most of the recent work with mixture diversity has focused on the effect of increasing plant diversity on DM yield. Research results from clipping and grazing studies, however, have been mixed. For instance, research in clipped plots showed both a positive (Hector et al., 1999; Bullock et al., 2007) and a negative (Skinner et al., 2004; Tracy and Sanderson, 2004b; Annicchiarico et al., 1995; Piano and Annicchiarico, 1995) effect of increasing mixture complexity on DM yield. A series of studies conducted in Pennsylvania with dairy and beef cows showed an increase in DM production for the more complex mixtures (Sanderson et al., 2005; Skinner et al., 2006; Deak et al., in press). On the other hand, a grazing study conducted with beef steers in Illinois found that complex mixtures did not improve yield under grazing (Tracy and Faulkner, 2006). The use of different forage species, environments, and management (e.g. fertilization, cutting and grazing systems) in each of the studies are the major factors that obstruct unifying conclusions and ultimately resolve the yield-diversity debate (Sanderson et al., 2004, Isselstein, 2005; Hector and Loreau, 2005). There might be a tradeoff between forage diversity and yield, but this should be weighed against the added benefits derived from plant diversity (e.g., able to better tolerate climatic extremes, improved nutrient cycling, and improved soil properties; Sangha et al., 2005).

Recent research on the influence of forage diversity on pasture production in the northeast USA demonstrates that not only the number of forage species is important to increase forage production, but also the particular species play a significant role in achieving greater productivity (Sanderson et al., 2005; Skinner et al., 2006; Skinner et al., 2004; Deak et al., 2004). Thus, pasture performance could be improved by combining carefully selected forage species. Unfortunately, information on how to select and combine forage species for improved DM production is lacking in the Northeast USA (Sanderson et al., in press). In some countries there are formal programs in place for selecting and evaluating forage mixtures (Kessler and Suter, 2005). Selecting species based on previous research that evaluated complex mixtures could be an alternative for the northeast USA, because there are no such formal programs in this region.

It has been reported that complex mixtures produce more consistent DM yield (Clark et al., 2001). Fluctuation in climate has been implicated as a major reason for inconsistent pasture production (Belesky et al., 1999) and yield loss associated with droughts can be as high as 50% of annual DM production in the northern prairies (Dunn et al., 2005). Complex mixtures have produced more consistent yields compared to simple mixtures due to greater DM production in dry years (Sanderson et al., 2005; Skinner et al., 2004; Skinner et al., 2006). Thus, complex mixtures could increase sustainability of forage production by diminishing environmentally related production risks.

Another advantage of complex mixtures is that floristically diverse pastures are less prone to weed invasion (Tracy et al. 2004; Tilman 2001; Tilman 1997). Weeds reduce yield and lead to early replanting of pastures (Grekul and Bork, 2004; Seefeldt et al., 2005; DiTomaso, 2000). Pastures are most vulnerable to weed invasion during establishment, making weed management during this period essential in obtaining increased forage production (Lewis and Hopkins 2000, Miller and Stritzke, 1995; Willard, 1967). Willard (1967) suggested that grass-legume mixtures are more efficient in competing with weeds than pure stands, but recent research did not confirm this hypothesis (Spandl et al., 1999).

The use of chemical weed management during establishment of either simple or complex mixtures of forages is limited to pre-plant application of broadleaf herbicides due to their incompatibility with legumes. Alternatively, weed management through companion crops has been long used and researched. Companion crops have many added benefits beyond weed management as noted by Hampton et al. (1999), Miller and Stritzke, (1995), Moyer et al. (1995), and Simmons et al. (1992), but they also can reduce forage production due to companion crop-forage competition (Hampton et al., 1999). In rangeland re-vegetation programs, the use of mixtures composed of species with various growth forms is the best way to suppress weeds (DiTomaso, 2000), but the mechanism by which increased plant diversity decreases weed invasion is not clear (Tracy and Sanderson, 2004a). It has been proposed that weed invasion is controlled by the particular forage species present (Ruijven et al., 2003). Hence species selection is crucial for invasive weed suppression (DiTomaso, 2000). Seed weight, seedling growth rate, and seedling morphology appear to be the most important factors affecting competitive ability during establishment (Harris, 2001; Lodge, 2000; Blaser et al., 1952). Consequently, early-emerging seedlings have higher relative growth rates compared to later-emerging seedlings. The earlier emergers continually increase their ability to preempt resources thereby gaining a greater competitive ability. Thus, mixtures with a fast establishing plant species may be more resistant to plant invasion. Both perennial grasses and broadleaf species have proven successful in competing with rangeland weeds (DiTomaso, 2000). Further research is needed to evaluate the use of increased forage diversity by the addition of fast establishing forage species to mixtures to decrease weed invasion during forage establishment.

The management of complex mixtures, however, presents some problems. One disadvantage is that botanical composition of forage mixtures changes over time in response to the environment and grazing management (Lauriault et al., 2006; Belesky et al., 2002a; Belesky et al., 2002b; Carrere et al., 1997). As a result of these shifts in botanical composition, nutritive value of complex mixtures changes over time. Additionally, White et al. (2004) found that diverse plant communities had inferior nutritive value compared to less diverse vegetation. However, in that study the less diverse plant communities were dominated by ryegrass and white clover (which are very high in nutritive value) whereas unimproved native grasses dominated the more diverse-communities. In contrast to this study, Deak et al. (in press) found that complex mixtures had similar nutritive value to simple mixtures and that the major factor influencing nutritive value was the grass-legume ratio of mixtures as found by others in simple grass-legume mixtures (Sheaffer et al., 1990; Zemenchick et al., 2002). Therefore, management of plant-diverse pastures should aim to maintain a grass-legume ratio of about 30% to 50% legumes).

In rotational grazing systems, the length of rotation cycle and duration of grazing period are key in maintaining an optimum ratio of grass to legume. Currently Pennsylvania State University extension has grazing recommendations for cool-season grasses and pure legume stands (Hall, 2004), yet recommendations for grazing grass-legume mixtures are scarce. Mixtures grazed based on canopy height (following Penn State's recommendation for cool-season grasses) lead to a decrease in legume content in both simple and complex mixtures (Deak et al., in press). Research conducted in Argentina with diverse cool-season grass-alfalfa mixtures concluded that grazing alfalfa-grass mixtures when the alfalfa reached bud stage or basal regrowth of 5 to 7.5 cm increased alfalfa content of the mixture (Barbarossa and Miñon, 2001; Refi and Martin, 2001). Therefore, basing grazing time decisions on the legume developmental stage rather than on the average sward height might maintain the legume content of the mixture and improve forage nutritive value.

A major problem that adoption and use of complex mixtures face is that little research has focused on the economic impact of plant diversity, yet this is surely of great importance for producers (Clark, 2001). Unfortunately, the little research conducted on the economic impact of forage diversity is inconclusive. On the one hand, based on a study on the partial economic effects of mixture complexity, it was concluded that complex mixtures were not economically beneficial in dairy production (Wedin et al., 1965). On the other hand, a recent study found that a complex mixture composed of six species improved net return of a dairy farm compared to pure grass (Sanderson et al., 2006). Economic analysis of complex mixtures in grazing situations is scarce in part because it is both labor and time consuming due to the large amount of land, livestock, and personnel resources required. An alternative to field experiments is the use of computer simulation to study the economic impact of alternative management options.

Modeling of agricultural systems began in the 1960's with the advent of computers and modeling has increased as computers have become more accessible and powerful (Rickert et al., 2000). The Integrated Farm System Model (IFSM) is prominent among the many computer simulation models available because it integrates all major production aspects at the whole farm level. The IFSM calculates the economic return based on feed production and purchase, feed utilization, production costs, and income from production sales. Additionally IFSM estimates environmental aspects related to the specific production and soil characteristics. The IFSM and its predecessor the Dairy Forage System Model (DAFOSYM) have been used to evaluate alternative management scenarios such as species composition and pasture productivity (Corson et al., 2006), soybean and small grain production and use implications on dairy farms (Rotz et al., 2001; Rotz et al., 2002), and alternative silage systems on dairy farms (Borton et al., 1997). Therefore, the IFSM appears to be a viable complement to field studies to evaluate the economic impact of complex mixtures at a whole farm scale.

Simple grass-legume mixtures are recommended for livestock producers due to uncertainties about the performance of complex mixtures. This recommendation dates back to the 1950s when the best alternative was to mix a grass and a legume well adapted to the environment and the perspective management (Blaser et al., 1952). Nevertheless, if carefully planned complex mixtures were proven to increase yield and sustain forage production while decreasing weed invasion and ultimately improving farm profitability in Pennsylvania’s heterogeneous environment, livestock producers would benefit through increased economic sustainability.

Further investigations are needed to shed light on unstudied aspects of complex mixtures. Research should focus on answering questions including: i) are complex mixtures composed by fast establishing forage species a viable alternative for weed management during forage establishment, ii) do complex mixtures yield higher and more consistently under rotational grazing management, iii) what nutritive value can be expected from complex mixtures, iv) what is the best grazing management option to maintain an adequate grass-legume proportion, and v) is there an economic advantage for planting more diverse forage mixtures?

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CHAPTER 2

WEED SUPPRESSION DURING FORAGE ESTABLISHMENT

Weeds reduce yield and lead to early replanting of pastures. In Canada, the yield loss in a perennial pasture was estimated to be 2 kg ha^{-1} for each kilogram of Canada thistle (*Cirsium arvense* L.; Grekul and Bork, 2004). In New Zealand, forage production was estimated to be reduced by 42 and 72% due to the presence of bull thistle (*Cirsium vulgare* Savi) and musk thistle (*Carduus nutans* L.), respectively (Seefeldt et al., 2005).

The vulnerability of pastures to weeds is the greatest during establishment (Lewis and Hopkins 2000). Hence weed management often is needed to avoid stand reduction (Vough et al., 1995). Weed management is especially difficult during the establishment of perennial forages, because forage seedlings are often less competitive than weedy species (Miller and Stritzke, 1995). The establishment of a weed-free productive forage stand is essential in obtaining high dry matter (DM) yield (Miller and Stritzke, 1995), and is the basic principle of weed management in forages (Willard, 1967).

Even though Willard (1967) stated that grass-legume mixtures are more efficient in controlling weeds than pure stands, research is not conclusive on the effect of cool-season grasses and alfalfa mixtures on weed management. Willard (1967) found that the addition of orchardgrass to alfalfa dramatically reduced weed DM at first harvest. On the other hand, Spandl et al. (1999) reported that none of the cool-season grasses evaluated in combination with alfalfa reduced weed content at first harvest. Moreover, fewer weed management options are available during the establishment of grass-legume mixtures because broadleaf herbicide may injure legumes. Thus, herbicide options often are limited to pre-plant application.

Among the weed management options for forages and pastures, the use of companion crops has been extensively researched. The use of companion crops provides quick ground cover and soil erosion control, reduces weed invasion, reduces pesticide use, increases feed production, and increases cash flow (Miller and Stritzke, 1995; Hampton et al., 1999; Simmons et al., 1992; Moyer et al., 1995). However because of companion crop-forage competition, companion crops can produce detrimental effects on the forage DM yield (Hampton et al., 1999).

A similar concept to companion cropping is the use of more diverse mixtures. Increasing plant species diversity in pastures could help avoid weed invasion (Sheley and Carpinelli, 2005; Tilman, 2001). The use of successional management, where short-lived plants are used to suppress invasive weeds followed by the subsequent seeding of native forage species, has been proposed as an ecological weed management tool for rangelands (Krueger-Mangold et al., 2006). Combining these two theories, by using complex forage mixtures composed of some highly competitive and short-lived forage species, might decrease weed invasion during forage establishment. Mixtures composed of species with various growth forms are the best way to suppress weeds in rangeland re-vegetation programs (DiTomaso, 2000). In the establishment of mixed swards substantial competition occurs among grass and legume seedlings and weeds that may germinate from the seed bank (Sanderson and Elwinger, 1999; Lodge, 2000), leading to complex interactions, which complicate the separation of forage effects on weeds (Lewis and Hopkins 2000). Thus, the mechanism by which increased plant diversity decreases weed invasion is not clear (Tracy and Sanderson, 2004). At a small scale (1 m^2), weed invasion is controlled by the particular species present (Ruijven et al., 2003). Hence, species selection is crucial for invasive weed suppression (DiTomaso, 2000). Early-emerging individuals have higher relative growth rates compared to later-emerging individuals. The earlier emergers continually increase their ability to preempt resources thereby gaining a greater competitive ability. A dominance hierarchy is established among plant species during emergence, which will influence future development of the individual plant (Ross and Harper, 1972). Among the many factors affecting competitive ability during establishment, seed weight, seedling growth rate, and seedling morphology appear to be the most important (Harris, 2001; Lodge, 2000; Blaser et al., 1952).

Both perennial grasses and broadleaf species have proven successful in competing with rangeland weeds (DiTomaso, 2000). Wiersma et al. (1999) found that annual ryegrass or festulolium reduced weed invasion during establishment of alfalfa and increased yield and forage quality. Therefore increasing forage mixture complexity by the addition of fast establishing forage species (FEFS) could reduce weed invasion, and increase forage DM yield at first harvest.

A series of studies were carried out both in the field and greenhouse to evaluate the use of fast establishing forage species and complex mixtures as a cultural method of weed suppression during forage establishment.

MATERIALS AND METHODS

Experiment 1

This experiment was set up to evaluate the use of complex mixtures of forages to suppress weeds during establishment under field conditions. Six forage species were selected based on their adaptation to the environment and on their performance in a related experiment (Deak et al., 2004). These species were planted in pure stands and combined so that each mixture was dominated by a different species and a mixture that had equal proportions of each species in accordance with the simplex design (Table 2-1; Cornell, 2002; Ramseier et al., 2005). The optimum seeding density for forage species changes with the specific environment and imposed management. As a general recommendation, 750 to 1100 seeds m^2 is enough to achieve high DM yield (Hall, 2005). In this experiment, six pure stands and seven forage mixtures at two seeding densities (700 and 1000 live seeds m^{-2}) and two seeding times (late-summer and spring) were evaluated. Soil fertility was brought up optimum levels following soil test recommendations. The study was conducted at the Pennsylvania State University Haller Farm, State College, PA (40º51’ N lat, 77º 51’ W long, 350 m above sea level). The seven forage mixtures were composed of different seeding ratios of ‘Tekapo’ orchardgrass, ‘Bronson’ tall fescue, ‘Winter’ alfalfa, ‘Starfire’ red clover, ‘Viking’ birdsfoot trefoil, and ‘Puna’ chicory (Table 2-1). The experimental design was a randomized complete block with two replicates.

The experimental site was used for grazing two years before establishment, and laid fallow for the year before establishing this experiment. During the fallow year, glyphosate was applied on 15 July and 10 August at a rate of 300 g a.i. ha^{-1}. The experimental site was then disked three times. The seed of each treatment was mixed prior to seeding. Plots of 2.5 m^2 were seeded with a 5-row cone planter with 15.24 cm spacing.

For each seeding time (late-summer 2002 and spring 2003), one sample was collected from each plot to estimate botanical composition when the first harvest would normally occur (25 cm sward height on average). Plots were sampled on 5 May 2003 (217 days after emergence) and on 5 August 2003 (101 days after emergence) for late-summer and spring seeding, respectively.

