PASTURE GROWTH ANALYSIS: THE RELATIONSHIP BETWEEN HERBAGE MASS AND HERBAGE ACCUMULATION RATE

THESIS

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By

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ABSTRACT

The frequency and intensity of herbage defoliation have been the focus of many grassland systems studies, since these directly affect the plant’s capacity for harvesting light (leaf area), water and minerals (root) and ultimately carbohydrate synthesis. Those changes and the degree that they occur affect the herbage mass accumulation within a period of time. Sigmoid curves such as the Gompertz are accepted functions for accurately describing pasture herbage mass over time and their derivative describes the rate of herbage accumulation. By combining those two relationships, a time-independent relationship can be developed between standing herbage mass (HM) and the rate of herbage accumulation (HAR). The objectives of this research were: i) develop Gompertz growth curves and determine their time independent form, ii) investigate whether there was a seasonal pattern in those equation parameters, iii) use the time-independent parameters to create a model to predict rate of herbage accumulation based on the standing herbage mass, iv) validate the model with contrasting defoliation treatments, and v) investigate factors affecting the calibration of the rising plate meter (RPM) for measuring herbage mass in pastures. Herbage mass was measured weekly during 11 to 12 growth periods at three north-central USA locations (Columbus and Coshocton, OH, and Arlington, WI) during 2008. Those data were fit to Gompertz equations and time independent HAR vs herbage mass curves were determined. That relationship has
potential use for pasture management by defining the optimum herbage mass at which HAR, is maximized. The optimum herbage mass varied between 1600 and 4000 kg dry matter (DM) ha\textsuperscript{-1}. The parameters from the time independent function of HAR vs herbage mass were used to develop a spreadsheet model to predict rate of herbage accumulation based on the standing herbage mass across the entire growing season, and a study was conducted from 20 May to 27 October 2009 near South Charleston, OH to calibrate the model parameters and validate the model predictions. Monoculture plots of tall fescue \textit{[Schedonorus phoenix} (Scop.) Holub, formerly \textit{Festuca arundinacea} Schreb.] (TF), orchardgrass (\textit{Dactylis glomerata}) (ORG), Kentucky bluegrass (\textit{Poa pratensis}) (KBG) and a mixture (MIX) of those three species were submitted to four defoliation treatments: 3600 to 2800 kg DM ha\textsuperscript{-1} (Tall-Tall, TT), 3300 to 2400 kg DM ha\textsuperscript{-1} (Tall-Short, TS), 3600 to 1800 kg DM ha\textsuperscript{-1} (Hay) and 3000 to 1600 kg DM ha\textsuperscript{-1} (Variable, V). The amount of variation explained by the regressions of observed on predicted model values for herbage mass ranged from 0.48 to 0.88 and 11 out of 25 regressions were not significant difference for $m = 1$ and $c = 0$. For treatments Hay and V, the model underestimated the standing herbage mass, whilst overestimating herbage mass in treatments TT and TS. Treatment TT had the lowest difference between predicted and observed values; however the Hay treatment was the only treatment with a slope not different from 1 and an intercept not different from zero. The model underestimated herbage accumulation for TF, ORG, and MIX; whilst overestimating it for KBG. All species regressions had an intercept different ($P<0.05$) from zero and a slope significantly different ($P < 0.10$) from 1. The model showed promise in predicting the effect of defoliation on subsequent herbage accumulation rate; however, some refinement is required, especially when
predicting herbage accumulation at residual herbage mass \( \leq 1600 \text{ kg DM ha}^{-1} \).

Investigations of the seasonal and species effects on the RPM calibrations were conducted in five Ohio environments: Columbus 2008 (COL08) and 2009 (COL09), two sites at Coshocton (COSH1, COSH2) in 2008 and South Charleston in 2009 (SCH09). There was an effect of calendar week \((P = 0.0021)\), environment \((P = <0.0001)\), environment x week \((P = <0.0001)\), and at SCH09 species \((P = 0.0078)\) on herbage mass.

A pattern of rapidly decreasing slope coefficient values was observed in spring in all environments followed by increasing coefficients the remainder of the season, suggesting the existence of underlying processes responsible for the seasonal changes.
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CHAPTER 1:

INTRODUCTION

Pastures are an ecosystem in which productivity and sustainability are dependent on biotic and abiotic factors and their interactions. Some factors such as rainfall distribution, solar radiation and temperature cannot be controlled. However, farmers can manage soil fertility and plant nutrient status, species composition and the defoliation regime, to optimize the herbage mass. Of these options, soil fertility, plant nutrient status and species composition are relatively slow to change, whilst defoliation remains the most important short-term pasture management option. The two predominant components of defoliation, intensity and frequency of defoliation, directly affect the plant’s capacity for harvesting light (leaf area), taking up water and minerals (root) and ultimately carbohydrate synthesis. Moreover, the impact of herbage removal on meristems and tillering affects pasture persistence and sustainability. Prescriptions of herbage mass management that optimize herbage accumulation were first developed in detail by Brougham (1955).

Herbage accumulation over time has been described using various forms of the sigmoid curve. The derivative form of the sigmoid curves that relates herbage mass and accumulation rate, and has practical application, the measurements of the standing herbage mass can be used to predict the herbage accumulation rate (Morley, 1986; Thornley and Johnson, 1990; Cacho, 1993). Woodward (1996) demonstrated the valuable use of sigmoid growth equations and their derivatives in modeling the impact of
management decisions such as frequency of defoliation, stocking rate and duration of grazing on herbage accumulation response. Parsons et al. (2000) also stressed the applicability of simple growth equations in modeling.

The objectives of my research reported here: a) develop Gompertz growth curves and determine their time-independent form, b) investigate whether there was a seasonal pattern in those equation parameters, c) use the time-independent parameters to create a model to predict rate of herbage accumulation based on the standing herbage mass, d) validate the model with contrasting defoliation treatments, and e) investigate factors affecting the calibration of the rising plate meter (RPM) for measuring herbage mass in pastures.

This thesis contains five chapters. Chapter 2 presents a literature review of key topics relevant to my research, such as processes involved in grass growth, analysis of herbage accumulation, the effect of defoliation on herbage accumulation, and modeling herbage accumulation. Chapter 3 presents data from fitting Gompertz growth curves to herbage accumulation of cool-season grasses, development of a time-independent relationship between standing herbage mass and the rate of herbage accumulation, and an investigation of whether there were seasonal patterns of the parameters of those equations. The majority of Chapter 3 represents a manuscript written by Dr. David Barker and accepted for publication in Agronomy Journal in 2010. I contributed to the collection of field data, statistical analyses of the data, and I expanded the results and discussion included here to compare summer regrowth curves in plots that had been allowed to accumulate herbage growth during the spring with summer regrowth in plots that had been clipped regularly during the spring. Chapter 4 focuses on development of a model that predicts herbage accumulation based on the standing herbage mass. Chapter 5
shows the development of calibrations for the RPM used to estimate the standing herbage mass reported in Chapters 3 and 4. In addition, Chapter 5 describes seasonal and species effects on the RPM calibrations. This information will be useful in future studies employing the RPM as well as on farms where the RPM is being used to measure available pasture mass for guiding grazing management decisions.
CHAPTER 2:
LITERATURE REVIEW

Herbage Accumulation Analysis

Hodgson (1979) defined herbage accumulation (HA) as the change in mass between successive measurements and as the difference between herbage growth and disappearance. Herbage accumulation rate has been assessed by several methods in an effort to describe and predict accumulation in pastures (Parsons et al., 1988b). The most common approach is based on herbage mass at two or more consecutive harvest dates and calculating the average change in mass per unit of time.

Mathematical descriptions of HA

There are mainly three approaches to describe HA in the literature: fitting a polynomial, the classical approach and the functional approach. Conceptually, the simplest mathematical descriptions of HA have been to fit a polynomial function to the herbage mass data over time (Bluett et al. 1998; Volesky and Anderson, 2007). The classical approach produces the mean values of the derivatives which are obtained from relatively large harvest intervals (Hunt, 1978). The functional method uses various sigmoid equations to describe the time dependence of biomass accumulation (Cacho, 1993; Belesky and Fedders, 1995). There has been some debate about the use of the classical vs. the polynomial fitting approach (Causton, 1991). Irregular growth curves have often been produced by the classical approach (Hunt and Parsons, 1977; Cacho,
The use of specific growth equations (functional approach) has been preferably adopted (Poorter and Garnier, 1996). The advantages and disadvantages of fitted mathematical functions to describe plant growth are discussed by Hunt (1979).

The choice of the most appropriate equation that describes growth/accumulation over time is critical (Araujo, 2003; Parsons et al., 2001). Parsons et al. (1988) point out that the use of different methods of describing growth/accumulation is the reason for lack of agreement between studies comparing grazing management strategies. The choice of a growth equation is influenced by the biological parameters that in turn affect the goodness of fit and degree of complexity for data input. Sometimes modifications are needed (Parsons et al, 2001; Thornley and France, 2005) to produce “qualitatively realistic” (Kaine and Tozer, 2004) and biologically acceptable results. To illustrate, Thornley and France (2005) modified the logistic equation in order to predict growth not only as a function of time, but also as influenced by growth-limiting factors such as light, temperature and nutrient availability. For instance, when evaluating leaf area growth, the rate of change of the parameters was dependent on temperature. A similar approach was sought by Bahler et al. (1989) in evaluating the effect of temperature on alfalfa germination.

One common equation used to fit the herbage accumulation pattern of pastures is the sigmoid, or S-shaped function, which after a slow growth period, HA rate if maximized followed by a period which the HA approaches an asymptote with time. This trajectory reflects the inherent potential growth and its interaction with the environment (Fitzhugh, 1976). Gompertz, logistic and Weibull are growth functions widely adopted in a diversity of fields such as, ecology (Tjørve, 2003), crop science (Morley, 1968; Bahler et al., 1989; Belesky and Fedders, 1995; Avanza, 2008), animal science (Spray and Widdowson, 1993).
1950; Zullinger et al., 1984; Forni et al., 2009), medicine (Norton, 1988; Tabatabai et al., 2005), microbiology (Chen and Hoover, 2007), economics (Meade and Islam, 2006) and demography (Olshansky and Carnes, 1997). Thornley and France (2007) provide a detailed mathematical explanation of these growth equations. Among the suite of sigmoidal functions, the Logistic and Gompertz have been the most widely used to describe herbage accumulation over time (Brougham, 1956; Birchman and Hodgson, 1983; Cacho, 1993; Belesky and Fedders, 1995; Parsons et al., 2000; Belesky et al., 2002; Burns et al., 2002). The most widely used equation to describe plant growth dependence on time is the logistic equation (Table 3.1) (Birch, 1999; Thornley and France 2005). It was first developed by Pierre Francois Verhulst in 1843 (Law, 2003) to describe Belgian demographic changes. Many modifications have been made to its original version (Richards, 1959; Bahler et al. 1989; Cacho, 1993). This equation is a density-dependent symmetric model, which means that, as the organism density increases, it assumes fewer resources are available, thus reducing the growth rate. The logistic curve is symmetric, thus the maximum growth rate coincides with half of the maximum mass accumulation and the rate of acceleration and deceleration of mass accumulation are the same. This symmetry may not be true in some circumstances, resulting in underestimating growth at high population density (Law et al., 2003). Various asymmetric modifications have been proposed (Cacho, 1993; Thornley and France, 2005). Parsons et al. (2001) demonstrated that the logistic function more accurately describes pasture growth more accurately for swards recovering from a severe than from a lenient defoliation.

The Gompertz equation was developed by the British mathematician Benjamin Gompertz in 1825 to create a mortality model. The decrease in rate of herbage accumulation can be a result of ‘senescence or development and differentiation’
(Thornley and France, 2007) of the population in question. The use of the Gompertz equation is attractive to pasture growth analysis because of its asymmetric feature, which from a mechanistic interpretation means that the factors driving the acceleration (C assimilation) and deceleration of pasture growth (C lost) do not occur at the same rate and equally over time, but change as a function of the physiological and morphological state of the sward. Briefly, these driving factors are carbon assimilation through photosynthesis (photosynthetic efficiency), carbon allocation (source to sink relationships), biomass allocation (shoot to root) and tissue senescence and differentiation. The original Gompertz equation, as seen in Table 2.1, has three parameters and the initial value for biomass is assumed to be zero. However, pasture ecosystems usually do not fit this assumption because they are comprised of perennial species that always have an initial (residual) herbage mass at the beginning of any regrowth cycle. Because of this, a modification to the Gompertz was necessary for the work presented in this thesis, as shown in Table 2.1. The predicted yield is a function of four parameters: 1) \( Y_{\min} \), the lowest herbage mass (lower asymptote), 2) \( Y_{\Delta} \), the difference between the upper and the lower asymptote, and 3) \( a \), which can be interpreted as a position parameter in that it modifies the vertical position of the curve, but usually has no biological meaning (Richards, 1959), and 4) \( b \), a rate constant that describes the rate of change in herbage mass by unit of time. From its derivative form, four useful variables can be determined: 1) the maximum growth rate (corresponding to the point of inflection of the sigmoid curve) (kg DM/ha/day), 2) the herbage mass that sustains this maximum growth rate and 3) the minimum and maximum herbage mass to keep pasture growth within a range of 90% of the maximum growth rate.
The Weibull function is suitable when, at time zero, the population mass is zero such as for seed germination (Bahler et al., 1989) or plant pathology studies in which the disease rate starts at zero. The Weibull function is widely used to investigate animal growth, disease progression, diameter distribution of trees and biomass accumulation after germination. However, its use in pasture growth studies has been limited. It has been useful when applied to grazed pastures where grazing produces spatial patterns of herbage mass distribution due to selectivity, thus altering forage availability. This phenomenon usually leads to a skewed distribution of herbage mass, which seems to be accurately assessed by the Weibull function (Remignton et al., 1992; Barthram et al., 2005).

The sigmoid growth curve is characterized by four phases (Fig. 2.1) which can be physiologically and morphologically explained:

1) **Phase of slow herbage mass accumulation**: there is insufficient leaf area to intercept solar radiation and the development and expansion of new tissues occurs at the expense of carbohydrate reserves in stems bases, rhizomes, and stolons in grasses.

2) **Phase of exponential growth**: the increase in rate of herbage accumulation is directly related to an increase in leaf area, thus more light can be intercepted and consequently an increase in photosynthesis occurs. In addition, in the early stage of this phase young leaves are responsible for light absorption and photosynthesis. Young leaves are known as being more photosynthetically efficient due to the age of chloroplasts and chlorophyll. The maximum rate of growth determines the end of this phase and is known as the point of inflection. It is likely that this point is when 95 to 100% of light is intercepted, also described as the optimum leaf area (Harris, 1978). Defoliation
management studies often aim to investigate whether this phase of exponential growth can be extended or if specific practices can prolong the phase where the maximum growth rate occurs.

3) Phase of decreasing rate of herbage accumulation: As dry matter increases, older leaves become the dominant fraction in the upper layer of the canopy, which decreases the photosynthetic efficiency of the canopy due to aging of the photosynthetic apparatus. As a consequence of aging, leaf senescence begins in the lower layers of the sward. Moreover, the increase in leaf area is not matched by the increase in photosynthetic rate due to shading of the lower leaves in the canopy.

4) Phase of ceiling yield: This phase occurs when the maximum yield is approached before the herbage mass begins to decline due to increasing rates of senescence. During this phase, the rate of senescence and decomposition are equivalent to the rate of the development of new leaves, resulting in constant mass (Cacho, 1993).

Besides quantifying herbage accumulation in grazing systems, the sigmoid growth curves are useful for describing the pattern of forage mass accumulation as influenced by defoliation management or forage species. This is especially true when its derivative is used to investigate the effect of defoliation on rate of accumulation. Cacho (1993) illustrated the importance and application of using an equation that relates herbage accumulation rate to a feature describing the sward conditions rather than relating it to time. Furthermore, herbage accumulation rate can be described as a function of the herbage mass by integrating the herbage mass time dependent function (sigmoid curve) and the growth rate as a function of time (first derivative). Figure 2.2 illustrates a generalized relationship between the standing herbage mass and accumulation rate for a
Gompertz growth equation. Its mathematical function is listed in Table 2.1. The growth rate increases concomitantly with herbage mass until around 4400 kg DM/ha when the maximum instantaneous growth rate, 35 kg DM/ha/day, occurs. For purposes of comparison to the Gompertz sigmoid curve, this description corresponds to phases one and two with the maximum instantaneous rate of herbage accumulation occurring at the point of inflection. The growth rate steadily decreases at herbage mass >4400 kg DM/ha (phase 3 of the sigmoid curve).

The relationship between herbage mass and growth rate shows potential for improving the efficiency of grazing systems. Grazing management practices which maximize pasture growth have been sought for years by researchers and producers alike. Therefore, continuing with Fig. 2.2 as a practical example, if the aim is to optimize herbage growth, the sward should be grazed from 5100 kg DM/ha down to 3300 kg DM/ha, which would maintain HAR within an arbitrary range of 90% of the maximum (35 kg DM/ha/day). In other words, the relationship previously described does not only predict the effect of herbage mass on rate of growth, but also can be used to suggest guidelines for defoliation regimes. Further applicability is found in studies investigating the stability of grazing systems (Noy-Meir, 1975) and comparing animal productivity under intermittent and continuous grazing (Bircham and Hodgson, 1983). Most feed budget challenges faced by pasture managers require quick, short-term decisions, thus demanding forecasting tools that are fast and easy to use. Using relationships similar to that shown in Fig. 2.2, a farmer would be able to estimate the HAR by measuring the actual standing herbage mass and thus know how the current defoliation intensity affects pasture productivity and sustainability.
The science of plant growth analysis plays an important role in grazing management studies; however, some considerations should be noted before attempting to describe and predict pasture growth. Although many methods have been used in growth analysis, the use of the functional approach for pastures is the most widely adopted. The biological interpretation of the equation parameters should be understood, the goodness of fit of the model to the measured data should be evaluated, and whether the model predicts reasonable herbage mass values. The derivative form of the sigmoid curve is particularly interesting for use in pasture studies, especially when the rate of change of HAR is expressed as a function of herbage mass.

**Defoliation Effects on HA**

In grass swards, tiller population and the processes of leaf appearance, elongation and life span (aging and senescence) characterize herbage mass accumulation. The dynamic biological process of plant development and expansion in time and space is known as morphogenesis. Plant morphology is genetically determined, but it is also modified by environmental conditions and defoliation.

The impact of defoliation on tiller production depends on the time of year, frequency and intensity of defoliation, initial number of tillers (Davis, 1988), self shading conditions and the removal of apical meristems (Harris, 1978). Increasing frequency and intensity of defoliation has resulted in high number of tillers; however, tiller number is inversely related to tiller weight (compensation theory) (Johnson and Parsons et al., 1985). Bullock et al. (1994) reported a greater decline in tiller number of grazed ryegrass
and Agrostis mixed swards during the winter than spring or summer. This is explained by
the fact that tiller production is seasonal while the rate of tiller senescence is quite
constant over the year. It has been observed that grazing can stimulate tiller production
(Parsons et al., 1983). Some grass species are more tolerant to grazing (less exposed
meristems, high ability to allocate assimilates) and usually exhibit increased tillering
under grazing.

Studies investigating the impact of defoliation pattern on herbage production have
focused on comparing intermittent and continuous stocking systems; although there is
evidence elsewhere (Parsons et al. 1988, Parsons et al., 2000) that the sward state is a
better guide to develop grazing strategies than the defoliation strategy per se. However,
there are still controversies in the literature about the effect of herbage production of
intermittent and continuous stocking (Harris, 1983; Parsons et al., 1988; Parsons et al.,
2000; Lemaire et al., 2009). Over the last 50 years of studies on the effect of defoliation
on herbage production, there is evidence that more severe defoliation and shorter
regrowth times are detrimental to herbage accumulation rates (Harris, 1978). More
recently, investigators have suggested that increasing defoliation efficiency depends on
herbage removal frequency and leaf lifespan (Lemaire and Chapman, 1996; Lemaire et
al., 2009).

Dry matter production has been the main variable reported in investigations of the
impact of defoliation on pastures, but its effects can be reported from other perspectives
such as tillering, rate of leaf appearance, leaf elongation and senescence, and
physiological responses (Davidson and Milthorpe, 1966; White, 1973; Donaghy
and Fulkerson, 2002). Defoliation results in modification in the activities of all plant
organs and the process of regrowth depend on the characteristics of the residual herbage
(Davies, 1988). The physiological responses to defoliation depend not only on the amount of leaf area remaining after defoliation but also on the photosynthetic capacity of those leaves. Removing younger leaves has a greater negative feedback on regrowth due to their high photosynthetic efficiency (Davies, 1988). After a severe defoliation, the carbohydrate supply cannot be met by photosynthesis and regrowth occurs at the expense of carbohydrate reserves until adequate leaf area is reestablished. There is evidence that the priority of carbon allocation to shoots can be detrimental to root development (Richards, 1993). Consequently, a decrease in the nitrogen supply to the plant can occur after severe defoliation and plant nitrogen reserves are also important for regrowth (Thornton et al, 2000). Because the carbohydrates are mainly stored in the base of stems, rhizomes or stolons, the stubble left after defoliation plays an important role in supporting regrowth. This is not only a response of the remaining physical stored reserves, but also to the removal of apical meristems. If the removal of apical meristems occurs, the regrowth is due to the development of basal and lateral meristems, which are slower to development than apical meristems.

The importance of the residual leaf area remaining after defoliation, to sward productivity and sustainability has been extensively reported in the literature (Brougham, 1956; Parsons et al., 1988; Davies, 1988). Modification of the leaf area of the sward affects leaf size, leaves per tiller and tiller density (Nelson, 2000). Leaf area corresponding to 95% of light interception has long been suggested as the ideal guideline for defoliation. Parsons et al. (2000) illustrated that a sward recovering from high leaf area exhibited low growth rates. In contrast, swards under frequent and severe defoliation had low leaf area, received constant supply of light and, due to low self shading, were in a high red:far red and blue light environment. That scenario leads to swards with high
tiller density and short leaves (Mazzanti et al., 1994). Although the leaves remaining in that sward have high photosynthetic efficiency, it is not enough to overcome the decline in herbage yield due to low leaf area. In contrast, swards under intermittent defoliation during the period of regrowth exhibit a constant increment in leaf area which leads to a greater degree of self shading. Therefore, after defoliation, the leaves remaining are less photosynthetically efficient.

**Standing Herbage Mass and Herbage Accumulation Rate**

Pastures should be considered as an ecosystem in which productivity and sustainability are dependent on the input of biotic and abiotic factors and their interactions. Some factors such as rainfall distribution, solar radiation and temperature cannot be controlled. Therefore, to optimize productivity of this ecosystem, farmers can manage soil fertility, plant nutrient status, species composition and defoliation. Of these options, soil fertility, plant nutrient status and species composition are relatively slow to change, whilst defoliation remains the most important short-term pasture management option. The two predominant components of defoliation, intensity and frequency, directly affect the plant capacity for harvesting light (leaf area), absorbing water and minerals (root), and ultimately synthesizing carbohydrate. Moreover, the impact of herbage removal on meristems and tillering affects pasture persistence and sustainability.

Prescriptions of herbage mass management that optimize herbage growth were first developed by Brougham (1955). Since then, most studies have focused on the maximization of forage yield when comparing intermittent to continuous grazing. Furthermore, forage yield has usually been interpreted as dependent on the rate of growth
under numerous possible combinations between intensity and frequency of defoliation. Thus, the impact of standing herbage mass on the growth rate has not been thoroughly investigated (Harris, 1983; Belesky and Fedders, 1995).