At each sampling, a 0.1 m^2 by 7.5 cm deep sod block was removed from each plot. From the sod sample, forage species were then cut at ground level, hand sorted, counted, washed, and dried at 60 °C for 48 h. In order to determine weed population and weed botanical composition, a 0.02 m^2 sub-sample was extracted from the original 0.1m^2 sod samples. Then weed species were cut at ground level, hand sorted, counted, washed, and dried. Botanical composition (both forages and weeds) was estimated based on dry matter percentage.

Forage dry matter and botanical composition data were analyzed with the PROC MIXED procedure of SAS (SAS Inst., 1999). The model for DM yield and botanical composition included the fixed effects of mixtures, seeding densities, and mixtures by seeding density. In addition, the model included the random effects of replicates and its interaction with the fixed effects. Botanical composition and DM data were transformed using the quadratic root to achieve normal distribution, however untransformed data are presented. When significant (*P*<0.05) effects due to forage mixtures and seeding densities were detected, mean separation was conducted by the PDIFF procedure adjusted for the Tukey option in SAS (SAS Inst., 1999). Data from each planting period (late-summer or spring) could not be pooled due to interaction with forage treatment and were analyzed separately.

Experiment 2

This experiment was carried out to evaluate weed suppression by a gradient of mixture complexity ranging from pure stand up to a seven species mixture. Species used were the same as in Experiment 1, except birdsfoot trefoil was replaced by 'Jumbo' white clover due to poor performance of birdsfoot trefoils and 'Tonga' perennial ryegrass was added to the most complex mixture (Table 2-2). Six forage treatments were seeded into tilled 3-by-6 m plots on 24 Aug. 2004 at the Pennsylvania State University Haller Farm, State College, PA (Table 2-2). Forage treatments 1 and 2 represented a typical orchardgrass pure stand; treatment 3 was a combination of orchardgrass-alfalfa commonly used in the northeast USA. The remaining mixtures were assembled to maximize forage production in the establishment year.

The forage treatments were mob-grazed with cow-calf pairs following two grazing schedules: 1) "Height" grazing schedule (grazing began whenever the mean height of the sward reached 25 cm.) or 2) "Morphology" grazing schedule (grazing began whenever the alfalfa reached bud stage). In both, cases the grazing animals were removed from the grazing area whenever the average stubble height reached 7.5 cm.

The experimental design was a split-plot arrangement of a randomized complete block design with four replicates. The grazing treatments were the main plots and forage treatments were the sub plots. Seeding density was 1000 live seeds m^{-2}. Soil fertility was brought up to optimum levels following soil test recommendations. Nitrogen was applied only to mixture 1 split into three applications of 84 kg ha^{-1} at green-up, after grazing in June, and after grazing in August.

To estimate herbage mass each plot was divided in fifths lengthwise. Within each fifth a random sample of 0.1-m^2 quadrat was clipped to a stubble height of 7.5 cm within an hour before the cattle were released to graze the plots. The five samples from each plot were combined and dried at 60°C for 48 h. Botanical composition was determined for the first and last harvests of each growing season by hand sorting sub-sample (approximately 150 g) from the combined samples before drying.

Dry matter yield and botanical composition data at first harvest were analyzed the same as in Experiment 1. The model for DM yield and botanical composition included the fixed effects of mixtures, grazing treatment, and mixture by grazing treatment. In addition, the model included the random effects of replicates, and its interaction with the fixed effects. In addition, red clover, perennial ryegrass, and chicory botanical composition effect on weed dry matter data were analyzed with the PROC REG procedure of SAS (SAS Inst., 1999).

Experiment 3

This experiment was set up to evaluate the use of fast establishing forage species combined into simple or complex mixtures to suppress weeds based on the results found in Experiment 2. Five forage treatments, four seeding ratios, and two weed treatments were seeded into 15-cm diameter pots under a controlled environment (greenhouse) in State College, PA. The same cultivars of orchardgrass, perennial ryegrass, alfalfa, red clover, and chicory as in the previous experiment were used in the mixtures (Table 2-3). These forage treatments consisted of an orchardgrass-alfalfa mixture and orchardgrass-alfalfa with the addition of a FEFS (red clover, perennial ryegrass, and chicory). Each FEFS was added at a rate of 12.5%, 25%, and 37.5% of total live seed (Table 2-3). Forage seeding density was 1000 live seeds m^{-2}. Weed treatments consisted of a winter annual species, represented by oil seed rape, and a summer annual species, represented by Japanese millet, planted at 500 live seeds m^2. Pots were thinned two weeks after establishment to achieve the species-specific density (Table 2-3). Additionally, all species (including weeds) were established as pure stands.

Each pot was fertilized with 46 kg N ha^{-1}, 92 kg P ha^{-1}, and 46 kg K ha^{-1} in two identical applications; immediately after thinning and a week after thinning. The average temperature during the experiment was maintained near 20 ºC (Fig. 2-1). The photoperiod was maintained at 16 hrs, with an average supplemental light of 700 µmols measured at canopy height.

The experimental design was a randomized complete block with four replicates and two runs; planted on 4 and 11 April. Emergence was recorded daily. Radiation interception one week before harvest was evaluated on all pure stands. Radiation was measured with the LI-1800 spectroradiometer (Li-Cor Inc. Lincoln, NE). Radiation interception was calculated by dividing the radiation at ground level by radiation above canopy times one hundred. All pots within each run were harvested 35 days after seeding. Herbage was clipped at ground level, hand sorted by species, dried for 48 hr at 60°C, and weighed.

Forage dry matter and botanical composition data were analyzed with the same procedure as in Experiments 1 and 2. The model included the fixed effects of mixtures, seeding ratios, and weed treatments and all possible interactions. The model also included the random effects of replicates and its interaction with the fixed effects. Forage DM data were transformed using the aquare root to achieve normal distribution, however untransformed data are presented. When significant effects due to forage mixtures, seeding ratio, and weed treatments were detected, mean separation was conducted as previously described. When significant ($P<0.05$) seeding ratio effects were detected a polynomial analysis was carried out with the PROC REG procedure of SAS (SAS Inst., 1999).

RESULTS

Experiment 1

During late-summer 2002, planting conditions were less than optimum. Precipitation for the months of July and August were well below average (Fig. 2-2).

However, establishment was good with an average stand density of 495 forage plants m^{-2}. Forage plants completed emergence within two weeks of planting. Planting conditions for spring 2003 were ideal, and plants emerged 10 days after planting and established well (Table 2-4 and Fig. 2-2).

Weed pressure was high (1450 weed plants m^2) and similar for both planting dates. Weed proportion (expressed as percentage of total DM), however, was smaller in the spring seeding (37%) than in late-summer (81%). However due to a significant ($P>0.0001$) seeding time by mixture interaction, these means cannot be separated. Therefore, weed content and forage DM yield were analyzed individually for each seeding time.

In the spring planting, weed proportion depended on forage mixture (Table 2-5). Pure chicory or a mixture composed of 70% chicory had the smallest weed percentages. On the other hand, pure stands of alfalfa or birdsfoot trefoil yielded the greatest weed proportions and the smallest forage DM yield at first harvest. These results are consistent with DiTomaso (2000) who also found that mixtures composed of species with various growth forms could increase weed suppression.

In contrast, there were no differences in weed percentage and forage yield for the different forage treatments during the late-summer seeding. The differences in response during spring and late-summer establishment may be due in part to the interaction of forage seedlings with weeds. Weed flora at establishment was different for the two seeding times (Fig. 2-3 and Table 2-6). Weed flora in the late-summer seeded plots was composed primarily of winter annuals (60%), followed by perennials (35%) and summer annuals (5%). The weed flora for the spring seeding was characterized by a high percentage of perennial weeds (54%), followed by summer annual weeds (35%), and winter annual weeds (11%).

For both seeding times there were no differences in weed proportion when forage species were seeded at two densities. Our results contrast with Mohler (2001) who proposed increasing seeding density of crops to control weed invasion. This lack of response for both seeding times may be due to insufficient difference in seeding densities to elicit a significant decrease in weed population. Increasing seeding densities did not reflect in greater forage production for either the spring seeding or the late-summer planting. This contradicts Osman and Nersoyan (1986) findings in that higher seeding density tended to produce more forage biomass.

Experiment 2

Only data from the first harvest of the first year were analyzed and shown. Mixture diversity highly influenced weed percentages at first harvest ($P<0.001$). The response was independent of grazing schedule ($P = 0.38$). Weed proportion of the DM at first harvest decreased as forage mixture complexity increased (Table 2-7). This result supports Tilman (2001) and DiTomaso (2000) who proposed the use of complex mixtures as an effective weed management tool. Regression analysis of the data (weed content and forage DM production were regressed by species composition expressed as % of DM) revealed that certain species within the forage mixtures explained more than 80% of the variation in weed DM yield at first harvest. In fact, red clover (mixture 4), red clover-chicory (mixture 5), and red clover-chicory-perennial ryegrass (mixture 6) explained 91, 88, and 88% of the variation in weed yield at first harvest, respectively. Ruijven et al. (2003) working with grasses and forbs also found that particular species in the mixture were responsible for weed suppression.

Forage DM yield was significantly ($P<0.004$) greater in the “Height” grazing schedule (900 kg ha^{-1}) compared to the “Morphology” grazing schedule (626 kg ha^{-1}). Forage DM yield was affected by mixture complexity ($P<0.001$). As the number of species in the mixtures increased so did the forage yield at first harvest. Similarly to the percentage of weeds at first harvest, 91, 88, and 88% of the variation in forage DM yield was explained by red clover (mixture 4), red clover-chicory (mixture 5), and red clover-chicory-perennial ryegrass (mixture 6), respectively. The results of this study indicate that the additions of carefully selected FEFS are an effective cultural weed suppression method and they also increase forage yield at first harvest. Additionally, grazing earlier (“Height” grazing treatment) increases forage DM yield if weeds are present.

Experiment 3

FEFS effect under weed competition:

The two weeds used in this experiment had distinctive germination speeds and plant architecture which affected forage-to-weed competition. Emergence was evaluated on monocultures and oil seed rape, alfalfa, and red clover were the first species to emerge within 3 days after planting. Japanese millet, perennial ryegrass, orchardgrass, and chicory emerged 5 days after planting. Among many differences between the two weed species tested in this experiment, the leaf insertion angle and leaf size may have played an important part in light competition. Oil seed rape leaves are large and horizontal, whereas Japanese millet leaves are narrow, long, and more upright. Thus, oil seed rape probably shaded the forage species more than the Japanese millet. This difference in canopy architecture is evidenced by the percentage of intercepted light that reached ground level measured in monocultures one week before harvest. Japanese millet intercepted significantly less ($P<0.0001$) radiation compared to oil seed rape. About 38 % of the radiation measured at the top of the canopy of Japanese millet reached the ground compared to only 8 % for oil seed rape. Both early emergence and seedling morphology have been suggested to influence competitive ability during establishment (Lodge, 2000; Harris, 2001). Hence the combination of these characteristics might have led to greater competitive advantages of oil seed rape compared to Japanese millet.

Weed content at first harvest was analyzed separately for each weed due to significant interaction with both FEFS type ($P<0.0003$) and seeding proportion ($P<0.04$). For the oil seed rape there were no differences in weed content at first harvest neither by FEFS type ($P<0.25$) nor by seeding proportion ($P<0.16$). On the other hand, both FEFS type and seeding density influenced weed content at first harvest when competing with Japanese millet. The sole addition of chicory decreased weed content by 20% compared to the orchardgrass-alfalfa mixture (Table 2-8). The second best FEFS addition was the combination of all three FEFS (mixture 5). The proportion of FEFS to be included in a mixture to elicit weed suppression was difficult to determine even though the addition of 37.5% of FEFS had significantly less weed content compared to the absence of FEFS (mixture 1). There was only a 9 % reduction in weed content by increasing the FEFS seeding proportion (Table 2-8). The addition of high percentages (37.5%) of FEFS must be evaluated bearing in mind the potential negative effects of FEFS on the target forage species. Therefore the addition of chicory in low percentage appears to be the best option to suppress weeds at first harvest. This could be explained by the greater relative growth rate of chicory compared to the other FEFS (measured in monoculture, data not shown). In fact chicory was the only forage species whose relative growth rate was comparable to those of oil seed rape and Japanese millet. Relative growth rate has been mentioned as a competitive advantage by Nurjaya and Tow (2001).

Forage DM yield was evaluated separately for the two weed species due to a significant ($P<0.001$) weed by forage mixture interaction. For both weeds, the addition of FEFS increased forage production and it was independent of the proportion of FEFS in the seed mixture. Any mixture containing FEFS produced between 36 to 81% more forage DM compared to the orchardgrass-alfalfa mixture when competing against oil seed rape (Table 2-9). On the other, hand adding only chicory produced the greatest forage yield when competing with Japanese millet, followed by the addition of all three FEFS (Table 2-9). The addition of red cover reduced the total forage DM yield by 5% compared to the orchardgrass-alfalfa mixture. Thus, the use of any FEFS under extremely high weed pressure (that was simulated in this study by the oil seed rape) led to an increase on forage DM yield at the first harvest. Under low weed competition the sole addition of chicory produced the greatest forage DM yield increase compared to the orchardgrass-alfalfa mixture.

FEFS effect without competition:

In the absence of weeds, forage DM yield was affected by the addition of a FEFS but independent of the proportion of the FEFS in the seed mixture (Table 2-10). However, none of the FEFS influenced forage DM yield compared to the orchardgrass-alfalfa mixture (Table 2-10).

The addition of FEFS decreased orchardgrass-alfalfa DM proportion (Table 2-10). Chicory caused the greatest reduction in orchardgrass-alfalfa DM proportion and red clover the least reduction. The amount of FEFS in the seed mixture (expressed as percentage of total live seeds) explained 56% of the variation in orchardgrass-alfalfa DM proportion at first harvest. Polynomial analysis revealed that the orchardgrass-alfalfa proportion of total forage DM decreased by increasing the proportion of FEFS as follows: % orchardgrass-alfalfa = $97.76-2.2*\%FEFS +0.02*\%FEFS^2$. Hence, FEFS decreased the proportion of the target forage species (in this instance alfalfa and orchardgrass). These results agree with companion crops research using annual crop species in that forage yield is reduced at first harvest (Hampton et al., 1999). However in this study, the “companion crop” was a perennial forage species, therefore it is unnecessary to separate the forage DM yield into FEFS and target forage species.

There were general trends among the three experiments presented. In experiment 1, mixtures produced on average 65% more forage DM and had less weed content (24%) compared to the pure stands. Similarly in the second experiment weed proportion decreased and DM increased as mixtures became more complex. Results of Experiment 3 also showed a decrease of weed content and increased forage yield for the more complex mixtures. These similarities in results among different experiments with diverse combination of species and with a wide range of weeds gives supporting evidence to previous research that showed an inverse relationship between plant diversity and weed invasion (Sheley and Carpinelli, 2005; Tilman, 2001; DiTomaso, 2000)

CONCLUSIONS

These series of studies have shown that the use of complex mixtures or FEFS is a viable alternative to annual companion crops for weed suppression during establishment. The sole presence of one or more of the species studied seemed to be enough to reduce weed invasion during establishment. Moreover, the selection of FEFS is a key component of mixtures in achieving such suppression. Chicory appeared to be the most effective FEFS in all the studies, hence its use in forage mixtures is recommended during pasture renovation. However caution has to be exercised when adding FEFS to slow establishing forage mixtures, because they will also decrease the proportion of the target forage species. Thus, the addition of chicory or a combination of all three FEFS studied in a low proportion of the seeding mixture (≤12.5%) will help decrease weed invasion and increase forage yield at the first harvest.