Studies have focused on the sward state (leaf area, rate of senescence and tillering) and physiological processes (carbohydrate synthesis and allocation) to set guidelines for optimizing pasture utilization. Interestingly, the physiological processes such as the rate of photosynthesis and the rate of senescence ultimately quantify the herbage mass accumulation. Likewise, sward condition features such as leaf area, tiller population density and sward height can be correlated to herbage mass (Brougham, 1955; Bircham and Hodgson, 1983; Engel et al., 1987; Matthew et al., 1995). For instance, studies have demonstrated a linear relationship between leaf area index or sward height and herbage mass (Brougham, 1955; Trott et al. 1988; Harmoney et al., 1997). Leaf area index (LAI) has been the primary variable studied to understand the process of herbage mass accumulation; however, LAI cannot be measured easily by farmers or even by researchers. Parsons et al. (1988) demonstrated the importance of using sward state to guide management strategy. They recommend that the optimum time of harvesting is when the maximum average herbage accumulation rate is achieved. Although the sward state was based on leaf area index, the authors pointed out the possibility of replacing it with other sward measurements such as height, which is well known to be correlated to standing herbage mass. Many pasture managers already quantify in some fashion forage yield for feed budget calculations and use that information to guide stocking management decisions. If the rate of herbage accumulation can be predicted by measuring herbage mass, farmers will have a more powerful decision support tool.
The mathematical theory to support this approach was described in the herbage accumulation section of this chapter. Briefly, by differentiating a sigmoid growth equation it is possible to describe the dependence of HAR on herbage mass. The sigmoid curve has four parameters, which can be statistically calculated. Those parameters change over the seasons (Cacho, 1993), so does the relationship between herbage mass and growth rate and consequently its guiding management variables. For instance, the $Y_A$ had higher values during spring than autumn (Parsons et al., 1983; Johnson and Parsons, 1985; Cacho, 1993). Consequently, the use of fixed parameters across season does not provide an accurate model prediction.

A physiological mechanism for the relationship between the amount of herbage present to herbage accumulation rate is quite complex. Considering that the amount of herbage present is a consequence of the processes of growth, development, aging and senescence, one can investigate the ideal amount of herbage present that maximizes the process of growth and HA (available forage yield). The amount of herbage in the sward also has feedback effects on the processes that previously determined it: the photosynthetic efficiency, the balance between sink and source (carbohydrate partitioning and allocation), self-shading, water use (requirement and evapotranspiration), and root development and thus nutrient and water uptake. Brougham (1956) explained the maintenance of maximum HAR due to the interception of almost all the light reaching the sward, which can be interpreted as an optimum amount of herbage mass. Most studies investigating the relationship between herbage mass and growth rate, addressed with growth equations, were conducted in New Zealand and United Kingdom under pure ryegrass stands and clover-ryegrass mixed pastures. No literature has been found of
similar research conducted under growing conditions and forage species common to United States.

Bluett et al. (1998) highlight the promising application of studying the relationship between herbage mass and the rate of growth when combined with other research results (Noy-Meir, 1975; Jonhson and Parsons, 1984; Parsons et al., 2001). The relationship between herbage mass and growth rate can be combined with stocking rate scenarios to investigate stability of pasture systems (Noy-Meir, 1975; Bircham, 1981; Parsons et al., 2001). In addition, not only does the use of simplified sigmoid growth equations and their derivatives provide scope for more detail in the other components of the model, but it also facilitates determination of the optimum herbage mass to maximize growth rate when comparing different defoliation regimes (Parsons et al., 2001). Cacho (1993) provided valuable insight on the use of the sigmoid growth equation and its derivative form for pasture growth under grazing. The author also discussed the impact of using different growth equations. The use of a modified logistic equation resulted in a 10% higher value for the maximum growth rate when compared with the logistic equation used by Bircham and Hodgson (1983). Nevertheless, few studies have been conducted to gain an understanding of the use of the derivative growth equation and the applicability of its parameters to grazing management.

The classical pasture growth study conducted by Brougham (1956), found that the maximum growth rate in winter corresponded to a herbage mass between 1166 kg DM/ha and 747 kg DM/ha above a stubble of 2.5 cm. Bircham and Hodgson (1983) found under continuous stocking management of mixed temperate pastures a maximum growth rate of 118 kg DM/ha/day, which occurred at a predicted herbage mass of 1200 kg DM/ha at a LAI of 2.5 and sward height of 3.5 cm. Some care should be taken into account when
interpreting growth rate results. The increase in forage mass can be expressed either as
gross herbage accumulation, green plus senescent material in the sward, or as net herbage
accumulation, resulting from the processes of growth and senescence. The latter can be
determined by subtracting the former from a senescence rate equation. Recently, the use
of equations that take into account the rate of senescence have been advocated as
preferable; however, the use of a linear or dynamic senescence model is controversial
(Bircham and Hodgson, 1983; Johnson and Parsons, 1985; Parsons et al., 2001; Duru et
al., 2002). To illustrate, the maximum growth rate of 118 kg DM/ha/day reported by
Bircham and Hodgson (1983) was calculated with the total dry matter, but when based on
the net herbage production the maximum growth rate had a value of 75 kg DM/ha/day. In
contrast, much lower values for the maximum instantaneous growth rate were found by
Bluett et al. (1998) during winter. For a mixed pasture of ryegrass and white clover they
reported a growth rate of 32 kg DM/ha/day at an optimum herbage mass of 2494 kg
DM/ha, while for a mixed cooksfoot (Dactylis glomerata), dogstail (Cynosurus cristatus)
and browntop (Agrostis capillaris) pasture it was 19 kg DM/ha/day at 1638 kg DM/ha.
Those studies addressed the influence of herbage mass on the rate of growth by using a
quadratic model rather than the differential of a sigmoid growth equation as seen in
Cacho (1993); however, the logistic model produced lower residual variation (Bircham
and Hodgson, 1983). This methodology created a single equation for the whole
experimental period and this might be the reason for the high variability presented in
Bluett et al. (1999). Harris (1983) investigating intermittent and continuous stocking of a
white clover-ryegrass pasture concluded that the standing herbage mass and accumulation
rate exhibited a positive correlation during spring, but not in summer. The author stressed
the use of measurements of standing herbage mass as a tool to forecast accumulation rates.

Those results suggest that the HAR can be optimized by managing the standing pasture mass. In addition, forage quality may be investigated concomitantly to the optimum herbage mass to meet livestock nutritional requirements.

**Modeling Herbage Growth in Grazed Ecosystems**

Peart et al. (1998) define a model as ‘the set of equations and results that quantitatively describe the operation of a system’. One application of modeling is to collate information that can be interpreted and used as a decision support tool to improve the system management. Modeling agricultural systems in general is challenging, because biological processes being investigated are hierarchy organized and their interactions do not always produce a constant prediction (Jonse and Luyten, 1998) and this is not different for grazing systems.

Livestock production on pastures is a complex system in which its components, animal, plant and soil, dynamically interact resulting in feedbacks not always easy to predict. The development of grazing system models has occurred more recently than cropping system models, however, they have been constantly improved by adding driving variables and processes in order to account for the system complexity as realistically as possible. Milne and Sibbald (1998) argue that the modeling of pasture management has been developed at a slower pace than the modeling of key processes of pasture systems. There are a wide variety of models that simulate grazing systems, the sub-models included depend on what question the researcher wants to answer: forage growth, forage quality, canopy architecture, animal diet selection, animal performance or its ecological
function. Nevertheless, usually the interaction between those factors is what most attracts the interest of researchers.

Regardless of the level of complexity or the scope of the model in question, the basis for simulating grazing ecosystems is to model forage growth. Herbage accumulation over time has been characterized by a sigmoid growth equation and the use of a logistic function has been widely adopted (Morley, 1986; Thornley and Jonhson, 1990; Cacho, 1993; Woodward et al., 1993). Comparisons of different sigmoid growth equations in grazing system models are common in the literature, however, most interest is on the biological meaning of the curve produced (parameters, symmetric vs asymmetric). Woodward (1996) demonstrated the valuable use of simple grazing models (with a single differential equation) to improve management decisions regarding the frequency of defoliation, stocking rate, duration of grazing and investigating the pasture stability state (Noy-Meir, 1976; Woodward et al., 1993). Parsons et al. (2000) also stressed the applicability of simple growth equations. These authors argue that although conventional growth functions seen in the literature cannot replace the physiological sub-models, they are useful to predict forage growth in practical models (farm scale), highlighting the benefits of modifying this equation in order to produce more acceptable outcomes. In addition, they question the real necessity of details when modeling grazing ecosystems, which depends on the intended use of the model.

Some grazing system models have included a sub-model to take into account the process of senescence, because the animal consumes primarily green material and the proportion of each component impacts the forage quality. The complexity of this sub-model also varies (Bircham and Hodgson, 1983; Johnson and Parsons, 1985; Parsons et al., 2000). More complex approaches to simulate forage growth over time include
investigations of the responses to environmental conditions (Wright and Hanks, 1981; McCall and Bishop-Hurley, 2002), nutrient uptake (Greenwood et al., 1991; Gastal et al., 1992; Sheery et al., 1996; Plenet and Lemaire, 1999; Duru and Delaby, 2003), photosynthesis (Thornley, 1998; Peri et al., 2003), respiration (Thornley and Cannell, 2000), species composition (Thorley et al., 1995; Carlassare and Karsten, 2003) and defoliation (Parsons et al., 1986, Woodward et al., 1995; Duru et al., 2000; Cros et al., 2003).

Modeling most of these variables requires high input and long term studies to be created and validated, which are usually site-specific (Herrero et al., 1999). For example, the Hurley Pasture Model is a well known grassland ecosystem simulation which has been in development over 20 years and contains four main sub-models: plant, animal, soil and water. It is important to note that the simulation of ecosystem dynamics is based on the role of carbon and nitrogen. This model was designed to understand the dynamics of grassland systems and answer “what-if” questions in order to predict long term consequences; however, it is intended for research rather than for use on farms. Farm scale models must be simple, with few input variables and producing predictions that are easy to understand so that farmers can use them as a tool to evaluate risk (Milne and Sibbald, 1998; Cros et al., 2003; Holden and Brereton, 2008). Thus, it is desirable to have models with input variables that farmers can control (fertility, forage availability, frequency and intensity of defoliation), so they can simulate the impact of modifying management practices. For example, the DairyMod was designed to allow farmers to simulate scenarios of a pasture based dairy system in Australia by integrating pasture growth, animal intake and physiology, water and nutrient dynamics and stocking management (Johnson et al., 2003).
The impact of defoliation, frequency and intensity on plant and animal production has also been the focus of many researchers primarily when comparing the performance between continuous and intermittent grazing (Parsons et al., 1986, Woodward et al., 1995; Cros et al., 2003). More recently, there has been increasing demand for grazing systems simulators that are able to describe not only the accumulation of herbage mass, but also its vertical distribution (Milne and Sibbald, 1998). This arises from the need to integrate the plant sub-models with the animal performance sub-models, which take into account the impact of canopy architecture on animal intake behavior and thus on animal performance. In addition, more complex models that describe plant-animal interactions and responses at the bite scale have been developed (Moris, 1969; Schiwinning and Parsons, 1999; Parsons et al., 2000). By understanding the responses on a bite scale (patch states), spatially explicit models can be created rather than temporal ones (Parsons et al., 2000; Chapman et al., 2007). Another field of study that applies to modeling grazing systems is the investigation of the impact of climate change on grassland ecosystems (Thornley and Cannell, 1997) and the role of management on environmental improvement (water, soil, wildlife, carbon sequestration).

Substantial progress on modeling grazing systems has been made. Holde and Brereton (2008) and Milne and Sibbald (1998) present excellent reviews of this progress. However, according to Milne and Sibbald (1998) current grazing models have four constraints that need to be addressed: the different goals producers have for permanent pastures, reliable estimates of daily pasture production which can be used as an input to animal production models, predictions of the effect of grazing management on forage production but also on the short and long term pasture sustainability, and lastly, development of simple pasture data inputs that are easy to measure. In this context, the
use of simple approaches to assess forage growth and its response to defoliation are very attractive and supported when creating models designed for adoption by farmers.
<table>
<thead>
<tr>
<th>Equation</th>
<th>Herbage mass†</th>
<th>Rate of herbage accumulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symmetric logistic‡</td>
<td>$Y = \frac{Y_{\Delta}}{1 + e^{-(a-b)t}} + Y_{\min}$</td>
<td>$\frac{dy}{dt} = \frac{Y_{\Delta}b e^{a-bt}}{(1+e^{a-bt})^2}$</td>
</tr>
<tr>
<td>modified Gompertz</td>
<td>$Y = Y_{\Delta} e^{a^{br}} + Y_{\min}$</td>
<td>$\frac{dy}{dt} = bY_{\Delta} e^{ae^{br}} \ln\left(\frac{1}{e^{ae^{br}}}\right)$</td>
</tr>
<tr>
<td>modified Weibull</td>
<td>$Y = Y_{\Delta} \left(1 - e^{-\left(\frac{t}{a}\right)^b}\right) + Y_{\min}$</td>
<td>$\frac{dy}{dt} = \left(\frac{b}{a}\right) \left(\frac{t}{a}\right)^{b-1} e^{-\left(\frac{t}{a}\right)^b}$</td>
</tr>
</tbody>
</table>

Table 2.1: Sigmoid growth equations used to describe herbage mass accumulation over time and their respective instantaneous growth rates.

![Fig. 2.1: A sigmoid growth curve and its division into four phases.](image-url)
Fig. 2.2. A generalized relationship between rate of herbage accumulation and standing herbage mass. The arrow represents the range of herbage mass utilization in order to maximize herbage accumulation rate.
CHAPTER 3:
ANALYSIS OF HERBAGE MASS AND HERBAGE ACCUMULATION RATE USING GOMPERTZ EQUATIONS

ABSTRACT

Sigmoid equations are recognized as representative of the pattern of herbage accumulation during a growth period; however the various equations and their variability among locations and during the growing season have not been well described. The objectives of this study were to find the most suitable, four-parameter sigmoid equations to fit measured herbage mass and to investigate how the patterns of herbage accumulation (i.e. equation parameters) varied with time of year and location. Herbage mass was measured approximately weekly during 11 or 12 growth periods with a rising plate meter (RPM) at three north-central USA locations (Columbus and Coshocton, OH, and Arlington, WI) during 2008, and those data were fit to Gompertz equations. There were four replicates for each growth period. We found predictable relationships between instantaneous herbage accumulation rate (HAR_i) and herbage mass for each location and date. Time-independent HAR_i vs herbage mass curves have potential use for pasture management by defining the optimum herbage mass at which HAR_i is maximized. The optimum herbage mass varied between 1600 and 4000 kg dry matter (DM) ha^{-1} depending on location and date. Regrowth curves during the summer were compared for pasture having contrasting spring clipping management, and no statistical differences in
the equation parameters were observed. Allowing herbage mass to exceed the optimum point (e.g. delayed harvest), or harvesting to levels below the optimum point, will reduce the HAR$_i$. The HAR$_i$-herbage mass curves define a range of herbage mass within which pastures can be managed to achieve high HAR$_i$, and maintaining pastures within 90% of the maximum HAR$_i$ may be a practical target for producers.
INTRODUCTION

The sigmoid, or S-shaped, equation describes the accumulation of herbage mass towards an asymptote, over time. This trajectory reflects the inherent potential growth and its interaction with the environment (Fitzhugh, 1976). Of the many possible sigmoid functions, the Logistic and Gompertz have been most commonly used to fit herbage mass accumulation in pasture ecosystems (Brougham, 1956; Birchman and Hodgson, 1983; Cacho, 1993; Belesky and Fedders, 1995; Parsons et al., 2000; Belesky et al., 2002; Burns et al., 2002). Besides quantifying herbage accumulation in grazing systems, the sigmoid growth curves are useful for describing the pattern of forage mass accumulation as influenced by defoliation management or forage species. This is especially true when in its derivative form it is used to investigate the effect of defoliation on rate of accumulation. Cacho (1993) illustrated the importance and application of using an equation that relates herbage accumulation rate to a feature describing the sward conditions rather than relating it to time. Furthermore, herbage accumulation rate can be described as a function of the herbage mass by relating the herbage mass time dependent function (Fig. 3.3.1a, Table 3.1 Eq. 1) and the rate of accumulation as a function of time (Fig. 3.1b, Table 3.1 Eq. 2). This relationship, described by a time-independent growth equation, not only predicts the effect of herbage mass on rate of growth, but also can be the basis for defoliation management recommendations. Further applicability is found in studies investigating the stability of grazing systems (Noy-Meir, 1975) and comparing animal productivity under intermittent and continuous grazing (Birchman and Hodgson, 1983). Fig. 3.2 illustrates a generalized relationship between the standing herbage mass and accumulation rate for a Gompertz growth equation and the implications for grazing
management. A practical goal might be to maintain pastures within the range of 90% of maximum HAR_i. Excessive (or insufficient) forage removal (by grazing or machines) will result in reduced pasture accumulation rate.

Although prior work has validated use of sigmoid equations to model forage production, few studies have quantified variation in the equation parameters during a growing season. For instance, Thornley and France (2005) modified the logistic equation in order to predict growth not only as a function of time, but also as influenced by growth-limiting factors such as light, temperature and nutrient availability.

The objectives of this study were: a) to find the most suitable (four-parameter) sigmoid equations to fit measured herbage mass accumulation, b) investigate how the patterns of pasture growth (i.e. equation parameters) varied with time of year and location and c) test the hypothesis that one Gompertz equation could represent regrowth regardless of the prior spring clipping management (spring clipping vs. no clipping). In contrast to prior modeling work that has followed the pattern of herbage accumulation over time (i.e. confounded with changing temperature, soil moisture and reproductive status), we propose to develop equations from plots with different herbage mass (and consequently different HAR_i) on the same date.
MATERIALS AND METHODS

Sites and Experimental Design

Measurements were conducted at three north-central USA locations during 2008, Columbus and Coshocton, OH, and Arlington, WI. The Columbus site was located at the Ohio State University Donn Scott Airport, Columbus OH (40°04’ N, 83°05’ W) in pasture that had been mowed to maintain a height of 10 to 20 cm for the previous 2 to 3 yrs. The average botanical composition, determined by physical separation of five samples on 12 Aug 2008, was 73% tall fescue [Schedonorus phoenix (Scop.) Holub, formerly Festuca arundinacea Schreb.], 15% Kentucky bluegrass (Poa pratensis L.), 2% white (Trifolium repens L.) and red clover (T. pratense L.), and 10% other grasses and weeds. The soil was a Kokomo silty clay loam, 0-5% slope, a fine, mixed, superactive, mesic Typic Argiaquolls. The soil had a pH of 6.8, 3.8% organic matter, 86 mg P kg⁻¹ soil, and 233 mg K kg⁻¹ soil. Nitrogen fertilizer was applied on 9 Apr 2008 at 47 kg N ha⁻¹ as NH₄NO₃ and on 3 June 2008 at 56 kg N ha⁻¹ as urea.

Herbage accumulation at Columbus was measured during 11 growth periods, with the first and last periods commencing 8 April and 9 Sep 2008, respectively (Table 3.2, Fig. 3.3a). Herbage mass was measured approximately weekly, beginning 8 Apr 2008 and ending 5 Nov 2008, when all plots were harvested with a flail mower. Plots were 4.0 x 9.3 m, with four replicates in a randomized complete block design. For the first growth period, the first two measurements (early April) showed decreasing herbage mass that was attributed to decay of remnant dead vegetation from winter (dead matter was 77% of herbage mass on 8 Apr 2008; 41% on 6 May 2008, n=5) and those points were omitted.
from analysis. Except for the first growth period which was not mowed, all plots for subsequent growth periods were mowed to 7.5 cm at commencement of the respective growth period. The first four periods were harvested after 3 to 4 mo growth since it was assumed pastures might have reached ceiling herbage mass, but subsequent analysis of the data showed that plots may have been accumulating herbage mass after 4 mo, and the last seven growth periods were allowed to grow until they were harvested on 5 Nov 2008, at 7 cm stubble height. At Columbus, the four initial growth periods were 86 to 100 days, and subsequent growth periods were 57 to 155 days (Table 3.2).

The Coshocton site was located at the USDA-ARS North Appalachian Experimental Watershed, Coshocton OH, (40°21′51″ N, 81°46′56″ W) in pasture that had been in intermittent hay production and grazing for 3 to 4 yr. The average botanical composition, determined by physical separation of four samples on 6 Nov 2008, was 76% tall fescue, 4% Kentucky bluegrass, 10% white and red clover, and 10% other grasses and weeds. The soil was a Gilpin silt loam, 0-10% slope, mixed, active, mesic Typic Hapludults. The soil had a pH of 6.6, 2.8% organic matter, 234 mg P kg⁻¹ soil, and 117 mg K kg⁻¹ soil. Nitrogen fertilizer was applied as urea on 16 April and 5 June 2008 at 47 and 80 kg N ha⁻¹, respectively.

Herbage accumulation at Coshocton was measured during 11 growth periods, with the first and last periods commencing 8 April and 11 Sep 2008, respectively (Table 3.2, Fig. 3.3b). Herbage mass was measured approximately weekly, beginning 8 Apr 2008 and ending 6 Nov 2008, when all plots were harvested with a flail mower. Plots were 4.0 x 8.0 m, with four replicates in a randomized complete block design. For the first growth period, the first two measurements (early April) showed decreasing herbage
mass that was attributed to decay of remnant dead vegetation (dead matter was 90% of herbage mass on 8 Apr 2008; 27% on 9 May 2008, n=5) from winter and those points were omitted from analysis. Except for the first growth period which was not mowed, all plots for subsequent growth periods were mowed to 5.5 cm at commencement of their respective growth period. The first four periods were harvested after 3 to 4 mo growth since it was assumed pastures might have reached ceiling herbage mass, but subsequent analysis of the data showed that plots may have been accumulating herbage mass after 4 mo, so the last seven periods were allowed to grow until they were harvested on 6 Nov 2008, to 7 cm stubble height. At Coshocton, the four initial growth periods were 73 to 101 days, and subsequent growth periods were 56 to 153 days (Table 3.2).

The Arlington site was at the University of Wisconsin Arlington Agricultural Research Station (43° 18’ N, 89° 21’ W) in a monoculture of meadow fescue \( Schedonorus pratensis \) (Huds.) P. Beauv., formerly \( F. pratensis \) Huds. cv ‘Pradel’) that had been seeded in 15 cm rows on 2 May 2007. This pasture was mechanically harvested three times during 2007. The soil was a Plano silt loam, well-drained, fine-silty, mixed, superactive, mesic Typic Argiudoll. The soil nutrient concentrations to 15 cm depth were 130 mg K kg\(^{-1}\) soil, 26 mg P kg\(^{-1}\) soil, pH 6.8, organic matter 3.4%. At the start of each growth period, plots were mowed to 7.5 cm and 50 kg N ha\(^{-1}\) was applied as NH\(_4\)NO\(_3\).

Herbage accumulation at Arlington was measured during 12 growth periods, with the first and last periods commencing 1 May and 18 Sep 2008, respectively (Fig. 3.3c). Plots were 2.0 x 6.0 m, with four replicates in a randomized complete block design. Except for the first growth period which was not mowed, all plots for subsequent growth periods were mowed to 7.5 cm height at commencement of their respective growth
period. Herbage mass was measured approximately weekly during the period 1 May to 30 Oct 2008. At Arlington, the growth periods ranged from 41 to 99 days.

Herbage Mass Measurement

Herbage mass was measured approximately weekly at each site using a RPM (Ashgrove Pasture Plate, Ashgrove Industries, Ashhurst NZ) (Vartha and Matches, 1977). Calibration details are described in detail by Ferraro et al. (2009). Briefly, at each measurement date, five to 10 calibration samples were collected that comprised a RPM reading and the vegetation (clipped to ground level) within the 0.1 m² RPM area. The calibration samples were selected at random to represent the range of vegetation mass present, and included short and tall areas. Subsequent analysis showed no significant difference between stubble and leafy vegetation and a single calibration was used for pre- and post-harvest swards. Clipped samples were dried at 60°C for 48 hr. A regression (calibration) equation for each measurement date was calculated using the calibration data from the sample date and the preceding sample date, to reduce variation. Previous analysis (Ferraro et al., 2009) had shown the intercept was not significantly different from zero, and linear equations were forced through the origin.

At Columbus and Coshocton, herbage mass was measured using a plot harvester at the conclusion of each growth period (harvest dates in Table 3.2). At each harvest, herbage mass (above mowing height) was measured in a 1.1 x 8.0 m strip in the center of each plot. Harvested mass was calculated from the harvested FW and the DM percentage of a subsample that was dried at 60°C for 48 hr. The remaining stubble was measured with the calibrated RPM. Total final plot herbage mass was the total of harvested and
stubble mass. At Coshocton and Columbus, additional plots of the first three growing periods were established and clipped to 5.5 cm stubble after about 10 weeks of herbage accumulation. Those plots were allowed to regrow again and the herbage accumulation was measured until the end of the experiment. On the same dates as those plots were clipped to initiate a summer regrowth period, other plots were also clipped that had been maintained in the vegetative stage of growth throughout the spring by clipping every 2 wk. Herbage accumulation from the two contrasting spring managements was compared.