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Table 2-1: Seeding ratio of forage mixtures established at the Haller Farm near State College, PA, to determine the effect of such mixtures on forage production and weed invasion of the subsequent pasture, August 2002 and April 2003 (experiment 1).

Mixtures	Species percentages in each mixture
1	70% Orchardgrass / 6% Tall fescue / 6% Alfalfa / 6% Red clover / 6% Birdsfoot trefoil / 6% Chicory†
2	6% Orchardgrass / 70% Tall fescue / 6% Alfalfa / 6% Red clover / 6% Birdsfoot trefoil / 6% Chicory
3	6% Orchardgrass / 6% Tall fescue / 70% Alfalfa/ 6% Red clover / 6% Birdsfoot trefoil / 6% Chicory
4	6% Orchardgrass / 6% Tall fescue / 6% Alfalfa / 70% Red clover / 6% Birdsfoot trefoil / 6% Chicory
5	6% Orchardgrass / 6% Tall fescue / 6% Alfalfa / 6% Red clover / 70% Birdsfoot trefoil / 6% Chicory
6	6% Orchardgrass / 6% Tall fescue / 6% Alfalfa / 6% Red clover / 6% Birdsfoot trefoil / 70% Chicory
7	17% Orchardgrass / 17% Tall fescue / 17% Alfalfa / 17% Red clover / 17% Birdsfoot trefoil / 17% Chicory
8	100% Orchardgrass
9	100% Tall fescue
10	100% Alfalfa
11	100% Red clover
12	100% Birdsfoot trefoil
13	100% Chicory

† Percentages refer to the number of seeds of each species for every 100 seeds.

Table 2-2: Seeding ratio of forage mixtures established at the Haller Farm near State College, PA, to determine the effect of such mixtures on forage production and weed invasion of the subsequent pasture, August 2004 (experiment 2).

Mixtures	Number of Species	Species percentage in each mixture
1	1	100% Orchardgrass with 252 kg N ha^{-1}†
2	1	100% Orchardgrass (without nitrogen)
3	2	50% Orchardgrass / 50% Alfalfa
4	3	50% Orchardgrass / 30% Alfalfa / 20% Red clover
5	5	25% Orchardgrass / 25% Tall fescue / 20% Alfalfa / 20% Red clover / 10 % Chicory
6	7	15% Orchardgrass / 15% Tall fescue / 15% Perennial ryegrass / 15% Alfalfa / 15% Red clover / 15% White clover / 10 % Chicory

† Percentages refer to the number of seeds of each species for every 100 seeds.

Table 2-3: Seeding ratio and density of fast establishing forage species (FEFS); red clover, chicory, and perennial ryegrass in forage mixtures established in a controlled environment at State College, PA, to determine the effect of such mixtures on forage production and weed suppression at first harvest (Experiment 3).

FEFS proportion	Species percentage in each mixture
	Mixture 1
None	50% Orchardgrass / 50% Alfalfa†
	Mixture 2
Low	43.8% Orchardgrass / 43.8% Alfalfa / 12.5% Red clover
Medium	37.5% Orchardgrass / 31.3% Alfalfa / 25% Red clover
High	31.3% Orchardgrass / 31.3% Alfalfa / 37.5% Red clover
	Mixture 3
Low	43.8% Orchardgrass / 43.8% Alfalfa / 12.5% Chicory
Medium	37.5% Orchardgrass / 37.5% Alfalfa / 25% Chicory
High	31.3% Orchardgrass / 31.3% Alfalfa / 37.5% Chicory
	Mixture 4
Low	43.8% Orchardgrass / 43.8% Alfalfa / 12.5% Perennial ryegrass
Medium	37.5% Orchardgrass / 37.5% Alfalfa / 25% Perennial ryegrass
High	31.3% Orchardgrass / 31.3% Alfalfa / 37.5% Perennial ryegrass
	Mixture 5
Low	43.8% Orchardgrass / 43.8% Alfalfa / 4.2% Red clover / 4.2% Chicory / 4.2% Perennial ryegrass
Medium	37.5% Orchardgrass / 37.5% Alfalfa / 8.3% Red clover / 8.3% Chicory / 8.3% Perennial ryegrass
High	31.3% Orchardgrass / 31.3% Alfalfa / 12.5% Red clover / 12.5% Chicory / 12.5% Perennial ryegrass

† Percentages refer to the number of seeds of each species for every 100 seeds.

Table 2-4: Average monthly air temperature during 2002, 2003, 2004, and 2005 at the Haller Farm near State College, PA.

	Mean temperature				
Month	2002	2003	2004	2005	30-yr avg.
	-------------------------------------°C-------------------------------------				
January	1.6	-5.3	-7.1	-3.4	-3.1
February	1.5	-4.2	-2.8	-1.1	-2.1
March	3.6	3.0	4.0	0.3	2.6
April	10.7	9.3	9.5	9.6	9.0
May	13.7	14.3	17.6	11.7	15.1
June	21.1	18.6	18.3	20.6	19.7
July	23.5	21.8	20.6	22.4	22.1
August	23.1	22.2	19.8	22.0	21.0
September	19.1	16.5	17.7	18.2	17.0
October	9.9	9.8	10.2	11.2	10.9
November	4.8	7.6	6.5	5.8	5.0
December	-1.8	-0.2	-0.7	-3.6	-1.0

Table 2-5: Weed content as percent of DM yield and forage DM yield at first harvest of the forage mixtures in spring planting (experiment 1) at the Haller Farm near State College, PA.

Mixture	Weeds	Forage DM
	----%-----	--kg ha^{-1}--
70% Orchardgrass / 6% Tall fescue / 6% Alfalfa / 6% Red clover / 6% Birdsfoot trefoil / 6% Chicory	36 c†	3 604 a
6% Orchardgrass / 70% Tall fescue / 6% Alfalfa / 6% Red clover / 6% Birdsfoot trefoil / 6% Chicory	27 dc	2 867 a
6% Orchardgrass / 6% Tall fescue / 70% Alfalfa/ 6% Red clover / 6% Birdsfoot trefoil / 6% Chicory	37 c	3 461 a
6% Orchardgrass / 6% Tall fescue / 6% Alfalfa / 70% Red clover / 6% Birdsfoot trefoil / 6% Chicory	15 de	4 938 a
6% Orchardgrass / 6% Tall fescue / 6% Alfalfa / 6% Red clover / 70% Birdsfoot trefoil / 6% Chicory	25 dc	4 105 a
6% Orchardgrass / 6% Tall fescue / 6% Alfalfa / 6% Red clover / 6% Birdsfoot trefoil / 70% Chicory	9 e	3 950 a
17% Orchardgrass / 17% Tall fescue / 17% Alfalfa / 17% Red clover / 17% Birdsfoot trefoil / 17% Chicory	25 dce	3 384 a
100% Orchardgrass	39 c	2 493 a
100% Tall fescue	48 bc	2 398 a
100% Alfalfa	96 a	122 b
100% Red clover	26 dc	3 662 a
100% Birdsfoot trefoil	85 ba	257b
100% Chicory	9 e	4 720 a

† Within columns, means followed by the same letter are not significantly different according to Tukey's mean separation (*P* <0.05).

Table 2-6: Weeds identified in experiment 1 and 2 at Haller farm near State College, PA.

Scientific name	Common name	Growth habit
Bromus Sp.	Brome grass	Winter annual
Cerastium vulgatum	Mouse-ear chickweed	Perennial
Stellaria media	Chickweed	Winter annual
Circium sp.	Thistle	Perennial
Cpasella bursa-pastoris	Shepard's purse	Winter annual
Daucus carota	Wild carrot	Biennial
Setaria sp.	Foxtail	Summer annual
Poa pratenisis	Kentucky bluegrass	Perennial
Lamium amplexicaule	Henbit	Perennial
Lepidium campestre	Field peperweed	Winter annual
Thlapsi arvense	Pennyecress	Winter annual
Plantago rugelli	Blackseed plantain	Perennial
Polygonum pennsylvanicum	Pennsylvania smartweed	Winter annual
Agropyron Repens	Quackgrass	Perennial
Chenopodium album	Common lambsquarter	Summer annual
Lolium perenne	Ryegrass	Perennial
Amaranthus retroflexus	Redroot pigweed	Summer annual
Taraxacum officinale	Dandelion	Perennial
Trifoluim repens	White clover	Perennial
Oxalis stricta	Yellow woodsorrel	Winter annual

Table 2-7: Dry matter yield and weed content of the forage mixtures at first harvest (experiment 2) at the Haller Farm near State College, PA.

Entry	Weeds	Forage DM
	-------%-----	-----kg ha^{-1}----
Orchardgrass	90 a†	187 a
Orchardgrass (without nitrogen)	92 a	85 a
Orchardgrass / Alfalfa	75 b	425 a
Orchardgrass / Alfalfa / Red clover	44 c	1056 b
Orchardgrass / Tall fescue / Alfalfa / Red clover / Chicory	37 cd	1229 bc
Orchardgrass / Tall fescue / Perennial ryegrass / Alfalfa / Red clover / White clover / Chicory	26 d	1592 c

† Within columns, means followed by the same letter are not significantly different according to Tukey's mean separation (*P* <0.05).

Table 2-8: Weed content at first harvest when competing with Japanese millet (experiment 3).

Mixture	Weed Content
	-----------%--------
Orchardgrass / Alfalfa	70 a†
Orchardgrass / Alfalfa / Red clover	71 a
Orchardgrass / Alfalfa / Chicory	55 c
Orchardgrass / Alfalfa / Perennial ryegrass	67 a
Orchardgrass / Alfalfa / Red clover / Chicory / Perennial ryegrass	62 b
FEFS proportion	
	-----------%--------
None (0%)‡	70 a
Low (12.5%)	66 ab
Medium (25%)	65 ab
High (37.5%)	61 b

† Within columns, means followed by the same letter are not significantly different according to Tukey's mean separation (*P* <0.05).

‡ Percentages refer to the number of seeds of each species for every 100 seeds.

Table 2-9: Forage dry matter yield of the forage mixtures at first harvest when competing with two different weeds in a controlled environment† (experiment 3).

Mixture	Oil seed Rape	Japanese Millet
	----------------kg ha^{-1}----------------	
Orchardgrass / Alfalfa	480 c‡	2000 a
Orchardgrass / Alfalfa / Red clover	650 b	1900 a
Orchardgrass / Alfalfa / Chicory	840 a	3000 c
Orchardgrass / Alfalfa / Perennial ryegrass	780 ab	2300 a
Orchardgrass / Alfalfa / Red clover / Chicory / Perennial ryegrass	870 a	2600 b

† Average temperature: 20 °C, Photoperiod of 16 hrs, and average supplemental light of 700 μmols.

‡ Within columns, means followed by the same letter are not significantly different according to Tukey's mean separation (*P* <0.05).

Table 2-10: Dry matter yield and alfalfa-orchardgrass content of the forage mixtures at first harvest in a controlled environment† (experiment 3).

Mixture	Forage DM	Alfalfa-orchardgrass
	---kg ha^{-1}---	------------%------------
Orchardgrass / Alfalfa	4300 ab‡	100 a
Orchardgrass / Alfalfa / Red clover	3700 b	73 b
Orchardgrass / Alfalfa / Chicory	5000 a	40 e
Orchardgrass / Alfalfa / Perennial ryegrass	3900 b	66 c
Orchardgrass / Alfalfa / Red clover / Chicory / Perennial ryegrass	4700 a	52 d

† Average temperature: 20 °C, Photoperiod of 16 hrs, and average supplemental light of 700 µmols.

‡ Within columns, means followed by the same letter are not significantly different according to Tukey's mean separation (*P* <0.05).

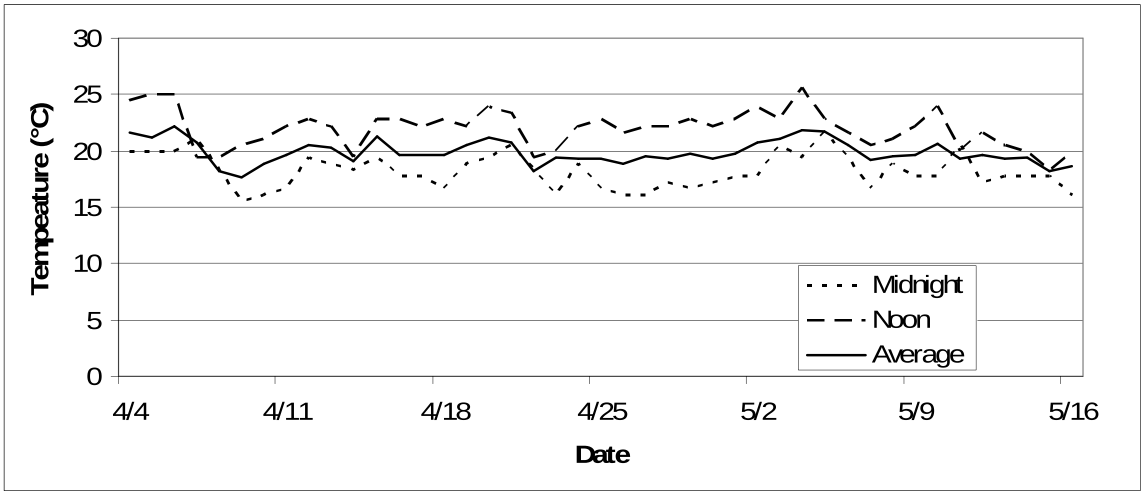

Fig. 2-1: Noon, midnight, and average temperature during the greenhouse experiment in Celsius degrees.

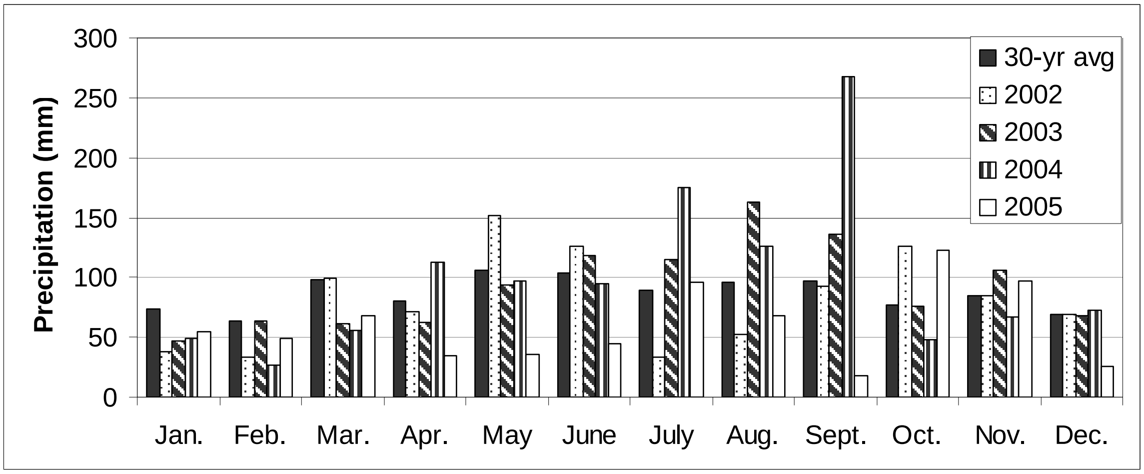

Fig. 2-2: Monthly precipitation during 2002, 2003, 2004, and 2005 at the Haller Farm near State College, PA.