**Statistical Analysis**

Herbage mass (average from four replicates for five to 10 measurement dates after defoliation to a low residual height) was fit to sigmoid equations (Fig. 3.1a) using PROC NLIN in SAS (SAS for Windows V 9.1, SAS Institute Inc., Cary, NC). Models were fit for symmetric logistic, Gompertz and Weibull functions (Table 3.1) with the model having the lowest error mean square being identified as the best fit to the data. PROC NLIN used the option Method=Newton, since this had the most reliable convergence; however Method=Gauss and Method=Marquadt also were almost as reliable in obtaining convergence. Differences in the final results of those methods were negligible. Parameter estimation by PROC NLIN had less error when a three parameter model ($Y_A$, a, and b) was used (rather than four parameters), and curve fitting was simplified by assigning $Y_{min}$ as the lowest herbage mass measured (always within the first three herbage mass measurements). An analysis was conducted to compare curves describing herbage accumulation during the summer from plots that had been clipped regularly during the
spring and plots that had been allowed to accumulate herbage with no clipping until the
initiation date of the growth period tested (pair of curves) (Appendix G). The model
tested was:

\[ Y_{ij} = \sum_{u=1}^{g} D_u \left[ Y_{Ai} \ast \exp \left( -a_i \ast \exp \left( -b_i \ast x_{ij} \right) \right) + d_i \right] + \varepsilon_{ij} \]

Where:

\( Y_{ij} \) = is the observed value in the j experimental unit in the I group;
\( D_u \) = dummy variable; 1 if \( Y_{ij} \) belongs to i group and 0 if not;
\( Y_{Ai} \) = the difference between the upper asymptote and lower for i group;
\( a_i \) and \( b_i \) = are the curve shape parameters for i group;
\( d_i \) = is the lowest herbage mass present at the beginning of growing phase of i
group;

\( \varepsilon_{ij} \) = the error term for the observation j in the i group.

Firstly, the Gompertz curve parameters were estimated without making any
restriction to the model (\( \Omega \)) and the residual sum of squares (SS\(_{R\Omega}\)) were calculated.
Secondly, the two models (group 1 and 2) were compared by testing the following null
hypothesis (\( H_{0}^{1} \)):

\( H_{0}^{1} \): \( Y_{A1} = Y_{A2}; a_1 = a_2 \) and \( b_1 = b_2 \) vs. \( H_{a} \) that at least one parameter is not equal.

When \( H_{0}^{1} \) was rejected the following hypotheses were tested:

a) \( H_{0}^{2} \): only \( Y_{A} \) is equal;

b) \( H_{0}^{3} \): only ‘a’ is equal;

c) \( H_{0}^{4} \): only ‘b’ is equal;

d) \( H_{0}^{5} \): ‘b’ and ‘a’ were equal.

For each of the hypothesis described above the respective SS\(_{Rx}\) was calculated.
The analyses of equality between models were conducted as describe in Regazzi (2003). The tests of hypotheses were performed using the chi-square test \( \chi^2_{\text{cal}} = -\text{Nln}(SS_{Ri}/SS_{Rx}) \) and reporting the respective p-values \( \chi^2_{\text{cal}} < \chi^2_{\text{tab}} \).

For each date on which herbage mass was measured (25 dates at approximately 1 wk intervals for each site), the measured herbage mass and the calculated \( \text{HAR}_i \) (calculated for that plot on that date using the Gompertz equations determined above) were fit to the time-independent, \( \text{HAR}_r \)-herbage mass equation (Fig. 3.2, Table 3.1 – Eq. 3) using PROC NLIN in SAS (SAS for Windows V 9.1, SAS Institute Inc., Cary, NC). Each data point comprised one observation on one plot and all replicates were used for the curve fitting (six to 31 points per analysis). The parameters estimated by PROC NLIN were \( Y_{\text{min}}, Y_{\Delta r}, \) and \( b \). The best model used was the one with lowest error mean square. Approximate standard errors for equation parameters were predicted by NLIN. The maximum instantaneous herbage accumulation rate (\( \text{HAR}_{i,\text{max}} \)), the optimum herbage mass (at which \( \text{HAR}_{i,\text{max}} \) occurred) and the critical range of herbage mass for >90% of maximum instantaneous herbage accumulation rate (\( \text{HAR}_{i,90\%} \)) were calculated for each equation using MS-Excel.
RESULTS

Weather Data

Climatic data were measured within 1 km of each site (data not shown). Rainfall was adequate for pasture growth at all sites from April through July, and averaged 125 mm per month, 28% above the 30-year average (data not shown). Conversely, August to October rainfall averaged 41 mm per month, 50% of the 30-year average, and probably limited pasture growth. At Coshocton, the April to October 2008 mean air temperature equaled the 30-year average, but Columbus and Arlington were 0.6 and 1.1°C below average, respectively. The average April to October 2008 air temperature at Columbus, Coshocton, and Arlington was 17.8, 17.7, and 14.7°C, respectively.

Curve Fitting

Forage accumulation was reliably predicted by all sigmoid growth equations, but was a better fit for the asymmetric equations than symmetric equations (data not shown). On average for 34 dates and locations, the average $r^2$ and error mean square for the symmetric logistic equation was 0.88 and $1.38 \times 10^5$, and for the Gompertz equation was 0.99 and $6.7 \times 10^4$, respectively. There was no appreciable difference in the goodness of fit among the asymmetric equations (Gompertz, Weibull, and asymmetric logistic). All subsequent analysis was done using Gompertz equations since these are more commonly used in the literature, and have simpler mathematical computation than for other equations. The Gompertz curves were used to show the accumulation of measured herbage mass over time (average for four replicates) (Fig. 3.3). The slope ($HAR_t$) was calculated for each experimental unit (plot) at each site (132 equations in total) for use in predicting the $HAR_t$-herbage mass curves.
Predicted HAR$_i$ and measured herbage mass were fit to the HAR$_i$-herbage mass equation (Table 3.1 Eq. 3) on 25 dates per site (Table 3.3). On approximately 33% of dates, PROC NLIN was unable to converge on a realistic result and a simplified model (with two parameters) was used by forcing the equation through HAR$_i$=0 at the average Y$_{\text{min}}$ for each site (1665, 1345, and 1360 kg DM ha$^{-1}$ for Columbus, Coshocton and Arlington, respectively) (Table 3.3). Unreliable parameter estimates were obtained for eight dates and were omitted from Table 3. Reasons for the inability to obtain parameter estimates included, a) insufficient data at high herbage mass early in the growing season (April), b) insufficient data at low herbage mass late in the growing season (September), and c) the failure of PROC NLIN to converge (even for a reduced, two-parameter model).

Some of the parameters for the HAR$_i$-herbage mass equations varied considerably during the growing season (Table 3.3). The Y$_\Lambda$ parameter showed the greatest seasonal variation. Values for Y$_\Lambda$ were low in spring (mean = 3688 kg DM ha$^{-1}$), increased to their maximum during late-May to June (mean = 6305 kg DM ha$^{-1}$), and decreased to their lowest values during August/September (mean = 3242 kg DM ha$^{-1}$), except for a slight increase in September/October at Columbus and Coshocton. The ‘b’ parameter [Table 3.1, Eq. 3] described the shape of the Gompertz curve and varied seasonally at the three sites. The highest values for b occurred in May, when the growth rate was highest (mean = 0.089). The lowest values for b occurred in late summer (August) (mean = 0.013), and increased slightly in autumn (September to October, mean = 0.020). Within each location, the parameter Y$_{\text{min}}$ did not vary appreciably during the growing season.

The parameters for the HAR$_i$-herbage mass equations varied among the three sites (Table 3.3). Values for Y$_\Lambda$ were similar for Columbus and Coshocton, but were slightly
higher for Columbus during June. The $Y_\Delta$ values were generally lower at Arlington than in Ohio. Values for $b$ were similar for the two Ohio sites, but were much lower than for Arlington. Values for $Y_{\min}$ were slightly greater in Columbus (1765 kg DM ha$^{-1}$) than Arlington or Coshocton (1360 and 1345 kg DM ha$^{-1}$, respectively).

Four important values with practical application were calculated for each week at each site during the growing season (Table 3.4). The highest values for maximum HAR$_i$ ($\text{HAR}_{i,\text{max}}$) at Arlington occurred during May (176.8 kg DM ha$^{-1}$ d$^{-1}$), and in Ohio occurred during June (86.8 and 66.2 kg DM ha$^{-1}$ d$^{-1}$ at Columbus and Coshocton, respectively). The $\text{HAR}_{i,\text{max}}$ decreased during the growing season, and the lowest values were usually observed during October at each site. The $\text{HAR}_{i,\text{max}}$ was greatest at Arlington, intermediate at Columbus and lowest at Coshocton. The optimum herbage mass (at $\text{HAR}_{i,\text{max}}$) also varied between seasons and sites, being greatest during summer in Ohio (5400 and 5700 kg DM ha$^{-1}$ at Columbus and Coshocton, respectively), and least in early spring and late fall at all sites (mean = 2835 kg DM ha$^{-1}$).

Of potential interest to pasture managers is the range of herbage mass (maximum and minimum) that ensures HAR$_i$ remains within 90% of $\text{HAR}_{i,\text{max}}$ (Fig. 3.2, Table 3.4). This range varied considerably during the year and between locations. The minimum herbage mass was similar among the three sites (mean = 2590 kg DM ha$^{-1}$), but was higher in June/July at Columbus (mean = 3625 kg DM ha$^{-1}$) than in spring or autumn, or in any season at Arlington. Recommendations for maximum herbage mass varied considerably between seasons and sites, and were relatively constant at Arlington (mean = 3340 kg DM ha$^{-1}$), but were much higher in summer (mean = 5965 kg DM ha$^{-1}$) than spring or fall in Ohio (mean = 3990 kg DM ha$^{-1}$).
The parameter values for Coshocton and Columbus for the model without restrictions, for the model testing $H_0^1$ and their residual sum of squares are presented in Tables 3.5 and 3.6, respectively. When the test of $H_0^1$ was significant, other hypotheses were tested restricting the number of parameters that were assumed to be equal. Only the hypotheses that best reflect the assumption are presented. For example, if the hypothesis that the parameters ‘a’ are equal ($H_0^3$) was not rejected and the hypothesis that the parameters ‘a’ and ‘b’ were equal ($H_0^5$) was not rejected as well, then only the latter hypothesis is presented since it encompasses the former hypothesis.

For most of the summer regrowth periods, statistical comparisons of parameters between the curves describing herbage accumulation after no spring clipping or with regular spring clipping (hereafter referred to as “new Gompertz curves”) showed no significant differences ($H_0^1$ not rejected, Table 3.7); meaning that one Gompertz growth model could be used for both curves describing regrowth for swards with contrasting spring clipping managements. The analyses of growing periods commencing 14 August at Coshocton and 17 July at Columbus resulted in rejecting the $H_0^1$ that all parameters were equal, and the $H_0^5$ hypothesis was accepted (Table 3.7). However, the significant difference was due to the $Y_A$ parameter meaning that both curves at each location had the same shape, but with quantitatively different values for $Y$. At Coshocton, the curve describing regrowth after no spring clipping had higher values for $Y$ than the new growth curves (with spring clipping), whilst in Columbus the opposite was found.

At Columbus and Coshocton, all plots were harvested at the conclusion of the study (Table 3.2). We found close agreement between the herbage mass estimates from the RPM and the forage harvester (harvester-herbage mass = 0.94 * RPM-herbage mass +
290, $r^2 = 0.95, P>0.001$), except for the first four growth periods when considerable lodging of reproductive material had been observed. Since we used a single RPM calibration for all plots, we had more confidence in the harvester than the RPM data for the lodged plots, and included the total herbage mass measured by the harvester (harvested + stubble herbage mass) during curve fitting.
DISCUSSION

The primary finding from this study was that herbage mass can be used to predict herbage accumulation rate when all other factors such as climate, pasture species and soil type are constant. For every date and location measured, the $\text{HAR}_t$-herbage mass relationship closely fit the time-independent form of the modified Gompertz equation (Table 3.1, Eq. 3). The only exception occurred in April, when the initial growth following winter made it biologically unfeasible to test the effect of high herbage mass. Even in this case, the strong positive relationships that were found were consistent with a positive effect of herbage mass on $\text{HAR}_t$ below the optimum herbage mass.