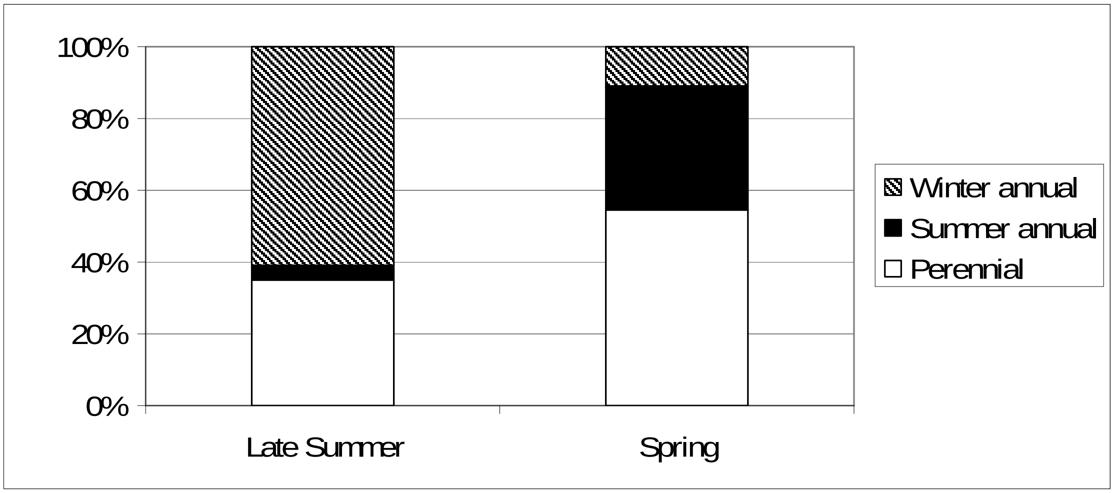

Fig. 2-3: Changes in weed flora at first harvest between late summer and spring establishment of forages (experiment 1) at the Haller Farm near State College, PA. Data is expressed as percentage (%) of total weed dry matter. Weed flora was pooled into three groups: perennials, summer annuals, and winter annuals based on their growth habits.

CHAPTER 3

GRAZING SCHEDULE EFFECT on FORAGE PRODUCTION and NUTRITIVE VALUE of DIVERSE FORAGE MIXTURES

Sustained forage production is a key element for successful livestock production in grazing systems. Sustained biomass production in natural grassland ecosystems may be influenced by plant diversity (Tilman, 2001). Recent research has investigated the influence of forage diversity on pasture production in the northeast USA (Skinner et al., 2006; Sanderson et al., 2005; Skinner et al., 2004; Deak et al., 2004; Tracy and Sanderson, 2004). Based on the findings of these studies it is clear that not only the number of forage species is important to increase forage production, but also the particular species play a significant role in achieving greater forage productivity (Sanderson et al., 2005; Skinner et al., 2006; Deak et al., 2004). Thus, pasture performance (dry matter (DM) production and nutritive value) could be improved by combining carefully selected forage species.

A challenge that arises in designing diverse pasture systems is the lack of information on how to select and combine forage species for improved DM production (Sanderson et al., in press). Selecting species based on their individual performance in the prevailing environment and combining them to formulate mixtures, would be an obvious approach. However, the performance of forage mixtures cannot be predicted from individual species performance in a pure stand. In some countries, there are formal programs in place for selecting and evaluating forage mixtures (Kessler and Suter, 2005).

Since in the northeast USA there are no such formal programs, selecting species based on previous research that evaluated complex mixtures provides a viable alternative.

The management of such complex mixtures (forage mixtures composed by more than 3 species) presents some problems. One disadvantage is that botanical composition of forage mixtures changes over time in response to the environment and grazing management (Lauriault et al., 2006; Belesky et al., 2002a; Belesky et al., 2002b; Carrere et al., 1997). Botanical shifts affect forage quality, complicating the estimation of the nutritional value of a pasture (Skinner et al., 2004; Crosthwaite et al., 1996; Wilson and Clark, 1960; Belesky, 1999). Previous research provides evidence that crude protein is positively related to legume content of a mixture, and neutral detergent fiber is positively related to grass content of a mixture (Sheaffer et al., 1990; Zemenchick et al., 2002: Deak et al., in press). Thus, it is important to maintain the grass-legume balance of swards through grazing management.

Length of rotation cycle and duration of grazing period are key to maintaining the grass-legume balance in rotational grazing systems. Pennsylvania State University extension recommends grazing tall, cool-season grasses when they reach an average of 20-25 cm of sward height, and to stop grazing when the stubble reaches 7.5 cm on average (Hall, 2004). On the other hand, alfalfa is recommended to be grazed in late pre-bud stage in spring, and every 35 days thereafter (Hall, 2004). However, recommendations for grazing grass-legume mixtures are not as clear-cut. Mixtures grazed based on canopy height (following Penn State recommendation for cool-season grasses) lead to a decrease in legume content in both simple and complex mixtures (Deak et al., in press). Grasses usually reached the target height before legumes reached bud stage (Deak et al., in press). Hence, the decrease of legumes both in simple and complex forage mixtures can be explained by the differences in re-growth rates between cool-season grasses and legumes. Basing grazing time decisions on the legume developmental stage rather than on the average sward height might maintain the legume content of the mixture. Barbarossa and Miñon (2001) showed that grazing a mixture of orchardgrass and alfalfa when the alfalfa reached bud stage or basal regrowth of 5 to 7.5 cm increased alfalfa content of the mixture and DM yield during the second and third year. Similarly, Refi and Martin (2001) working with a mixture of alfalfa (dormancy group 9), tall fescue, bromegrass, and white clover found that grazing when alfalfa reached bud stage or basal regrowth of 5 to 7.5 cm and leaving a stubble of 7.5 to 10 cm improved alfalfa content of the mixture.

The objective of this study was to evaluate the effects of grazing schedule on forage production, nutritive value, and botanical composition of pure grass stands, simple, and complex mixtures under rotational grazing management. We hypothesized that changing grazing initiation based on alfalfa development rather than canopy height would increase legume content of forage mixtures thereby improving forage nutritive value and with little effect on DM production.

MATERIALS AND METHODS

Six forage mixtures were seeded into tilled 3-by-6 m plots on 24 Aug. 2004 at the Pennsylvania State University Haller Farm, State College, PA. ‘Tekapo’ orchardgrass, ‘Bronson’ tall fescue, ‘Tonga’ perennial ryegrass, ‘Winter’ alfalfa, ‘Starfire’ red clover, 'Jumbo' white clover, and 'Puna' chicory were used in the mixtures (Table 3-1). The first three forage treatments represented commonly used cool-season grass planted alone or in combination with alfalfa. The fourth treatment had the addition of red clover as an alternative to the typical grass-legume mixture. The two complex mixtures tested (mixtures 5 and 6) were combinations of species commonly used in the northeast USA that have performed adequately in previous research (Sanderson et al., 2005; Skinner et al., 2006; Deak et al., in press)

The forage treatments were mob-grazed five or six times per growing season (Table 3-2) with 12 to 14 cow-calf pairs (*Bos taurus*) of mixed breeds following two grazing schedules: 1) "Height" grazing schedule: grazing began whenever the mean height of the sward reached 25 cm; or 2) "Morphology" grazing schedule: grazing began whenever the alfalfa reached bud stage. In both cases, whenever the target threshold was reached (either canopy height or development stage), the cattle were released onto the plots and allowed to remain until the sward height was reduced to an average of 7.5 cm, which took from 8 to 12 h. Average stocking density was 30 000 kg live wt ha^{-1}. After grazing, the dung was manually removed from the plots and the stubble was mowed so that none of it stood taller than 7.5 cm.

The experimental design was a split-plot arrangement of a randomized complete block design with four replicates. The grazing treatments were the main plots and forage treatments were the sub plots. The seeding density was 1000 live seeds m^{-2}. Soil tests in April 2004 indicated a pH of 6.4, 52 kg ha^{-1} of available P, and 498 kg ha^{-1} of available K in the surface 15 cm. Therefore, plots were fertilized in August 2004 with 67 kg P ha^{-1}. Nitrogen was applied only to treatment 1 split into three applications of 84 kg ha^{-1} at green-up, after grazing in June, and after grazing in August. Potato leaf hoper (*Empoasca fabae* H.) was controlled on 1 June 2005, 10 July 2005, 15 June 2006, and 18 July 2006 with lambda-cyhalotrin at 22 gr a.i. ha^{-1} applied to the entire study area.

To estimate herbage mass, each plot was divided in fifths lengthwise. Within each fifth a random sample of 0.1-m^2 quadrat was clipped to a stubble height of 7.5 cm within an hour before the cattle were released to graze the plots. The five samples from each plot were combined and dried at 60°C for 48 h. Botanical composition was determined for the first and the last harvests of each growing season by hand sorting a sub-sample (approximately 150 gr) from the combined samples before drying. Botanical composition data were determined as percentages of total DM.

Nutritive value was determined on hand-clipped samples from each harvest. After all grazing events of the 2005 and 2006 seasons, those samples that were sorted for botanical composition were reconstituted and ground to pass a 2-mm screen in a Wiley mill (Thomas-Wiley, Philadelphia, PA). Crude protein (CP), acid detergent fiber (ADF), neutral detergent fiber (NDF), and in vitro true dry matter digestibility (IVTDMD) were estimated by near infrared reflectance spectroscopy at a commercial laboratory (DairyOne Ithaca, NY). Two sets of forage nutritive value data were statistically analyzed. The first set was composed of the nutritive value at first harvest. We analyzed nutritive value of the first harvest separately because it would likely show the greatest difference between grazing treatments. For the second set, forage nutritive value data were averaged for each mixture and for each year weighted by DM yield. The weighted average for each nutritive value item (CP, ADF, NDF, and IVTDMD) for each mixture was calculated as (using CP as example): $WACP = (\Sigma CP_i * DM_i)/ \Sigma DM_i$.

Where:

- WACP represents the weighted average of CP (g kg^{-1} DM),
- CP_i represents the CP content (g kg^{-1} DM) of harvest i, and
- DM_i represents the DM of harvest i.

Dry matter yield, forage nutritive value at first harvest, weighted average nutritive value, and botanical composition data were analyzed with the PROC MIXED procedure of SAS (SAS Inst., 1999). The model for DM yield, forage nutritive value at first harvest, weighted average nutritive value, and botanical composition included the fixed effects of mixtures, grazing treatment, year, year by mixture, year by grazing treatment, and mixture by grazing treatment. In addition, the model included the random effects of replicates and their interaction with the fixed effects. Only botanical data was analyzed repeated over years due to non significant year by grazing treatment and forage treatment interaction. When significant ($P<0.05$) effects due to forage mixtures and grazing treatment were detected, mean separation was conducted by the PDIFF procedure adjusted for the Tukey option in SAS (SAS Inst., 1999).

RESULTS AND DISCUSSION

Air temperature was near average during the 2005 and 2006 growing seasons (Fig. 3-1). Rainfall during 2005 growing season was well below average; the spring of 2006 was near average (with the exception of May) and below average the remainder of that year (Fig. 3-2).

Botanical Composition

There were significant changes in species composition over the two grazing seasons due to grazing schedule (Table 3-3). In general, there were no differences among the major functional groups (grasses, legumes, and weeds). The “morphology” grazing treatment positively influenced the forb (chicory) content. Chicory content increased with greater time interval between grazing events probably because the additional time allowed this species to bolt (produce seed stalks; Sanderson et al., 2003). Among all species used in the experiment, only perennial ryegrass, chicory and red clover were affected by grazing schedule (Table 3-3). Both red clover and chicory benefited from less frequent grazing. On the other hand, perennial ryegrass flourished under more frequent grazing. Grass content of forage mixtures have been shown to increase with increasing defoliation frequency (Lauriault et al., 2006; Skinner et al., 2006). Unexpectedly, both alfalfa and orchardgrass content in the sward were not influenced by grazing frequency. This result contrasts with previous findings in that alfalfa decreased when grazed more frequently (Deak et al., in press; Lauriault et al., 2006; Barbarossa and Miñon, 2001; and Refi and Martin, 2001). The lack of change in the amount of alfalfa between grazing treatments could be explained by the extremely dry weather in 2005 and the somewhat dry year in 2006 compared to the relatively wet years (2003 and 2004 were above average rainfall) that dominated the study conducted by Deak et al. (in press). The difference in grazing frequency between the grazing treatments in the present study were smaller compared to those used by Lauriault et al (2006), which could be another reason for lack of response in alfalfa performance.

Mixture complexity highly influenced botanical composition. Grass content was not significantly different among treatments as forage mixtures became more diverse (Table 3-4). Legume content was greater in simple mixtures (2- and 3- species) compared to the complex mixtures (5- and 7- species mixtures). Chicory, the only forb tested, was only used in complex mixtures, and its content was similar in both mixtures. White clover and perennial ryegrass were used only in the 7-species-mixture. Red clover remained similar in all mixtures (Table 3-4). Tall fescue accounted for less DM in the 6-species mixture compared to the 5-species mixture. Additionally, as mixture diversity increased orchardgrass and alfalfa content decreased.

The grass-legume content of the mixtures remained similar during the experiment, but the specific compositions of the mixtures changed. This is the result of an even contribution of DM production among more species as diversity increased. This contrasts with previous research where a few species were responsible for a large proportion of the total DM production in complex mixtures (Sanderson et al., 2005; Skinner et al., 2006; Deak et al., in press).

Weed content was not affected by grazing treatment (Table 3-3). On the other hand, forage treatment greatly affected weed proportion. Weed content decreased as mixture plant diversity increased (Table 3-4). The orchardgrass monoculture without nitrogen had greater weed content than any other forage treatment. The addition of nitrogen to orchardgrass decreased weed content. However, the weed content of orchardgrass with nitrogen was greater compared to the most complex mixture tested (mixture 6; Table 3-4). Thus, weeds comprised a relatively important proportion of the pure stands and weed content decreased with increasing plant diversity as others have also noted (Sanderson et al., 2005; Skinner et al., 2006).

Forage Production

The different weather patterns in 2005 and 2006 affected the forage treatments; therefore, data are reported separately for each year. The grazing schedule by year interaction was not significant; hence data were pooled across years for analysis. The “height” grazing treatment produced 30% more DM (6 777 kg ha^{-1}) compared to the “morphology” grazing treatment (5 222 kg ha^{-1}) on average. This result contradicts previous research in the southern Rocky Mountains that showed no differences in DM production of tall fescue-legume mixtures by increasing grazing frequency (Lauriault et al., 2006). These researchers concluded that the forage species compensated for environmental effects under irrigation; whereas, the current study showed an important effect of weather on grazing frequency. In 2005, a very dry year, there was an equal number of grazing events for both grazing treatments; however, the “height” treatment was grazed more frequently (Fig. 3-2, Table 3-2). Because of dry weather in 2005, the additional days between grazing events for the “morphology” grazing treatment did not improve forage accumulation. In 2006, greater rainfall led to an extra grazing event for the “height” treatment that might explain in part the greater DM production for this treatment. Thus, the major reason for inconsistency between the results of the present study and those of Lauriault et al (2006) might be that the current study was not irrigated.