These results emphasize the importance for pasture managers to monitor farm herbage mass. Herbage mass is a fundamental measure of a production system. Firstly, measurements of average herbage mass for a farm (cover) can be used to ensure herbage is being appropriately utilized and is not being over- or under-utilized by grazing livestock. Secondly, measurements of herbage mass before and after an area is grazed can be used to calculate livestock intake (by the method of forage disappearance) (Macon et al., 2003). In addition to these two applications, the $\text{HAR}_t$-herbage mass curves, in conjunction with measurements of herbage mass allow a manager to ensure that pastures are maintained within an acceptable range of herbage mass and avoid any reduction of growth rate due to excessive, or deficit mass.

In this study we measured total herbage mass and made no consideration of forage quality. We made no attempt to control reproductive development during May and June, and the herbage mass that accumulated for the first four growth periods had significant amounts of stem and dead material. The $\text{HAR}_t$-herbage mass curves have immediate
relevance to applications that might require maximum herbage mass, such as for ligno-
cellulosic energy production. In many cases, these areas only have a single harvest at the
day of the season. Belesky and Fedders (1995) have shown that Gompertz equations are
valid for warm-season (C4) species, and it is likely that herbage mass will be maximized
with several harvests rather than a single end-of-season harvest. Modeling could be used
to compare the benefit of increased herbage mass compared to the additional harvesting
costs.

The asymmetric logistic equations were a better fit to measured herbage mass data
than the symmetric equations. In every case, the rate of increasing pasture growth rate
(below optimum herbage mass) was greater than the rate of decreasing pasture growth
rate (above the optimum herbage mass). Presumably the processes for initial growth
following defoliation (use of stored carbohydrates, leaf extension, and initiation of new
leaves and tillers) were more rapid than the processes leading towards growth
suppression (leaf shading, loss of tiller density, and leaf senescence and death).
Ecologically, those plants able to show rapid initial growth after defoliation might have
an advantage over their slower neighbors.

One practical implication of the asymmetric HAR, herbage mass relationship
(Fig. 3.2) is that at low herbage mass (below the optimum herbage mass), the relationship
between herbage mass and HAR, is steeper than at high herbage mass. Thus, below the
optimum herbage mass, a small change in herbage mass (say 500 kg DM ha⁻¹) will have a
greater effect on HAR, than at high herbage mass. Two implications of this are: a) an
error in estimating herbage mass could have a greater effect on HAR, at low than high
herbage mass, and b) the effect of intensive defoliation could be to reduce HAR, more severely than the effect of failure to control surplus herbage mass.

**Effects of Season and Location**

The Gompertz equation parameters varied during the growing season and among locations. Additional research is required to develop a broader suite of parameters for specific locations. Alternatively, there may be potential for the approach of Thornley and France (2005) to add parameters to a logistic model to specifically accommodate effects such as seasonality. The equality of parameters in most of the growing periods when comparing regrowth after contrasting spring clipping managements supported the assumption that the parameters of the Gompertz equation reflected the prevailing environmental factors during that period of forage accumulation. Further evaluation is required to understand the impact of environmental factors on the rate of change of the parameters. In addition, the results indicated that the use of seasonal values for the Gompertz parameters should be developed. This concept can be applied to studies modeling the effect of defoliation management on herbage accumulation rate.

Studies have reported that the rate of regrowth of a defoliated sward is dependent on the residual mass (Parsons et al, 1988) and the age of the sward (Parsons et al., 1983). The regrowth plots, before harvesting, represented an older sward structure than the new growth plots that had been maintained in a vegetative state throughout the spring. Swards at an advanced age have lower photosynthetic efficiency which can be detrimental to herbage accumulation in the following regrowth period (interval between defoliation). In addition, the high mass accumulation in the first growing period of the regrowth plots
may have resulted in high self-shading, which is known to decrease photosynthetic efficiency and tillering. However, our results indicated that the sward state of the previous phase of accumulation of herbage mass did not affect the pattern of regrowth. This was presumably because, in contrast to previous studies, this study was not conducted under frequent defoliations presenting one defoliation at the end of the designated growing period; although new plots were mowed a few times to control growth mainly in spring. In grass swards, tiller population and the processes of leaf appearance, elongation and life span (aging and senescence) characterize herbage mass accumulation, with the tiller being the most affected by the management imposed on the sward. More frequent and severe defoliation has resulted in a sward with a smaller, but greater number of tillers than a sward under more lenient defoliation (Parsons et al., 1983). Based on this, the similarity between previously unclipped plots and plots regularly clipped during the spring might have resulted from the compensation in tiller size. The previously unclipped plots might have had fewer, but heavier tillers that had developed, while the regularly clipped plots might have had a high number of smaller tillers.

The Gompertz equations are relatively simple, requiring as few as five points to fit a curve and can be developed relatively easily to predict HAR$_i$ for specific locations. The values for HAR$_{i\text{-max}}$ (Table 3.4) were consistent with growth rates that occur within the locations measured. Arlington had the highest HAR$_{i\text{-max}}$ of any date or location (176.8 kg DM ha$^{-1}$ d$^{-1}$ on 14 May 2008), and had higher average HAR$_i$ than the Ohio sites during May and July. Arlington HAR$_{i\text{-max}}$ was only half the Ohio sites in August and September. A shorter, more intense growing season is typical for more northern latitudes. Total
potential annual forage production calculated for each location from \( \text{HAR}_{i\text{-max}} \) (Table 3.4), the number of days between \( \text{HAR}_{i\text{-max}} \) calculations, and totaled for all observations was 7830, 6880, and 10,080 kg DM ha\(^{-1}\) yr\(^{-1}\) for Columbus, Coshocton, and Arlington, respectively. These yields reflect the relative fertility and forage species of each location. Arlington had the best soil with a 1-yr old meadow fescue pasture, Columbus was of intermediate fertility with an old tall fescue-dominant pasture, and Coshocton had the lowest soil fertility also with tall fescue-dominant pasture.

Seasonal growth curves frequently show a pattern of high spring growth rate, a slump during summer, and a flush of production during fall (Johnson and Parsons, 1985; Denison and Perry, 1990). We found highest growth rates occurred in spring, but did not see evidence of any flush of production during fall. The climatic data (not shown) showed all three locations had below average rainfall in autumn, that likely prevented the autumn flush usually observed in north-central USA. One implication of the \( \text{HAR}_{i\text{-max}} \)-herbage mass curves (Fig. 3.2, Table 3.3) might be that high spring growth rates might be confounded with higher herbage mass that frequently occur at that time. Conversely, the reported ‘slump’ in summer growth rate is also likely confounded with the low herbage mass that usually occurs in summer. The seasonal pattern of forage growth rate observed at any location is not only affected by the prevailing climate, but is also the artifact of defoliation management and the resultant herbage mass (Johnson and Parsons, 1985; Belesky and Fedders, 1994).
Implications for Use of Grazing Exclosure Cages

One implication of this research relates to the interpretation of herbage accumulation within grazing exclosure cages. Exclosure cages are frequently used to measure the herbage accumulation rate on continually stocked pastures, i.e. where herbage growth and removal occur simultaneously, such that the net result is a fixed herbage mass over time. Where the herbage mass is below the optimum for \( \text{HAR}_{i,\text{max}} \), it can be concluded from the \( \text{HAR}_i \)-herbage mass curves that measured HAR within the exclosure cage will exceed the actual HAR under continuous stocking. Field et al. (1981) and Devantier et al. (1998) compared forage production predicted from livestock production with measurements using exclosure cages under continuous grazing, and found the measurements over-estimated forage production predicted from livestock production by 33% and 55% respectively. The difference between measured pasture growth rate within an exclosure cage, and actual pasture growth under continuous stocking will depend on the relative differences in actual herbage mass present. Using Fig. 3.3 as an example, if pasture mass under continuous stocking was 2100 kg DM ha\(^{-1}\), and average herbage mass within an exclosure cage was 3500 kg DM ha\(^{-1}\), the exclosure cage technique could over-estimate the actual growth rate by 100%. An alternate case is possible, where exclosure cages could under-estimate actual growth rates, in the situation where a continuously grazed pasture might be at the optimum herbage mass, and accumulation of additional herbage mass might slow the measured growth rate.
Implications for Rotational and Continuous Stocking

Among the greatest controversies within the forage industry is the debate about the effect of rotational and continuous stocking on forage production. Many recommendations are for pastures to be rotationally rather than continuously grazed, however, research does not always find a production advantage in support of this recommendation (Briske et al., 2008). There are many reasons for use of either rotational or continuous stocking management, other than maximizing herbage mass (e.g. effects on forage quality, avoidance of selective defoliation, etc), however most managers will aim to ensure high herbage mass production. The HAR$_i$-herbage mass curves suggest that pasture growth can be maximized by maintaining herbage mass at the optimum herbage mass (noting this varies during the season), which could be achieved by continuous, but variable, stocking (Johnson and Parsons, 1985). However, recommendations should not necessarily recommend continuous stocking per se, since continuous stocking at a herbage mass other than the optimum (either over or under) could result in lost production. One benefit of rotational stocking is that the variation in herbage mass might at some stage, be at the optimum herbage mass. Lax or infrequent harvesting (allowing high herbage mass) or intensive defoliation (resulting in low herbage mass) will both result in lost potential for forage production. One conclusion from the HAR$_i$-herbage mass relationship obtained in this study is that it is not so much the forage defoliation method (rotational vs continuous) that affects overall forage production, but the result of defoliation on herbage mass that is the primary issue.

The effect of deviations of herbage mass from the optimum for HAR$_i$-max is clearly shown in the HAR$_i$-herbage mass curves. Small departures will have a negligible effect
on HAR, and allow scope for application of rotational stocking strategies that might suit specific management requirements. We propose an arbitrary 90% of HAR$_{i\text{-max}}$ as being a reasonable range for herbage mass that might allow for practical guidelines of grazing management (Table 3.4). Of interest is that the upper limit for herbage mass is greater than what is usual for grazing management recommendations in Ohio. These upper values do not consider any effect on forage quality. Any accumulation of reproductive seedheads would likely increase herbage mass, but be detrimental to forage quality, and additional research is required to determine the dynamics of accumulation of digestible herbage mass rather than total herbage mass. It is likely that the herbage mass targets for maximum HAR will vary from the herbage mass targets for maximum digestible-HAR.
CONCLUSIONS

Gompertz equations were found to accurately predict herbage accumulation patterns throughout the growing season at three north-central USA locations. Parameters for the Gompertz equations varied during the growing season and among locations, and additional research is warranted to quantify the factors that affect these terms. A time-independent expression of the Gompertz equation may have potential use for pasture management by defining the relationship between HAR and herbage mass. This equation showed the optimum herbage mass at which HAR was maximum, and values varied between 1600 and 4000 kg DM ha\(^{-1}\) depending on location and date. Allowing herbage mass to exceed the optimum point (e.g. delayed harvest), or harvesting to below the optimum point, will reduce the HAR. The HAR-herbage mass curves define a range of herbage mass within which pastures can be managed to achieve high HAR, and maintaining pastures within 90% of the maximum HAR may be a practical target for producers. The HAR-herbage mass curves may be a useful tool for modeling the effect of defoliation patterns on herbage accumulation rate, and annual forage production.