Forage treatments greatly affected DM production (Table 3-5). For the 2005 growing season, the complex (5- and 7-species) mixtures produced more DM than the alfalfa-orchardgrass mixture or an orchardgrass pure stand (with or without N). The alfalfa-orchardgrass mixture produced the greatest yield in 2006 (Table 3-5). Similarly, Sanderson et al. (2005) found that complex mixtures produced greater yields in dry years compared to simple mixtures, but there were no differences among species mixtures in a wet year. In another study carried out in the northeast USA, Skinner et al. (2006) found that both under hay or grazing harvest treatment, the complex mixture produced greater DM yields compared to a 2-species mixture averaged over four growing seasons. In a New Zealand hill country study, it was found that complex mixtures of forages produced more herbage than simple mixtures due to the inclusion of certain functional groups (Dodd et al., 2004). On the other hand, recent research carried out in Illinois found that complex mixtures of grasses and legumes did not produce greater DM yield than simple mixtures (Tracy and Faulkner, 2006).

Improved performance of complex mixtures in previous research with pastures in the northeast USA was mainly due to the “sampling effect” (Sanderson et al., 2005; Skinner et al., 2006; Deak et al., in press). The sampling effect is one of the mechanisms hypothesized to be responsible for improved yield in diverse plant environments (Minns et al., 2001). This theory states that as the number of species is increased, so is the chance of including a highly productive species that will dominate the mixture. Another proposed mechanism for increased yield as a result of greater plant diversity is niche complementary (Tilman 1999). This theory states that in heterogeneous environments (both spatial and/or temporal heterogeneity) diverse species with differential competitive ability will perform the best and dominate part of the habitat where conditions are closer to the species optimal growth factors, but no species can fully exploit the entire range of conditions (Tilman 2001). Since in the present study the mixtures were not dominated by a single species, niche complementary might have been the mechanism responsible for increased yields. The difference in operating mechanisms between previous research conducted in the northeast USA and the present work may be in part because the complex mixtures tested in the current study were composed by the dominant species in the studies conducted by Sanderson et al. (2005), Skinner et al. (2006), and Deak et al. (in press).

It is important to note that the DM yield of complex mixtures was stable over the diverse climatic conditions experienced in 2005 and 2006. In contrast, DM yields increased by 23% for the three-species mixtures and increased up to 98% for the pure orchardgrass without N between 2005 and 2006. These results clearly showed that complex forage mixtures produce more consistent DM production as a result of their capacity to produce in dry years as noted by others (Skinner et al 2006; Sanderson et al., 2005). However, consistent DM yield in the current research could not be attributed solely to a highly productive, drought-stress tolerant species as found by Skinner et al. (2006) and Sanderson et al. (2005) because mixtures were not dominated by a single species.

The use of legumes in addition to grasses has been proven an efficient management alternative to the use of inorganic fertilizers (Malhi et al., 2002; Zemenchik et al., 2002). In the present study, the addition of alfalfa to a pure orchardgrass produced comparable DM production to a pure stand of orchardgrass fertilized with 250 kg N ha^{-1}. Similar results were found by researchers that have evaluated the use of legumes to avoid inorganic N fertilizers in clipped experiments (Malhi et al., 2002; Zemenchick et al., 2002; Berdahl et al., 2001). Even though in grazing systems nutrients, especially N, are replenished through excreta (Belesky et al., 2002b); our results showed that addition of alfalfa to pure orchardgrass DM yield was comparable to the orchardgrass with N (Table 3-5).

Forage Nutritive Value

Grazing Schedule:

Forage nutritive value at first harvest and weighted average nutritive value data were analyzed separately for 2005 and 2006 due to year by grazing treatment interactions. Additionally, in some instances there were grazing schedule by forage treatment interactions. In the case of such occurrence, data are shown for grazing treatment but were analyzed separately to elucidate how mixtures differentially responded to grazing treatments and results are reported in the forage treatment section.

There were differences in nutritive value between the grazing treatments at first harvest. For the 2005 first grazing, the “height” grazing treatment provided greater CP, IVTDMD, and smaller NDF concentration than the “morphology” treatment (Table 3-6). There was no difference in ADF concentration between grazing treatments during 2005. In 2006, the “height” treatment produced herbage of higher nutritive value than the “morphology” grazing treatment (Table 3-6); however NDF showed a significant grazing schedule by mixture treatment interaction. The differences in nutritive value between grazing treatments can be attributed to a delay in the first harvest of the “morphology” treatment, which allowed some species to be more mature than in the “height” treatment (Table 3-2). Delaying first harvest has been shown to reduce nutritive value of the forage due to advance in plant maturity (Albrecht and Hall, 1995). Fewer differences in nutritive value between grazing treatments were found over the entire growing season (weighted average values). However, the “height” treatment provided lower ADF and higher CP contents in 2006 and 2005, respectively. In 2005, NDF and IVTDMD contents of the “height” treatment were lower and higher, respectively compared to the “morphology” treatment, but due to grazing schedule by forage treatment interaction these parameters were analyzed separately for each grazing event and data are presented in the next section. The small differences in forage nutritive value data over the entire growing seasons between grazing treatments could be a result of the small differences in grass-legume ratio between grazing treatments. Others have reported that grass-legume proportion influences nutritive value (Sheaffer et al., 1990; Zemenchick et al., 2002: Deak et al., in press).

Forage Treatment:

The effect of forage treatments on nutritive value at first harvest was influenced by both plant diversity and the use of N fertilizer on the orchardgrass. In general, as mixture complexity increased the nutritive value improved (Table 3-7). This finding contrasts with White et al. (2004) who found that increasing mixture complexity negatively affected CP and IVTDMD, primarily because the legume content was smaller in the high diversity treatment in the White et al. (2004) study. On the other hand, Deak et al. (in press) found slight differences in nutritive value among mixtures of 2 to 9-species. In another study, simple mixtures produced greater CP only in one of three years; however, the mechanism responsible for those results was not clear (Tracy and Faulkner, 2006).

The addition of inorganic N to orchardgrass improved nutritive value compared to the orchardgrass without N; nonetheless, an increase in CP content was the only significant difference noted for both grass monocultures at first harvest and over the entire growing season (Table 3-7 and Table 3-8). Nitrogen increases CP content of cool-season grasses in clipped experiments (Follett and Wilkinson, 1995; Malhi et al., 2002; Zemenchik et al., 2002); however the N effect on nutritive value of forages in grazing systems has not been documented. The grazing animal accounts for a large proportion of N cycling in pastures (Belesky et al., 2002b) hence N fertilization effects on nutritive value might be less evident in a grazing system than under cutting. In our case, the addition of N to pure grass under grazing had similar effects as those reported earlier (Follett and Wilkinson, 1995; Malhi et al., 2002; Zemenchik et al., 2002).

Forage nutritive value evaluated over the entire growing season showed that ADF and NDF decreased as species richness increased (Table 3-8). Neutral detergent fiber had the greatest differences among forage treatments. Additionally, whenever data were analyzed separately for each grazing treatment (NDF in 2005 and IVTDMD in both years) nutritive value of complex mixtures remained similar. This suggests a greater flexibility of complex mixtures in maintaining adequate nutritive value independent of the grazing schedule.

CONCLUSIONS

Grazing schedule had little effect on botanical composition. Mixture complexity reduced legume content. Weeds were prevalent in grass monocultures, and there was a downward trend in weed content as diversity increased. Contrary to our hypothesis, grazing treatments altered DM production. The "height" grazing treatment produced greater DM yield that was likely a consequence of weather conditions during the growing seasons. The addition of legumes to pure grass stands improved nutritive value, DM production, and reduced use of N fertilizer in grazing systems. Mixture complexity improved DM production in a dry year, but produced inferior DM yield in more favorable weather conditions. More importantly variability in DM yield decreased between years with increasing mixture complexity. There were differences in nutritive value both by grazing treatment and mixture complexity at first harvest. These differences declined over the entire growing season. Based on this research, it would be advantageous to begin the first grazing of the year based on canopy height. Finally, the use of complex mixtures composed of forage species adapted to the environment can be an alternative to grass-legume mixtures or grass monocultures in drought prone environments where consistency in DM production is more important than top forage productivity.

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Table 3-1: Seeding ratio of forage mixtures established at the Haller Farm near State College, PA, to determine the effect of such mixtures on forage production and weed invasion of the subsequent pasture.

Mixtures	Species percentage in each mixture
1	100% Orchardgrass with 252 kg N ha^{-1}†
2	100% Orchardgrass (without nitrogen)
3	50% Orchardgrass / 50% alfalfa
4	50% Orchardgrass / 30% alfalfa / 20% red clover
5	25% Orchardgrass / 25% tall fescue / 20% alfalfa / 20% red clover / 10 % chicory
6	15% Orchardgrass / 15% tall fescue / 15% perennial ryegrass / 15% alfalfa / 15% red clover / 15% white clover / 10 % chicory

† Percentages refer to the number of pure live seeds of each species for every 100 seeds.

Table 3-2: Grazing dates for the forage mixtures during 2005 and 2006 at the Haller Farm near State College, PA.

Year	"Morphology" grazing	"Height" grazing
2005	23 May, 27 June, 28 July, 19 Sep., 14	16 May, 14 June, 18 July, 1 Sep., 30
2006	17 May, 30 June, 26 July, 30 Aug., 10	8 May, 8 June, 10 July, 14 Aug., 18

Table 3-3: Influence of grazing schedule in botanical composition during 2005 and 2006 growing seasons. Values are averages of the first and last grazing event of each growing season.

Functional Groups	Morphology	Height	SE †
	--------as % of sward dry matter---------		
Grasses	39.7	42.5	2.4
Legumes	34.6	37.0	2.7
Weeds	11.6	13.0	1.1
Forb (Chicory)	24.8 a‡	15.9 b	2.3
Species			
Alfalfa	17.3	20.6	2.3
Orchardgrass	33.3	35.5	2.3
Perennial ryegrass	4.0 a	13.2 b	1.8
Red clover	23.5 a	14.1 b	2.0
Tall fescue	9.5	11.3	1.1
White clover	4.2	5.1	1.0

† SE, Standard error of the mean.

‡ Within rows, means followed by the same letter are not significantly different according to Tukey's mean separation (*P* <0.05).

Table 3-4: Influence of forage treatment on botanical composition contribution during 2005 and 2006 growing seasons. Values are averages of the first and last grazing event of each growing season.

Functional Groups	Forage Treatments						
	1†	2	3	4	5	6	SE ‡
	------------------------------ % of sward dry matter---------------------------						
Grasses	65.3 a§	58.6 a	32.1 b	36.1 b	25.7 b	28.8 b	4.2
Legumes			40.5 a	44.9 a	27.2 b	28.0 b	3.1
Weeds	15.1 b	24.7 a	10.3 bc	9.6 bc	7.9 bc	6.2 c	1.9
Forb (chicory)					21.1	19.7	2.4
Species							
Orchardgrass	65.3 a	58.6 a	32.2 b	36.2 b	9.3 c	4.9 c	4.1
Alfalfa			40.0 a	20.1 b	9.7 c	6.0 c	2.4
Red clover				24.6	16.7	15.1	2.5
Tall fescue					14.7 a	6.1 b	1.1
Chicory					21.1	19.7	2.4

† 1, Orchardgrass with N; 2, Orchardgrass without N; 3, Orchardgrass-alfalfa; 4, Orchardgrass-alfalfa-red clover; 5, Orchardgrass-alfalfa-red clover-tall fescue-chicory; 6, Orchardgrass-alfalfa-red clover-tall fescue-chicory-white clover-perennial ryegrass.

‡ SE, Standard error of the mean.

§ Within rows, means followed by the same letter are not significantly different according to Tukey's mean separation (*P* <0.05).

Table 3-5: Dry matter yield of the forage treatments grazed at the Haller Farm near State College, PA. Data were not averaged over the two years due to a forage treatment by year interaction.

Forage treatment	Year	
	2005	2006
	----------------kg ha^{-1}--------------	
Orchardgrass with N	4272 b†	7468 bc
Orchardgrass without N	2636 a	5221 a
Orchardgrass-alfalfa	4378 b	8510 c
Orchardgrass-alfalfa-red clover	5745 bc	7082 bc
Orchardgrass-alfalfa-red clover-tall fescue-chicory	6472 c	6624 b
Orchardgrass-alfalfa-red clover-tall fescue-chicory-white clover-perennial ryegrass	6816 c	6772 b
SE ‡	433	408

† Within a column, means followed by the same letter are not significantly different according to Tukey's mean separation (*P* <0.05).

‡ SE, Standard error of the mean.

Table 3-6: Forage nutritive value at first harvest and over the growing season (weighted average) influenced by grazing treatment under grazing at the Haller Farm near State College, PA.

Grazing Treatment	ADF†		NDF		CP		IVTDMD	
	2005	2006	2005	2006	2005	2006	2005	2006
	--g kg^{-1}--							
	Nutritive value at first grazing							
Morphology	276	282 a‡	395 a	478 a§	167 a	179 a	835 a	878 a
Height	271	262 b	370 b	425 b	188 b	209 b	868 b	931 b
SE ¶	5.6	3.1	6.5	11.0	3.1	3.3	4.1	5.4
	Weighted average nutritive value							
Morphology	256	276 a	406	465 a§	207 a	215	865 a§	884§
Height	265	247 b	415	427 b	221 b	225	876 b	870
SE	3.1	2.6	7.1	5.9	2.2	4.5	2.6	11.3

† ADF: acid detergent fiber, NDF: neutral detergent fiber, CP: crude protein, IVTDMD: in vitro true dry matter digestibility.

‡ Within a column, means followed by the same letter are not significantly different according to Tukey's mean separation (*P* <0.05).

§ Significant grazing schedule by forage treatment interaction data were subsequently analyzed separately for each grazing treatment.

¶ SE, Standard error of the mean.

Table 3-7: Forage nutritive value at first harvest influenced by forage treatment at the Haller Farm near State College, PA. In vitro dry matter digestibility data are an average of 2005 and 2006 growing seasons, ADF, NDF, and CP data were not averaged over the two years due to a forage treatment by year interaction. Additionally, NDF in 2006 was not averaged over grazing treatments due to a forage treatment by grazing schedule interaction.

Forage Treatment	ADF†		NDF			CP		IVTDMD
	2005	2006	2005	2006		2005	2006	2005-2006
	-----------------g kg^{-1}-----------------							
				Height	Morphology			
1‡	279 ab§	281 ab	372 bc	485 a	573 a	178 b	191 ab	879 bc
2	291 a	286 a	407 a	493 a	556 a	148 c	163 c	866 c
3	293 a	288 a	398 ab	407 b	505 ab	161 c	186 b	863 c
4	257 c	265 bc	360 c	425 b	473 b	205 a	212 a	871 bc
5	265 bc	263 c	374 bc	390 bc	393 c	191 ab	209 a	886 ab
6	256 c	251c	385 abc	350 c	369 c	184 b	206 a	903 a
SE ¶	6.1	4.6	8.8	11.9	19.4	4.1	5.7	2.8

† ADF: acid detergent fiber, NDF: neutral detergent fiber, CP: crude protein, IVTDMD: in vitro true dry matter digestibility.

‡ 1, Orchardgrass with N; 2, Orchardgrass without N; 3, Orchardgrass-alfalfa; 4, Orchardgrass-alfalfa-red clover; 5, Orchardgrass-alfalfa-red clover-tall fescue-chicory; 6, Orchardgrass-alfalfa-red clover-tall fescue-chicory-white clover-perennial ryegrass.

§ Within a column, means followed by the same letter are not significantly different according to Tukey’s mean separation (*P* <0.05).

¶ SE, Standard error of the mean.

Table 3-8: Forage nutritive value over the growing season (weighted average) influenced by forage treatment at the Haller Farm near State College, PA. Acid detergent fiber and CP data were not averaged over the two years due to a forage treatment by year interaction. Additionally, NDF in 2006 and IVTDMD both 2005 and 2006 were not averaged over grazing treatments due to a forage treatment by grazing schedule interaction.

Forage Treatment	ADF†		NDF			CP		IVTDMD			
	2005	2006	2005	2006		2005	2006	2005		2006	
	g kg^{-1}										
				Height	Morphology			Height	Morphology	Height	Morphology
1‡	262 bc§	277 a	442 c	489 a	570 a	226 a	218 a	894 b	892 c	856	898 a
2	278 a	276 a	472 d	477 ab	545 a	198 c	196 b	875 ab	874 bc	882	881 abc
3	263 b	264 ab	410 b	406 bc	460 b	211 b	225 a	874 ab	864 b	873	872 c
4	252 d	261 b	389 ab	441 b	463 b	225 a	226 a	864 a	831 a	863	878 bc
5	256 bcd	254 b	375 a	393 cd	389 c	213 ab	228 a	868 a	861 b	879	885 abc
6	252 cd	239 c	376 a	354 d	362 c	210 bc	229 a	881ab	868 b	869	894 ab
SE ¶	3.5	3.5	7.7	10.1	12.5	3.3	4.6	4.8	4.9	17.1	5.1

† ADF: acid detergent fiber, NDF: neutral detergent fiber, CP: crude protein, IVTDMD: in vitro true dry matter digestibility.

‡ 1, Orchardgrass with N; 2, Orchardgrass without N; 3, Orchardgrass-alfalfa; 4, Orchardgrass-alfalfa-red clover; 5, Orchardgrass-alfalfa-red clover-tall fescue-chicory; 6, Orchardgrass-alfalfa-red clover-tall fescue-chicory-white clover-perennial ryegrass.

§ Within a column, means followed by the same letter are not significantly different according to Tukey's mean separation ($P < 0.05$).

¶ SE, Standard error of the mean.

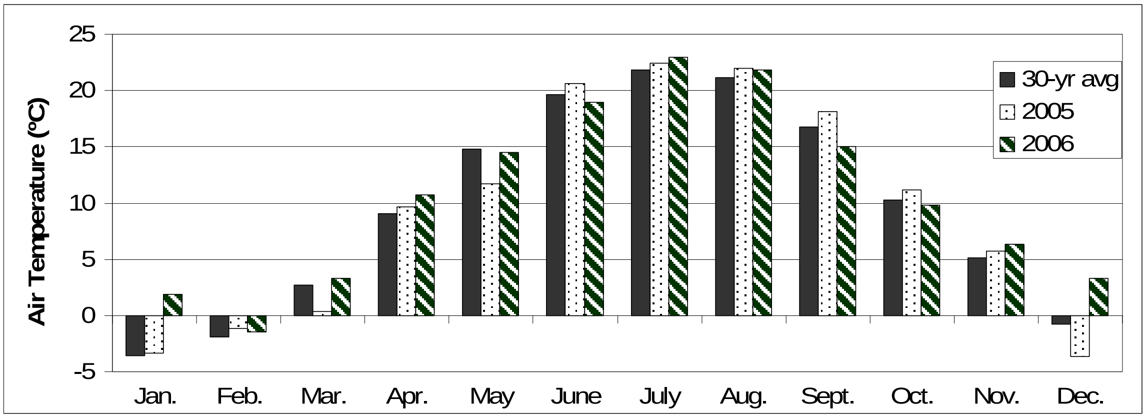

Fig. 3-1: Average monthly air temperature during 2005 and 2006 at the Haller Farm near State College, PA.

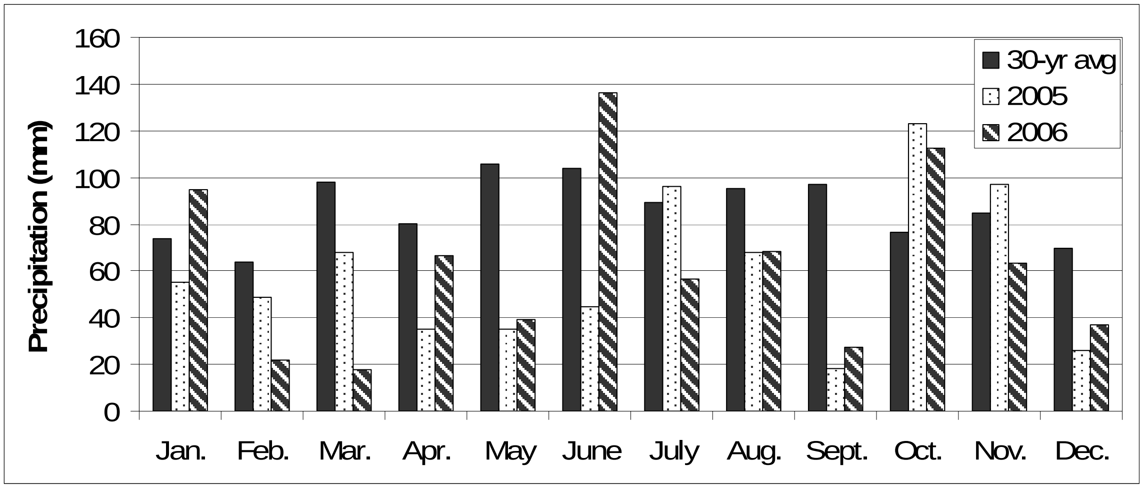

Fig. 3-2: Monthly precipitation during 2005 and 2006 at the Haller Farm near State College, PA.

CHAPTER 4

SHORT- and LONG-TERM ECONOMIC ANALYSIS of FORAGE MIXTURES and GRAZING STRATEGIES

Management-intensive rotational grazing as part of a livestock production system has been increasing in the USA (Casler and Undersander, 2005). This trend is mainly supported by increased net profits from decreased feeding and harvest costs (Dart et al., 1999). Rudstorm (2004) reported that management-intensive rotational grazing systems improve net profit of dairies in the north central USA. Many studies in the northeast USA show an increase in profits from $40 to $300 per cow for management-intensive rotational grazing systems compared with confined dairies (Aiello, 2004).

Animal production (either milk or meat) in grazing systems depends on the combination of forage quantity and quality produced. Research in natural grassland ecosystems has shown that environments with broader plant biodiversity tend to provide higher and more consistent community biomass (Tilman, 2001). Many researchers have explored the yield-diversity hypothesis in deliberately controlled plant diversity experiments with mixed results. Research in clipped plots showed both a positive (Hector et al., 1999; Bullock et al., 2007) and a negative (Piano and Annicchiarico, 1995; Tracy and Sanderson, 2004) impact of increasing mixture complexity on dry matter (DM) yield.

Similarly research conducted under grazing did not yield a clear cut answer. In Canada, a study conducted with mixtures ranging from pure stands of up to six species mixtures found that the more diverse mixture yielded more consistently compared to less diverse mixtures (Clark et al., 2001). In the northeast USA, research with dairy cows showed an increase in DM production for the more complex mixtures (composed of 3 to

6 species mixtures; Sanderson et al., 2005). More recently, a study conducted with beef steers in Illinois found that complex mixtures did not improve yield under grazing (Tracy and Faulkner, 2006). Although complex mixtures did not consistently produce top yields; they usually produce more consistent yields and out-produce simple mixtures in dry years (Sanderson et al., 2005; Skinner et al., 2004; Skinner et al., 2006). Fluctuation in climate is a major reason for inconsistent pasture production (Belesky et al., 1999). For instance, in the northern prairies drought reduced pasture yield by 50% (Dunn et al., 2005). Hence, the use of complex mixtures could decrease environmental production risks.

Even though much effort has been spent in clarifying the relationship between mixture complexity and DM production, little research has focused on the economic impact of different mixture complexities and grazing strategy on a whole farm scale. In a study conducted in Minnesota on the partial economical effects of mixture complexity, the researchers concluded that there was not an economic benefit in dairy production to plant complex mixtures (Wedin et al., 1965). More recently in a study that analyzed the economic impact of forage plant diversity on a whole farm scale, a 6-species mixture was found to improve net return compared to pure grass with nitrogen fertilizer (Sanderson et al., 2006).

Because mixtures (either simple or complex) are more difficult to manage than pure stands, farmers will only adopt them if there is a greater net profit. Economic analysis of pasture alternatives are both labor and time consuming due to the large amount of land, livestock, and personnel resources required. Thus, carrying out such studies in the “real world” becomes prohibitive. An alternative is to use computer simulation to study the economic impact of alternative management options.

Modeling pasture and animal production began in the 1960's with the advent of computers (Rickert et al., 2000). Since then, the use of production models has increased as computers have become more accessible and powerful (Rickert et al., 2000). Among the many computer simulation models available, the Integrated Farm System Model (IFSM) is prominent because it integrates all major production processes at the whole farm level. The IFSM calculates the economic return based on feed production and purchase, feed utilization, production costs, and income from production sales. Additionally, IFSM estimates environmental aspects related to the specific production and soil characteristics. The IFSM and its predecessor the Dairy Forage System Model (DAFOSYM) have been used to evaluate alternative management scenarios such as species composition and pasture productivity (Corson et al., 2006), soybean and small grain production and use implications on dairy farms (Rotz et al., 2001; Rotz et al., 2002), and alternative silage systems on dairy farms (Borton et al., 1997).

The objective of this study was to evaluate the economic impact of altering the grazing strategy and the forage base on a typical dairy farm of Pennsylvania. Specifically, the Integrated Farm System Model was used to asses: 1) the effect of changing the grazing initiation based on canopy height or plant morphology, 2) the effect of increasing forage species diversity from pure grass stands, simple grass-legume mixtures up to a seven-species mixture. The economic impact of these alternatives were measured based on feed production, feed use, and net returns of a typical dairy farm in Pennsylvania on a short term (2 years), long-term (25 years), and the differential impact on dry and wet years (5 consecutive years of each).

MATERIALS AND METHODS

The Integrated Farm System Model

The IFSM is a comprehensive model that was developed to evaluate alternative management options at a whole farm level. It integrates all important production aspects, from land use and cropping systems to timeliness of tillage, planting, and harvesting operations. The IFSM determines on a daily basis all resources and requirements for specific production objectives (e.g. dairy farms, beef operations, and cash crop farms). In addition, the model calculates all costs related to production and income from sales. It uses these economic inputs and outputs to generate an overall net return for the simulated farm. For a complete description of IFSM, refer to the IFSM reference manual (Rotz and Coiner, 2005).

The IFSM was slightly modified to accomplish the objectives of this study. In the case of the short-term analysis and in contrast to most previous uses of the IFSM, where all inputs are calculated based on the program set-up and user defined values, the pasture subroutine was modified to allow manual input of pasture production and nutritive values. Thus when pastures were specified (as part of the land use), the program read data generated in a field experiment (Chapter 3) instead of generating it through simulation. In the case of the long-term analysis, IFSM was used unmodified, but pasture yield was adjusted as needed (described in long-term analysis farm set up) to appropriately represent measured values.

Farm Description and Management Scenarios

<u>Short-term economic analysis</u>

To evaluate the grazing management and mixture complexity effect on net return of a dairy farm, two grazing scenarios and six forage treatments ranging from a monoculture up to a seven-species mixture (totaling eight different management scenarios, that is six forage alternatives plus two grazing management alternatives) were compared on a representative farm. Each scenario considered in the analysis was modeled as an established production system; hence the transition from one management alternative to another was ignored.

The base farm represented a typical dairy farm in Pennsylvania with 100 ha of land. The soil was a clay loam of medium depth with gently sloping terrain (3-8%). Crops were rotated with 30 ha of alfalfa, 40 ha of corn, and 30 ha of pasture. The stand life of the pasture affects economic returns of grazing dairies; with a greater net return with longer stand life (Sanderson et al., 2006). For the present study, stand life was set to 5 yr for all forage treatments to represent a typical or average stand life (Sanderson et al., 2006). Alfalfa was mainly harvested as silage (first, third, and fourth harvests) with some dry hay (second harvest). Corn was harvested as silage to fill the existing silo; the remaining corn was harvested as high-moisture grain. The pasture was grazed by all animal categories during the growing season. Alfalfa and corn silages were stored in bunker silos, and a stave silo was used for high-moisture grain.

The herd consisted of 100 lactating Holstein cows, 40 replacement heifers (> 1 yr old) and 35 heifers less than 1 year of age. Cow replacement rate was set at 35% per year.

Cows were milked in a double-six parlor. The annual target milk production was set at 9091 kg cow^{-1}. Protein needs were satisfied with a combination of soybean meal and a less rumenally degradable protein mix. All cattle were housed in a free stall barn. The manure was removed by daily scraping, stored for up to 6 months in a concrete tank, and applied to the cropland (corn and alfalfa).

Simulations were done for two consecutive years using weather data collected at State College, PA. Prices were set to represent long-term relative prices in current values, which were not necessarily current prices (Table 4-1 and Table 4-2). A real interest rate of 6% year^{-1} was applied to all investments in machinery and facilities. Property tax was set at 2.3% of the estimated assessed value of land and buildings.

Two grazing management scenarios and six forage treatments (represented by the pasture land use) were simulated and compared (Table 4-3). These scenarios were achieved by modifying the pasture sub-routine of the IFSM model. Thus, the yield and quality for the 30 ha of pastureland were taken from a field experiment carried out near State College, PA (for details on how the experiment was managed, refer to Chapter 3).

The two grazing management alternatives were: a “height-based grazing schedule” (grazing began whenever the mean height of the sward reached 25 cm, which is a standard grazing guideline) or a “morphology-based grazing schedule” (grazing began whenever the alfalfa reached bud stage). The effects of these two grazing managements were evaluated in a field experiment and were represented by the variation in forage DM production and nutritive value used as input for the pastureland.

In all management scenarios evaluated, the major factors altered were forage DM production available for grazing and its nutritional value. Both forage production and its nutritional value were specified for each grazing event and each mixture evaluated. The mixtures were set up to reflect the effect of nitrogen fertilization on a cool-season grass pasture (by comparing mixtures 1 and 2; Table 4-3) and to compare the effect of increasing plant diversity of the mixtures on the overall economics of the farm (by comparing the effects of mixtures 1, 3, 4, 5, and 6). All forage treatments were grazed following the height-based grazing and the morphology-based grazing.