ACKNOWLEDGEMENTS

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Figure 3.1. a) A typical Gompertz curve of above-ground herbage mass (Y) for a 180-d growth period (t=days of growth), showing four phases of the sigmoid growth curve, and b) instantaneous herbage accumulation rate (HAR$_i$) (slope of Fig. 3.1a).
Figure 3.2. The time-independent relationship between instantaneous herbage accumulation rate ($HAR_i$) (from Fig. 3.1b) and herbage mass above ground-level (from Fig. 3.1a). The maximum instantaneous herbage accumulation rate ($HAR_{i\text{-max}}$) was 33.1 kg DM ha$^{-1}$ d$^{-1}$ and the critical range of herbage mass for >90% of maximum instantaneous herbage accumulation rate ($HAR_{i\text{-90\%}}$) (29.8 kg DM ha$^{-1}$ d$^{-1}$) was between 2760 and 4170 kg DM ha$^{-1}$. 
Figure 3.3. Average above-ground herbage mass and the associated Gompertz curves for growth periods beginning on various dates at, a) Columbus, OH, b) Coshocton, OH, and c) Arlington, WI. Symbols are the average of four replicates. Alternating closed and open symbols are used to distinguish sequential growth periods.
<table>
<thead>
<tr>
<th>Equation</th>
<th>Herbage mass†</th>
<th>Instantaneous herbage accumulation rate</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gompertz‡</td>
<td>( Y = Y_A e^{at} + Y_{\text{min}} )  [Eq. 1]</td>
<td>( \frac{dy}{dt} = bY_A e^{at} \ln \left( \frac{1}{e^{at}} \right) )  [Eq. 2]</td>
<td>Richards (1959) Draper and Smith (1981)</td>
</tr>
<tr>
<td>Symmetric logistic</td>
<td>( Y = \frac{Y_A}{1 + e^{-b(t-a)}} + Y_{\text{min}} )</td>
<td>( \frac{dy}{dt} = \frac{Y_A b e^{-a-bt}}{(1+e^{-a-bt})^2} )</td>
<td>Eq. 4 in Landsberg (1977)</td>
</tr>
<tr>
<td>Symmetric logistic (or autocatalytic)</td>
<td>( Y = \frac{Y_A}{1+ae^{-bt}} + Y_{\text{min}} )</td>
<td>( \frac{dy}{dt} = \frac{Y_A abe^{-bt}}{(1+ae^{-bt})^2} )</td>
<td>Richards (1959)</td>
</tr>
<tr>
<td>Asymmetric logistic</td>
<td>( Y = \frac{Y_A}{1+at-b} + Y_{\text{min}} )</td>
<td>( \frac{dy}{dt} = \frac{Y_A abc^{-b-1}}{(1+at)^2} )</td>
<td>Cacho (1993)</td>
</tr>
<tr>
<td>Weibull</td>
<td>( Y = Y_A \left( 1 - e^{-\left( \frac{t}{a} \right)^b} \right) + Y_{\text{min}} )</td>
<td>( \frac{dy}{dt} = \left( \frac{b}{a} \right) \left( \frac{t}{a} \right)^{b-1} e^{-\left( \frac{t}{a} \right)^b} )</td>
<td>Hunt (1982)</td>
</tr>
</tbody>
</table>

† \( Y \) = herbage mass (or yield); \( Y_{\text{min}} \) = the lower asymptote for herbage mass (i.e. minimum residual); \( Y_{\text{max}} \) = the upper asymptote for herbage mass (i.e. ceiling mass); \( \Delta Y \) = the difference between \( Y_{\text{max}} \) and \( Y_{\text{min}} \); \( a \) & \( b \) = curvature or shape coefficients; \( t \) = time (days of growth)

‡ equations modified by adding \( Y_{\text{min}} \) to account for the initial herbage mass

Table 3.1. Some common sigmoid equations and their respective ‘rate of change’ functions.
<table>
<thead>
<tr>
<th>Location</th>
<th>Starting date (2008)</th>
<th>Harvest date (2008)</th>
<th>RPM Total</th>
<th>Mower Stubble†</th>
<th>Mower Harvested</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Columbus</td>
<td>8 Apr‡</td>
<td>17 July</td>
<td>4933§</td>
<td>1821</td>
<td>5190</td>
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†measured by calibrated RPM  
‡not mowed from the prior winter (average 2439 and 2796 kg DM ha⁻¹ at Columbus and Coshocton, respectively)  
§plots lodged

Table 3.2. Starting date and ending date (harvest) for 11 growth periods, and the total herbage mass above ground-level (kg DM ha⁻¹) measured by rising plate meter (RPM) and mower, at Columbus and Coshocton, OH (mean of four replicates).
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‡HARI-herbage mass equation was forced through a fixed $Y_{min}$ for that specific site since there was insufficient data for a three parameter model; there was no applicable standard error.

Table 3.3. Parameters for instantaneous growth rate (HAR$_i$)-herbage mass curves (Table 3.1 – Eq. 3, $Y_{min}$, $Y_\Delta$, and b), their standard errors, and $r^2$ for three sites and various observation dates during 2008 (n= 6 to 31) (continued).
### Table 3.3. Continued

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**Wisconsin**

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Table 3.4. Maximum instantaneous growth rate (HAR$_{i\text{-max}}$), the optimum herbage mass (at HAR$_{i\text{-max}}$), and the minimum and maximum herbage mass for >90% of HAR$_{i\text{-max}}$ for three sites and various observation dates (see Table 3.3 for Gompertz equation parameters and statistics) (continued).
Table 3.4. Continued.

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### Table 3.5. Coshocton Gompertz curve parameters estimated for new (N) and regrowth (RG) curves for the non-restricted model ($\Omega$) and for the test of hypothesis $H_{0}^{1}. H_{0}^{5}$ was tested when $H_{0}^{1}$ was rejected. The residual sum of squares ($SS_{R}$) is presented.

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<td>$b$</td>
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SS$_{R}$ = 4,022,780  4,031,288  2,550,620  2,729,895  472,745  707,431  606,863

$Y_{\text{min}}$ = the lower asymptote for herbage mass (i.e. minimum residual); $Y_{\Delta}$ = the difference between $Y_{\text{max}}$ and $Y_{\text{min}}$; $a$ & $b$ = curvature or shape coefficients.
Table 3.6. Columbus Gompertz curve parameters estimated for new (N) and regrowth (RG) curve for non restricted model (Ω) and for the test of hypothesis $H_0^1$. $H_0^5$ was tested when $H_0^1$ was rejected. The residual sum of squares is presented.
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*- Nnl(SS $\Omega$/SS$_{H0x}$) where N is the total sample number.
† df ν is the difference between the number of parameters estimated in the model without restrictions and the number of parameters estimated in a given $H_0$.

Table 3.7. The statistics for testing the $H_0^1$ (all parameters do not differ significantly between regrowth and new growth curves). A second hypothesis tested is presented when $H_0^1$ was rejected.
CHAPTER 4:

MODELING THE EFFECT OF DEFOLIATION ON THE HERBAGE ACCUMULATION RATE OF COOL-SEASON GRASSES BASED ON STANDING HERBAGE MASS

ABSTRACT

The ability to predict the effects of defoliation on herbage accumulation would be very useful in making grazing management decisions on farms. The residual standing herbage mass is proposed as a useful basis for predicting subsequent herbage accumulation rate following defoliation. The objective of this study was to develop and validate a model using Gompertz equations and its derivatives to predict herbage accumulation based on measurements of standing herbage. Monoculture plots of tall fescue [Schedonorus phoenix (Scop.) Holub, formerly Festuca arundinacea Schreb.], (TF), orchardgrass (Dactylis glomerata) (ORG), Kentucky bluegrass (Poa pratensis) (KBG) and a mixture (MIX) of those three species were submitted to four defoliation treatments: 3600 to 2800 kg DM ha\(^{-1}\) (Tall-Tall, TT), 3300 to 2400 kg DM ha\(^{-1}\) (Tall-Short, TS), 3600 to 1800 kg DM ha\(^{-1}\) (Hay) and 3000 to 1600 kg DM ha\(^{-1}\) (Variable, V). In addition to comparisons between predicted and measured values of herbage mass, total harvested yield and total accumulated herbage mass were evaluated. The amount of variation explained by the regressions of observed on predicted values from the model ranged from 0.33 to 0.88, the root mean squared error (RMSE) ranged from 192 to 456 kg DM ha\(^{-1}\), and 11 out 25 regressions had no significant difference for slope \((m) = 1\) and intercept \((c) = 0\). For
treatments Hay and V the model underestimated the herbage accumulation, but overestimated for treatments TT and TS. The model showed promise in predicting the effect of defoliation on herbage accumulation rate and the resultant harvested yield; however, some refinement of parameter calibration is required when the initial herbage mass is $\leq 1600$ kg DM ha$^{-1}$. 
INTRODUCTION

Many studies have been conducted to understand the dynamics of managed grasslands, especially with regard to the impact of defolation frequency and intensity on herbage accumulation (Parsons, 1988; Cros et al., 2003). Although the literature has considerable information about defoliation practices to maximize herbage accumulation (Parsons et al., 2000), the idea of modeling those responses at a farm scale is extremely attractive (Jouven et al., 2006).

The accumulation of herbage mass over time has been characterized using a sigmoid curve. Its derivative form, which relates the rate of accumulation to herbage mass, has valuable applications because measurements of the standing herbage mass can then be used to predict the rate of herbage accumulation (Morley, 1968; Thornley and Johnson, 1990, Cacho, 1993). For example, Woodward (1998) demonstrated the use of sigmoid growth equations and their derivatives in modeling the impact of management decisions such as frequency of defoliation, stocking rate, and duration of grazing on herbage accumulation response. Parsons et al. (2000) also stressed the applicability of simple growth equations in modeling. Those authors have argued that although conventional growth functions such as those reported in the literature cannot replace physiologically-based sub-models in mechanistic models, they are nevertheless useful in developing practical models of herbage accumulation for guiding management decisions on farms.

To our knowledge, models have not previously been developed that relate herbage mass to herbage accumulation for cool-season grass species in the Midwestern USA. In Chapter 3 of this thesis, the foundation of this concept was outlined. Here, I extend that concept by developing a predictive model for herbage accumulation based on
measurements of standing herbage mass for several cool-season grass species common to Ohio. The specific objectives of this study were: a) fit Gompertz curves to measured herbage accumulation in several cool-season grass species and determine their time independent derivatives, b) use the parameters of the time independent functions for developing a model to predict rate of herbage accumulation based on the standing herbage mass; c) validate the model under contrasting defoliation treatments.
MATERIALS AND METHODS

Site Details

This investigation was conducted from 20 May to 27 October 2009 at the Western Research Station of the Ohio Agricultural Research and Development Center near South Charleston, OH (39°51'47" N, 83°40'19" W). The soil was a tile-drained Kokomo silty clay loam (fine, mixed, superactive, mesic Typic Argiaquolls). Soil analysis (0 to 15 cm depth) found soil pH of 6.7, phosphorous at 41 mg kg\(^{-1}\), potassium at 113 mg kg\(^{-1}\) and 1.7\% organic matter. The long-term annual average temperature was of 10.8°C and long-term total average annual precipitation was 105.7 cm.

The experimental area consisted of 76 individual plots, 18 plots of each sward species: TF, ORG, KGB and MIX. The plots (1.1 x 7.6 m) were established on 21 August 2008 at seeding rates of 24.6, 16.8, and 16.8 kg/ha for monoculture stands of TF, ORG, and KGB, respectively. For MIX, the components were seeded at 12.0, 8.5 and 8.5 kg ha\(^{-1}\) of TF, ORG, and KGB, respectively. In autumn 2008, plots were not mowed. Before initiating the experiment in May 2009, the plots were clipped to a 7.5 cm stubble height to eliminate weeds and improve sward uniformity. Nitrogen was applied as urea at a rate of 55 kg N ha\(^{-1}\) in late September 2008, 78 kg N ha\(^{-1}\) in mid-March 2009, and 56 kg N ha\(^{-1}\) in late August 2009.

Treatment Design

In order to investigate the impact of standing herbage mass on the rate of herbage accumulation and develop a model to predict herbage accumulation based on the standing
herbage mass, the present study was divided into three phases: determination of model parameters, development of the herbage dry matter accumulation model, and model validation under different defoliation treatments.

**Determining Model Parameters**

Model parameters were developed for time-dependent curves of herbage mass accumulation by fitting the measured herbage mass to Gompertz growth equations. The derivatives of those equations produced the prediction of herbage accumulation rate over time. By combining those two previous mathematical functions, a time independent function of rate of herbage accumulation on herbage mass was produced for each day of herbage mass measurement. The parameters of that function were: $Y_\Delta$ (the difference between minimum and maximum standing herbage mass), $Y_{\text{min}}$ (minimum standing herbage mass) $a$ and $b$ (curve shape parameters). From those parameters, it was possible to develop the relationship between standing herbage mass and rate of herbage accumulation over the experimental period and investigate the seasonal pattern of the parameters ($Y_\Delta$, $Y_{\text{min}}$ and $b$). For further detailed description of this approach see Chapter 3 and Barker et al. (2010).