Long term economical analysis:

To evaluate long term impact of the alternative management scenarios on the overall farm economics, the IFSM model was used to simulate farm production over 25 years of weather. The farm described in the previous section was used. In contrast to the short-term analysis, the IFSM model was calibrated to generate the average DM yields obtained in the field experiment (Chapter 3). This was accomplished by modifying the yield potential of the pasture land. Additionally, the model was run to determine the impact of these alternative management scenarios in net return during dry and wet years. Long-term weather data (103 yr data from The Russell E. Larson Agricultural Research Center near State College) was analyzed to find a string of 25 years that had five dry years, five wet years, and fifteen normal years (Fig. 4-1). Dry and wet years were defined as years with total rainfall during the growing season (May to September) 25% below and 25% above average, respectively (Smart et al. 2005). The weather data used for the simulation was from State College, PA (1960-1985). For the 25-yr run, the pasture yield was calibrated to produce, on average, the same DM production generated by the field study (average of both years; Chapter 3). Then from the original weather data file, the five dry and five wet years were extracted and saved as new weather files for the dry and wet runs. For the dry years, pasture yield was calibrated to produce, on average, the DM produced in 2005 in the field experiment, and for the wet years, pasture yield was calibrated to produce, on average, the DM produced in 2006 in the field experiment. Data are reported on average for 25 years, the 5 driest years, and the 5 wettest years.

RESULTS AND DISCUSSION

The economic simulations presented here were run on a representative dairy farm of Pennsylvania. Thus, the economic and production results presented here may not reflect actual values obtained by specific producers and should be interpreted in the context of the comparisons based on their relative importance.

Short-Term Analysis

Differences in economic return between the two grazing managements were mainly due to a lower pasture production in the morphology-based grazing treatment (Table 4-4). Consequently, less forage was sold from the farm using the morphology-based treatment which led to a decrease in net return of 8% compared to the height-based grazing treatment. On the other hand, the morphology-based grazing treatment produced more consistent net returns year to year compared to the height-based grazing treatment as evidenced by a smaller coefficient of variation (CV; Table 4-4). Production risk in this study (both for the short-term and long-term) is mainly affected by environmental risks since input and output prices remained constant. Therefore, the long-term data is a better predictor of production risk because it encompasses a broader array of climatic situations.

In general, there were few differences among all variables studied due to pasture plant diversity (Table 4-4). Forage treatment mainly affected forage DM production and subsequently the amount of excess forage for sale and the income generated by those sales (Table 4-4). Additionally, seed and fertilizer costs were affected by the different forage treatments. Nevertheless, complex mixtures (treatments 5 and 6) generated greater net returns compared to either the simple mixtures or pure grass stands (Table 4-4). The seven-species mixture generated the greatest net return and the pure orchardgrass with nitrogen yielded the smallest net return.

These results agree with those of Sanderson et al. (2006) in that forage plant diversity increased net return and in contrast to the results reported by Wedin et al. (1965). These inconsistencies in the economic impact of increasing plant diversity may be explained in part by the economic analysis procedures used in these studies. Wedin et al. (1965) only determined the partial economic analysis of milk production due to increased forage complexity whereas Sanderson et al. (2006) and the present study analyzed the economic impact at a whole farm scale. Additionally, milk production levels greatly differed among these studies. The lowest milk production corresponded to the study carried out by Wedin et al. (1965) at 16 kg cow^{-1} day^{-1}, followed by the present study at 30 kg cow^{-1} day^{-1}, and up to 35 kg cow^{-1} day^{-1} for the Sanderson et al. (2006) study. Another reason that might explain these differences among the three studies is the amount of N fertilizer used and its price. Wedin et al. (1965) and Sanderson et al. (2006) applied 157 kg N ha^{-1} and 168 kg N ha^{-1}, respectively, whereas the present study used

250 kg N ha^{-1}. Nitrogen fertilizer price was 10 ¢ kg^{-1} more expensive in Sanderson et al. (2006) than in the present study and no price was reported in Wedin et al. (1965) but it is likely that N price relative to milk and seed prices has increased since 1965.

It is interesting to note that the addition of N to a pure stand of orchardgrass increased forage production (as shown by the amount of forage grazed; Table 4-4) but this increase in DM production was not reflected in the overall farm net return. This effect is explained by the relatively high price of N fertilizer and the level of N applied, which offset the increase in forage production. Thus when fertilizer prices are high, lowering the application rates or including legumes in pastures are cost effective alternatives. The economic advantage of using grass-legume mixtures rather than straight grass with addition of N fertilizer has been noted by Malhi et al. (2002).

The production risks decreased (evidenced by the lower CV for the net return) as pasture diversity increased (Table 4-4). Similarly, Sanderson et al. (2006) noted a decrease in production risk as plant diversity increased and attributed this result to more consistent forage production by the complex mixtures. Increased plant diversity has been suggested to improve biomass production consistency in natural grasslands (Tilman, 2001). Other research in the northeast USA has noted that complex mixtures improved DM production in dry years (Sanderson et al., 2005; Skinner et al., 2004; Skinner et al., 2006). In the present study, the first year (2005) was dry, and similar to previous findings, complex mixtures produced greater forage production compared to simple mixtures and pure grass stands (data shown in Chapter 3). Additionally, forage DM production represented a significant proportion of the variation of the net return (Fig. 4-

2). Therefore, the consistency in net return for complex mixtures reflects their consistent DM production.

Analyzing long-term (103 years) weather patterns for State College, on average, we can expect a dry year every sixth year (Fig. 4-1). The frequency of dry years in the northeast USA is much lower compared to the 1 in 3 years reported by Smart et al. (2005) in the Great Plains. Nevertheless, due to the difficulty in predicting the occurrence of a dry year, and because complex mixtures on average produced similarly to simple mixtures, it is prudent management to use complex mixtures to cope with droughts. Consequently, planting complex mixtures could be a useful alternative to help manage for environmental uncertainty by reducing production risks.

Long-Term Analysis

Long-term trends might be better predictors of how different forage treatments affect the overall farm economics. In general, the results obtained by the long-term analysis are similar to those of the short-term analysis. The height-based grazing treatment produced more forage DM on pasture, which in turn increased the sale of excess forage. The morphology-based grazing treatment needed more protein and mineral supplements and less purchased grain compared to the height-based grazing treatment. These differences in feed quantities purchased led to a greater feed cost for the morphology-based grazing treatment (Table 4-5). In all, the height-based grazing treatment produced greater net return compared to the morphology-based grazing due to greater income from feed and bedding sales and lower feed costs (Table 4-5). Additionally, production risk was smaller (lower CV) for the height-based grazing treatment compared to the morphology-based grazing treatment. This result contradicts the short-term analysis were the opposite was found. Since the long-term data is a better predictor of production risk because it encompasses a broader array of climatic situations, grazing the pastures based on the sward height appears to be economically sound management.

The economic effect of forage treatments was different in the long-term analysis compared to the short-term analysis. The pure orchardgrass with N produced greater net return compared to orchardgrass without N (Table 4-5). The major reason for this difference was that in the 25 yr simulation the excess forage produced by the addition of N offset the greater production costs (mainly N fertilizer; Table 4-5). Additionally, orchardgrass without N increased the required protein and mineral supplements possibly as a response to lower protein in the pasture forage. Nevertheless, using a simple alfalfa-orchardgrass mixture improved net return compared to orchardgrass with N as noted previously by Malhi et al. (2002). Comparing the simple mixtures (forage treatments 3 and 4) to the more complex forage mixtures (treatments 5 and 6), differences in feed produced, production costs, and net returns were small. However, forage treatment 6 produced the greatest net return with the smallest production risk (Table 4-5). The 25 year simulations confirm the short-term results in that planting complex mixtures improved overall farm economics.

In addition to the long-term analysis, the five driest years and the five wettest years were analyzed to evaluate the differential impact of mixture complexity under such climatic extremes. The results of these simulations showed that not only was pasture production affected, but both corn and alfalfa production also decreased (Tables 4-6 and

4-7). It is important to note that forage treatments responded differently to such climatic events. During dry years, net return increased as mixture complexity increased (Table 4-6). This is the result of an increase in pasture production in dry years by increasing the number of species in a mixture as noted by others (Sanderson et al., 2005; Skinner et al., 2004; Skinner et al., 2006). In fact, the differences in pasture production in dry years were such that production systems using forage treatments 1, 2, and 3 required the purchase of forage whereas forage treatments 4, 5, and 6 produced excess forage. During the years where rainfall was above average, both the simple mixtures (treatments 3 and 4) produced more forage and greater net returns compared to the other treatments. It is also interesting to note that the addition of N to pure grass stands led to greater net return in wet years compared to dry years (Tables 4-6 and 4-7). More importantly when comparing the difference in net return obtained by a particular forage treatment in dry and wet years, the net return using complex mixtures was reduced only by 25 to 27%. On the other hand, reductions in net return ranged from 36% for a three species mixture up to 55% for pure grass stands. This gives supporting evidence to the increased consistency both in DM yield and net return of the complex mixtures as noted by Sanderson et al. (2006). Therefore, complex mixtures are an appealing option for dairy producers that use grazing. Grazing treatment in dry and wet years yielded similar results to the long-term analysis. The height-based grazing treatment produced greater net returns both in dry and wet conditions due to greater pasture production (Tables 4-6 and 4-7). Furthermore, annual net returns during dry years represented only 56% of those of wet years for the morphology-based grazing treatment compared to 62% for the height-based grazing treatment.

CONCLUSIONS

This series of simulations indicated that grazing management and pasture species diversity affect overall farm net return. This is mainly a consequence of greater pasture DM production by certain grazing/forage treatments. Grazing schedules following canopy height rather than plant morphology increased pasture DM production and net returns. The use of N fertilizer in pure stands of grass increased DM production both in the short- and long-term analysis but only increased net returns in the long run. Increasing mixture complexity increased net return both in the short- and long-term analyses. Furthermore, botanically diverse forage mixtures had smaller production risk in all analyses. In dry years, complex mixtures generated the greatest net returns whereas in wet years a simple orchardgrass-alfalfa mixture generated the highest net return. However, when comparing the performance of forage treatments between wet and dry years, the more complex mixture gave less decrease in net return compared to the simple mixtures. Consequently complex forage mixtures are a useful alternative for pastures in dairy farms to manage forage production risks in dry years and thereby increase and stabilize annual net returns.

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Table 4-1: Important economic parameters and prices used for the analysis of different grazing management and forage alternatives on a representative Pennsylvania dairy farm. Prices were set to represent long-term relative prices in current value, which were not necessarily current prices.

Parameter	Value	Parameter	Value
Labor wage rate	\$11h^{-1}	Animal and feed prices	
Diesel fuel price	\$0.60 L^{-1}	Cull cow	\$0.99 kg^{-1}
Property tax rate	2.3 %yr^{-1}	Calf	\$80 animal^{-1}
Land rental	\$250 ha^{-1}	Milk	\$0.33 L^{-1}
Annual livestock expenses	\$238 cow^{-1}yr^{-1}	Straw bedding	\$110 t DM^{-1}
Cow free-stall barn (initial cost)	\$1000 cow^{-1}	Corn grain	\$118 t DM^{-1}
Feed commodity shed (initial cost)	\$70 cow^{-1}	Alfalfa hay	\$138 t DM^{-1}
Fertilizer prices		Soybean meal	\$266 t DM^{-1}
Nitrogen	\$0.78 kg^{-1}	Protein mix	\$395 t DM^{-1}
Phosphorus	\$0.73 kg^{-1}	Mineral/vitamin mix	\$325 t DM^{-1}
Potassium	\$0.431 kg^{-1}		
Annual cost of seed and chemicals		Economic life	
New forage stand	Variable (table 2)	Storage structures	20 yr
Established forage	\$15 ha^{-1}	Machinery	10 yr
Corn following other crops	\$135 ha^{-1}	Salvage value	
Corn following corn	\$155 ha^{-1}	Structures	0 %
Real interest rate	6.0 %yr^{-1}	Machinery	30 %

Table 4-2: Costs of establishing forage treatments used for the analysis of different grazing management and forage alternatives on a representative Pennsylvania dairy farm. Costs were based on actual inputs used and prices paid in establishing the forage mixtures in Chapter 3.

Item	Price	Forage Treatment					
		1	2	3	4	5	6
	---$/kg----	--------------------------$/ha------------------------------					
Alfalfa	9.3			110.3	66.1	44.1	33.1
Chicory	13.2					25.1	25.1
Orchardgrass	6.7	89.2	89.2	44.6	44.6	22.3	13.4
Perennial ryegrass	5.0						30.8
Red clover	6.5				36.5	36.5	11.09
Tall fescue	3.1					28.5	27.4
White clover	10.8						15.6
Total seed cost		89.2	89.2	138.0	147.3	156.6	162.5
Total cost of seed & chemicals		117.2	117.2	143.8	140.7	144.5	146.9
Field operation costs		$/acre					
Disking	$32/pass	64.0					
Harrowing	$24.7/pass	49.4					
Conventional Planting	$34.6/pass	69.2					
Total forage tillage & planting		182.2					
Glyphosate Herbicide	$17.2 L^{-1}	68.8					
Herbicide application	$19.8/pass	39.5					
Total chemical		108.3					

Table 4-3: Seeding ratio of forage treatments established at the Haller Farm near State College, PA, to determine the effect of such treatments on forage production and weed invasion of the subsequent pasture, August 2004 (experiment 2).

Mixtures	Species seed percentage in each mixture†
1	100% Orchardgrass with 252 kg N ha^{-1}
2	100% Orchardgrass (without nitrogen)
3	50% Orchardgrass / 50% Alfalfa
4	50% Orchardgrass / 30% Alfalfa / 20% Red clover
5	25% Orchardgrass / 25% Tall fescue / 20% Alfalfa / 20% Red clover / 10 % Chicory
6	15% Orchardgrass / 15% Tall fescue / 15% Perennial ryegrass / 15% Alfalfa / 15% Red clover / 15% White clover / 10 % Chicory

†Seed percentage is based on number of live seeds.

Table 4-4: Short-term (2 year) analysis of grazing management alternatives and forage mixture complexity on annual feed production, production cost, and net return of a representative Pennsylvania dairy farm.

Variable	Grazing Treatment		Forage Species Treatments†					
	Morphology	Height	1	2	3	4	5	6
Feed production	---------- tonnes DM ----------							
Alfalfa hay and silage	226	226	226	226	226	226	226	226
Grain crop silage	338	338	338	338	338	338	338	338
High-moisture grain	49	49	49	49	49	49	49	49
Grazed forage consumed	122	155	134	101	145	146	151	153
Forage sold	138	170	150	127	162	157	162	166
Grain purchased	227	231	233	223	230	232	229	228
Protein and mineral supplements	49	46	48	51	47	46	47	47
	---------- kg cow^{-1} ----------							
Average milk production	9043	9044	9044	9033	9044	9046	9047	9046
Production costs	---------- $ ----------							
Seed, fertilizer and chemical cost	11397	11398	15159	9309	10980	10931	10984	11022
Total feed cost	159054	157932	162454	158044	157697	157767	157625	157371
Total manure cost	19371	19390	19383	19373	19367	19415	19390	19354
Other costs‡	107773	107776	107776	107756	107775	107780	107782	107780
Income and net return	---------- $ ----------							
Income from feed and bedding sales	14365	17686	14399	17297	17375	15155	15759	16169
Income from milk and animal sales	322014	322059	322054	321725	322039	322113	322158	322129
Net return	49040	53254	46842	48130	52688	52307	53121	53794
SD net return	6701	8389	8530	9439	10338	7358	6321	6251
CV net return (%)	13.7	15.8	18.2	19.6	19.6	14.1	11.9	11.6

† 1, Orchardgrass with N; 2, Orchardgrass without N; 3, Orchardgrass-alfalfa; 4, Orchardgrass-alfalfa-red clover; 5, Orchardgrass-alfalfa-red clover-tall fescue-chicory; 6, Orchardgrass-alfalfa-red clover-tall fescue-chicory-white clover-perennial ryegrass.

‡ Milking facilities, livestock expenses, and property taxes.

Table 4-5: Long-term (25 year) analysis of grazing management alternatives and forage mixture complexity on annual feed production, production cost, and net return of a representative Pennsylvania dairy farm.

Variable	Grazing Management		Forage Species Treatments†					
	Morphology	Height	1	2	3	4	5	6
Feed production	---------- tonnes DM ----------							
Alfalfa hay and silage	227	227	227	227	227	227	227	227
Grain crop silage	244	244	244	244	244	244	244	244
High-moisture grain	58	58	58	58	58	58	58	58
Grazed forage consumed	156	203	176	117	193	193	196	204
Forage sold	90	148	115	45	135	135	140	149
Grain purchased	287	298	292	277	296	296	297	298
Protein and mineral supplements	44	38	41	51	39	39	39	38
	----------kg cow^{-1}----------							
Average milk production	9091	9091	9091	9091	9091	9091	9091	9091
Production costs	----------$----------							
Seed, fertilizer and chemical cost	10931	10931	15159	9309	10980	10931	10981	11020
Total feed cost	165365	162502	168218	165944	162967	162917	162877	162572
Total manure cost	19550	19548	19551	19552	19546	19544	19549	19548
Other costs‡	107868	107868	107868	107868	107868	107868	107868	107868
Income and net return	----------$----------							
Income from feed and bedding sales	10761	15409	12718	6846	14318	14328	14722	15497
Income from milk and animal sales	323568	323568	323568	323568	323568	323568	323568	323568
Net return	41547	49060	40651	37052	47507	47568	47998	49078
SD net return	8026	7092	7884	7244	7569	7476	7379	6732
CV net return (%)	19.3	14.5	19.4	19.6	15.9	15.7	15.4	13.7

† 1, Orchardgrass with N; 2, Orchardgrass without N; 3, Orchardgrass-alfalfa; 4, Orchardgrass-alfalfa-red clover; 5, Orchardgrass-alfalfa-red clover-tall fescue-chicory; 6, Orchardgrass-alfalfa-red clover-tall fescue-chicory-white clover-perennial ryegrass.

‡ Milking facilities, livestock expenses, and property taxes.

Table 4-6: Economic analysis of grazing management alternatives and forage mixture complexity on annual feed production, production cost, and net return of a representative Pennsylvania dairy farm in dry conditions. Data are results of simulation of the 5 driest years.

Variable	Grazing Management		Forage Species Treatments†					
	Morphology	Height	1	2	3	4	5	6
Feed production	tonnes DM							
Alfalfa hay and silage	145	145	145	145	145	145	145	145
Grain crop silage	242	242	242	242	242	242	242	242
High-moisture grain	17	17	17	17	17	17	17	17
Grazed forage consumed	131	169	129	77	129	173	193	204
Forage sold (purchased)	(44)	6	(48)	(107)	(47)	11	41	56
Grain purchased	308	318	307	300	307	319	326	330
Protein and mineral supplements	38	36	39	39	38	36	35	34
	kg cow^{-1}							
Average milk production	9091	9091	9091	9091	9091	9091	9091	9091
Production costs	$							
Seed, fertilizer and chemical cost	10931	10931	15159	9309	10980	10931	10981	11020
Total feed cost	169956	165529	174626	175111	170244	165205	163959	163616
Total manure cost	19678	19618	19694	19740	19682	19613	19590	19586
Other costs‡	107868	107868	107868	107868	107868	107868	107868	107868
Income and net return	$							
Income from feed and bedding sales	1246	2941	1070	0	1137	3244	5260	6535
Income from milk and animal sales	323568	323568	323568	323568	323568	323568	323568	323568
Net return	27312	33496	22452	20851	26913	34127	37413	39035
SD Net return	8306	7764	7225	6195	8048	7569	6314	6159
CV Net return (%)	30.4	23.2	32.2	29.7	29.9	22.2	16.9	15.8

† 1, Orchardgrass with N; 2, Orchardgrass without N; 3, Orchardgrass-alfalfa; 4, Orchardgrass-alfalfa-red clover; 5, Orchardgrass-alfalfa-red clover-tall fescue-chicory; 6, Orchardgrass-alfalfa-red clover-tall fescue-chicory-white clover-perennial ryegrass.

‡ Milking facilities, livestock expenses, and property taxes

Table 4-7: Economic analysis of grazing management alternatives and forage mixture complexity on annual feed production, production cost, and net return of a representative Pennsylvania dairy farm in wet years. Data are results of simulations of the 5 wettest years.

Variable	Grazing Management		Forage Species Treatments†					
	Morphology	Height	1	2	3	4	5	6
Feed production	------tonnes DM------							
Alfalfa hay and silage	247	247	247	247	247	247	247	247
Grain crop silage	244	244	244	244	244	244	244	244
High-moisture grain	72	73	73	73	73	72	72	72
Grazed forage consumed	180	216	215	156	216	212	198	204
Forage sold	144	186	185	116	186	182	165	172
Grain purchased	281	286	286	275	286	286	284	285
Protein and mineral supplements	41	38	39	46	38	39	40	39
	------kg cow^{-1}------							
Average milk production	9091	9091	9091	9091	9091	9091	9091	9091
Production costs	------$------							
Seed, fertilizer and chemical cost	10931	10931	15159	9309	10980	10931	10981	11020
Total feed cost	162738	161249	165531	162469	161298	161466	162103	161881
Total manure cost	19519	19541	19540	19520	19541	19539	19531	19534
Other costs‡	107868	107868	107868	107868	107868	107868	107868	107868
Income and net return	------$------							
Income from feed and bedding sales	14875	18731	18588	12208	18731	18285	16765	17440
Income from milk and animal sales	323568	323568	323568	323568	323568	323568	323568	323568
Net return	48319	53643	49217	45921	53594	52982	50833	51726
SD net return	4565	3621	3650	4495	3621	3998	4476	4265
CV net return (%)	9.4	6.8	7.4	9.8	6.8	7.5	8.8	8.2

† 1, Orchardgrass with N; 2, Orchardgrass without N; 3, Orchardgrass-alfalfa; 4, Orchardgrass-alfalfa-red clover; 5, Orchardgrass-alfalfa-red clover-tall fescue-chicory; 6, Orchardgrass-alfalfa-red clover-tall fescue-chicory-white clover-perennial ryegrass.

‡ Milking facilities, livestock expenses, and property taxes.

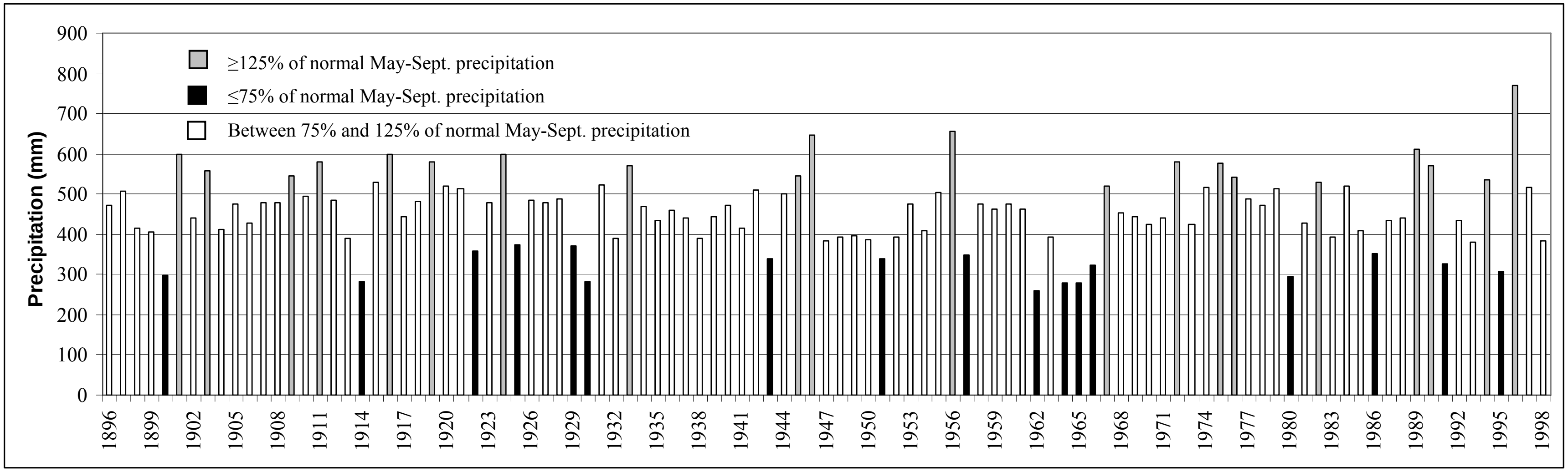

Fig. 4-1: Cumulative precipitation from May to September at the Rock Springs research station near State College (1896-1998). Average rainfall for May to September, is 460 mm.

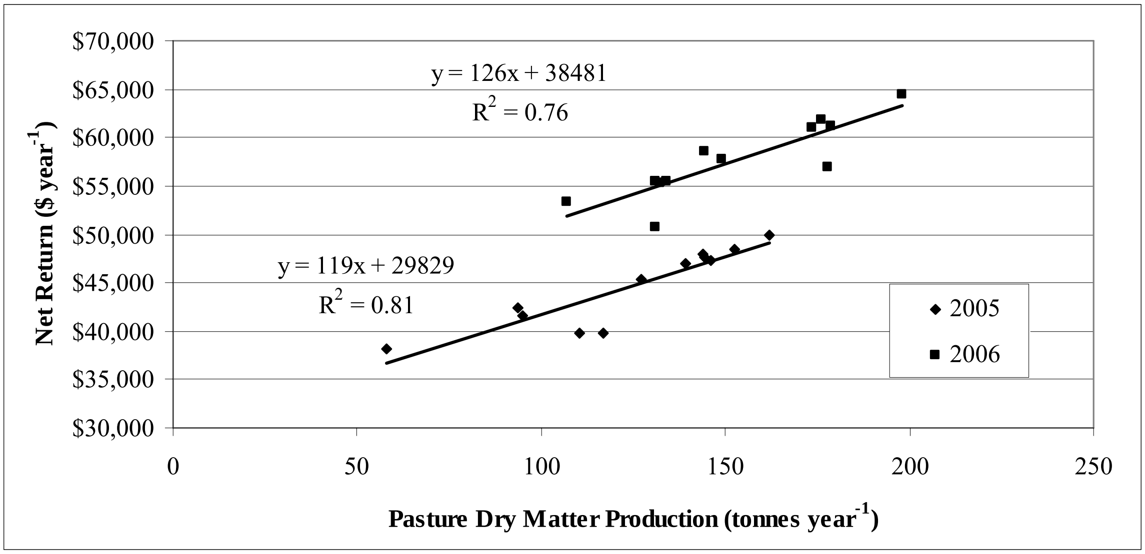

Fig. 4-2: Net return (\$ year^{-1}) regressed by total pasture production (tonnes DM year^{-1}) for 2005 and 2006 simulations. Data points represent the net return obtained at different levels of pasture production in the short-term simulations.

CHAPTER 5

CONCLUSIONS

This thesis investigated the potential benefits of increasing plant diversity of forage mixtures. The studies carried out are divided into three parts. In the first part, a series of studies were set up to evaluate weed suppression by using complex mixtures composed of fast establishing forage species (FEFS; e.g. chicory, perennial ryegrass, and red clover). These studies showed that the use of complex mixtures or FEFS is a viable alternative to annual companion crops for weed suppression during forage establishment. The selection of FEFS is a key component in achieving such suppression. In the present studies, chicory appeared to be the most effective FEFS, hence its use in forage mixtures will improve weed suppression during pasture renovation. On the downside, the addition of FEFS to slow establishing forage mixtures also decreased the proportion of the target forage species.

In the second part of the research, the use of two grazing schedules, 1) “morphology” grazing schedule; and 2) “height” grazing schedule were imposed on six forage treatments ranging from orchardgrass pure stands, simple grass-legume mixtures, up to a seven-species mixture. The “height” grazing treatment produced greater DM yield which was likely a consequence of weather conditions over the growing seasons. Grazing schedules had little effect on botanical composition. However, red clover and chicory flourished under the “morphology” grazing treatment whereas perennial ryegrass benefited from the “height” grazing treatment. The “height’ grazing treatment produced better nutritive value at first harvest compared to the “morphology” grazing treatment, however, these differences declined over the growing season. As mixture complexity increased, legume content decreased. On the other hand, weed proportion decreased as diversity increased. The addition of legumes to pure grass stands improved nutritive value and dry matter (DM) production as well as reducing the use of N in grazing systems. Complex mixtures produced more consistent DM yield compared to simple mixtures or pure grass stands. Additionally, mixture complexity improved DM production in a dry year, but produced lower DM yield than a simple orchardgrass-alfalfa mixture in more favorable weather conditions. Nutritive value was influenced by mixture complexity at first harvest, but these differences declined over the growing season.

The third part, evaluated the short- and long-term economic impact of the “height”, and “morphology” grazing managements along with the previously described forage treatments on a typical Pennsylvania dairy farm. A series of simulations indicated that farm net return was influenced by grazing management and pasture species diversity as a result of greater pasture DM production by certain grazing and forage treatments. Grazing schedules following canopy height rather than plant morphology increased pasture DM production and net returns. The use of N fertilizer in pure stands of grass increased DM production both in the short- and long-term analysis, but only increased net returns in the long-term analysis. Increasing mixture complexity increased net return and decreased production risks both in the short- and long-term. Complex mixtures generated the greatest net returns in dry years, whereas a simple orchardgrass-alfalfa mixture generated the best net return in wet years. However, complex mixtures performed more consistently than simple mixtures when comparing the farm net returns of forage treatments between wet and dry years.

The following recommendations are based on the series of studies conducted in this thesis:

1. The addition of chicory or a combination of all three FEFS studied (chicory, red clover, and perennial ryegrass) in a low proportion (≤12.5%) of the seeding mixture will help decrease weed invasion at establishment and increase forage yield at the first harvest.
2. Forage nutritive value and DM yield are optimized in the short term (2 yrs) by grazing forages based on canopy height
3. The use of complex mixtures composed of forage species selected for their performance in previous research can be an alternative to drought prone environments where consistency in DM production is more important than top forage productivity.
4. Complex forage mixtures are a useful alternative for pastures in dairy farms to manage forage production risks in dry years and thereby increase and stabilize annual net returns.

VITA

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Atila Deak was born on March 4, 1974, in Buenos Aires, Argentina. He received his B.S. degree in Agronomy from Universidad Nacional de La Plata in 1998. After graduation Atila worked for “La Tijereta” Seed Company for three years. He received his M.S. in Agronomy from The Pennsylvania State University in 2004. He is a member of the American Society of Agronomy and the Crop Science Society of America.