In order to develop the mathematical relationships described above, a range of standing herbage masses over the experimental period had to be created and measured. Three dates for initiating herbage mass accumulation were established (growth periods) in 2009: 9 April, 20 May, and 25 June. These initiation dates provided different levels of standing herbage mass on any given day during the experimental period. The growth periods beginning on 9 April and 25 June consisted of one plot of each monoculture
species and the MIX, whereas the period beginning 20 May had two plots (replicates) of each species and the MIX. Plots were mowed regularly to maintain growth in the vegetative stage until initiation of the measured herbage accumulation period (growth period). At initiation of each growth period, the plots were mowed to a 7.5 cm stubble and herbage was allowed to accumulate thereafter. Measurement of herbage mass was assessed indirectly with a rising plate meter (RPM) (Ashgrove Pasture Plate, Ashgrove Industries, Ashhurst NZ) by taking 10 readings per plot on each sampling day. To convert RPM readings to herbage mass, hand-clipped calibration samples were collected for each species every week, as described in detail in Chapter 5. However, the final calibration coefficients used were based on 2-week running averages. The weekly 2-wk calibrations were developed by combining data from the current week with data from the week prior. The RPM readings and plot yields were always measured on the two central rows of the 7-row plots. When plots from the growing period initiated on 9 April reached the reproductive phase, the canopy was too tall for accurate RPM readings. Thereafter, hand-clipped samples were collected to determine dry matter yield in those plots by cutting one sample at ground level within a 0.1 m² quadrat in each plot on each sampling date. All herbage samples were dried at 55°C in a forced air oven to determine the dry wt.

**Structure of the Model**

A model was developed to predict herbage mass accumulation based on standing herbage mass and respective rates of mass accumulation for each day throughout the growing season. The present model, described further here, was a modification of the original 2008 MS-Excel model reported by Barker et al. (2009). The original model was
created based on data from an herbage mass accumulation study using two other locations in Ohio in 2008 (Barker et al., 2010). The model predicts the rate of mass accumulation using the derivatives of Gompertz growth equations. The predicted herbage mass on a specific date resulted from adding the herbage mass and the rate of accumulation from the previous day. In order to predict the daily changes on rate of accumulation, it was necessary to determine the seasonal pattern in the Gompertz equations parameters ($Y_\Delta$, $Y_{\min}$ and ‘$b$’). The $Y_\Delta$, $Y_{\min}$ and ‘$b$’ values were determined from the mathematical function which related the rate of herbage accumulation to standing herbage mass (the time-independent Gompertz equation). Parameters were calculated as described in Barker et al. (2010) and thereafter 4th-order polynomial equations were fitted to describe the seasonal pattern for each parameter.

In 2009 the establishment of the three growing periods (initiated in April, May and June) allowed us to calculate the parameters from the time independent Gompertz equation from June through August. Therefore, it was necessary to estimate the parameters outside that time range, and for that the parameters from the 2008 original model were used. The objective was to create the 2009 seasonal pattern for the $Y_\Delta$ and ‘$b$’ parameters based on the polynomial fitted to the 2008 $Y_\Delta$ and ‘$b$’ parameters over time. Firstly, I calculated the numerical difference between average parameter values of 2009 and 2008 within the June to August time period. This numerical difference was used to adjust the 2008 values outside the June to August time period for use in 2009. If the numerical difference within the June to August period was greater in 2009, then we added the difference to the values of the respective 2008 parameter. Likewise, when the difference was smaller we subtracted that difference from the 2008 parameters.
Therefore, the seasonal pattern for 2009 parameters was assumed to be the same as in 2008; however, being constantly either higher or lower than the 2008 seasonal pattern.

**Defoliation Treatments**

This study was characterized by the creation of four standing herbage masses, and consequently in the rate of herbage accumulation, throughout the experimental period, with which the model of herbage mass accumulation could be validated. For this, harvest treatments were imposed on individual plots of the four species treatments. A split-plot restriction on treatment randomization was used. The four species treatments were subplots and defoliation treatments were assigned to whole plots in a randomized complete block design with three replicates. The defoliation treatments created different ranges in herbage removal and were based on preliminary results of the 2008 study reported by Barker et al. (2010). Harvest strategies were as follows:

1. **Tall – Tall (TT)**, plots were defoliated when they reached an average 3600 kg DM ha\(^{-1}\) to a residual mass averaging 2800 kg DM ha\(^{-1}\): representing frequent removal of a minimal mass, aiming to keep pastures as near to the mass that supported maximum herbage accumulation rate as practical.

2. **Tall – Short (TS)**, plots were defoliated when they reached 3300 kg DM ha\(^{-1}\) to a residual of 2400 kg DM ha\(^{-1}\): both initial and final mass values were within the 90% of maximum accumulation rate, based on preliminary 2008 results reported by Barker et al. (2010); however, the actual range in herbage mass at the time of defoliation obtained was wider than this target (4300 – 3000 kg DM ha\(^{-1}\)).
3. Hay, representing hay management cutting frequency. The plots were defoliated at 3600 kg DM ha\(^{-1}\) to a residual of 1800 kg DM ha\(^{-1}\), three times during 2009.

4. Variable (V), the plots were defoliated at an average of 3600 kg DM ha\(^{-1}\) to a residual of 1600 kg DM ha\(^{-1}\). The actual target mass at the time of defoliation was not achieved, but ranged from 4800 to 2700 kg DM ha\(^{-1}\). I intended to keep this treatment shorter than the mass range supporting 90% maximum accumulation, but this was not accomplished due to harvesting difficulties (weather and equipment delays); therefore, the defoliation scheme was variable.

Measurements of herbage mass were assessed once per week using the RPM method as described previously. Plots were harvested with a sickle bar harvester (Swift Machine & Welding LTD., Saskatchewan Canada) when the target herbage mass was reached, as described previously for each treatment. The RPM was used to calculate the harvested herbage mass by subtracting the average plate reading before and after harvesting and multiplying by the appropriate calibration coefficient. Total dry matter yield for each experimental unit was determined by summing all individual harvest events. Before harvesting, forage samples were randomly hand-clipped within each species subplot, at the respective harvest treatment stubble height. Thereafter, samples were dried at 55°C and ground through a Wiley mill (1-mm screen) before being analyzed for neutral detergent fiber (NDF) (ANKOM, 2003). Seasonal average values for NDF (weighted for yield at each harvest) were calculated for each experimental unit.
Model validation

The objective of the validation was to evaluate the accuracy of the model by comparing paired values of the predicted and RPM measured herbage mass for each regrowth cycle and harvest date. The validation of the model was conducted for each defoliation x species treatment combination, averaged across the three replicates. After the parameters of the model were appropriately modified for each species as described previously, the initial value of herbage mass in the model was set to the value actually measured at the beginning of the experimental period. For certain defoliation treatments with low residuals after cutting, herbage mass was not able to be predicted due to model constraints in handling low values of herbage mass near the model calibration limits, so the model prediction was initiated after one week of regrowth using the herbage mass on that date as a starting point, and continued the remainder of the growth cycle. From this process, the predicted herbage mass at the first harvest event was determined and compared with the measured mass. After cutting, the residual herbage mass was entered as the initial herbage mass value in the model for the following growth cycle. This procedure was repeated for consecutive growth cycles until the end of the experimental period (27 October). Additionally, comparisons of residual herbage mass, total forage yield removed, and total herbage accumulation were determined.

Statistical Analyses

The total herbage dry matter harvested and total herbage dry matter accumulated as measured with the RPM and the NDF data were analyzed using PROC MIXED of SAS. The statistical model considered the effect of defoliation treatment, species, and species x
defoliation treatment interaction, with replicates and replicate x defoliation treatment included as random variables. Means were compared using Fisher’s protected LSD ($P < 0.05$), which was calculated by multiplying the appropriate t-value times the standard error of the difference obtained from the PDIFF option of LSMEANS in the PROC MIXED analysis.

To measure the accuracy of the model, the observed (measured) values were regressed on the predicted values for herbage mass using all weekly observations. The analysis included an evaluation of: coefficient of determination ($r^2$), root mean square error (RMSE), and the probability of slope ($m = 1$) and intercept ($c = 0$) and their respective standard errors. A good correlation between observed and predicted values would have a slope of 1, an intercept of 0, a high $r^2$ and low RMSE.
RESULTS AND DISCUSSION

Climate

The May to October 2009 average air temperature was 16.5 C, which was 2.3 C below the long term average, and the total precipitation was 49.5 cm, or 6.1 cm below the long term average. The monthly average temperatures were similar to the long term averages, except for a cooler July (-2.8 C) and October (-2.0 C). May, June and August were drier then the long term monthly totals, -6.4, -8.6 and -2.8 cm of precipitation, respectively. Other months were above the long term monthly total precipitation.

Gompertz Curve Fitting and Rate of Herbage Accumulation

Although the initiation dates for accumulation of herbage mass to fit the Gompertz curves included only early and late spring (April, May and June), it was still possible to observe the seasonal pattern in the parameters of the Gompertz equations. The $Y_{\text{min}}$ values reported here (Table 4.1) correspond to the actual initial herbage mass measured by the RPM on the initiation dates when the sward was mowed to a 7 cm stubble height. Because the plots were clipped to the same initial residual height, the differences observed in $Y_{\text{min}}$ values across different herbage accumulation curves are likely a consequence of the increasing slope coefficient of the RPM calibration equation over time. The $Y_A$ (difference between the maximum and lowest yield) for all species, except the mix, was greater following the April than May and June initiation dates. This decline in $Y_A$ over time is in agreement with many other studies with temperate grasses (Brougham, 1956; Hunt, 1970; Barker et al., 2010). The greatest maximum herbage
accumulation rate was observed in the spring. Many studies have reported greater rates of herbage accumulation in late spring in response to changes in physiological processes and the interaction of those processes with environmental conditions (Parsons, 1988).

Besides lower values of maximum rate of accumulation during the later growth periods, the length of time to reach the maximum value became longer. Low values of maximum accumulation rate and more days required to achieve it as the season progresses may have an impact on grazing management (Parsons, 1988; Morley, 1968). The accumulation period beginning in April also presented the highest values for both ‘a’ and ‘b’ parameters (average 5.701 and 0.046, respectively, Table 4.1). Moreover, similar values for parameters ‘a’ and ‘b’ and the maximum accumulation rate were observed for TF, ORG and MIX during June. Morley (1968) stated that the parameters of a growth curve equation are controlled by temperature, photoperiod and the amount of photosynthetic light which has a greater impact on $Y_A$. He stated that the rate of herbage accumulation was not influenced by $Y_A$, because in the derivative form of the logistic growth equation the parameter $Y_A$ was not present. However, the logistic equation used in his work did not present $Y_{\text{min}}$, so it is assumed that the initial mass was zero. That assumption is not accurate for permanent pastures and many equations have been reported to take into account the initial preset herbage mass (Richards, 1959). Among the species we evaluated, Kentucky bluegrass had the lowest $Y_A$ and lowest maximum accumulation rate regardless of the initiation date.
Model Calibration

All species in this study had greater values for parameter ‘b’ within the period of evaluation (June to August) than the ‘b’ values from the 2008 model. Therefore, the difference between mean ‘b’ values shown here and those from 2008 were added to the ‘b’ values of 2008 equally over the growing season separately for each species (Fig. 4.1-4.4 a). From June to August the average ‘b’ value for the 2008 original model was 0.015, whilst for the 2009 model they were 0.019 for TF, 0.018 for ORG, 0.017 for KBG and 0.020 for MIX.

In contrast to what was observed for the ‘b’ values, the $Y_\Delta$ values were lower for all species in this study than in the 2008 model, thus the difference between the average $Y_\Delta$ values for the evaluation period were subtracted equally over the growing season (Fig. 4.1-4.4b). The average $Y_\Delta$ values from June to August for the 2009 model were 6810 for TF, 7385 for ORG, 6214 for KBG, 6667 for MIX while being 7796 kg DM ha$^{-1}$ for the 2008 model.

The original grazing model had three input parameters: $Y_\Delta$, $Y_{\text{min}}$ and ‘b’, determine from the time-independent form of Gompertz equation. The parameter ‘a’ was kept constant, based on a previous study (Barker et al., 2009). Based on the calculations above, daily predictions of $Y_\Delta$ and ‘b’ parameters were entered as the new input values in the original 2008 grazing model. For each species model, the $Y_{\text{min}}$ values were fixed over the growing season in the 2009 model: TF was 1613, ORG was 1431, KBG was 1532 and MIX was 1461 kg DM ha$^{-1}$.
Total Dry Matter Harvested, Accumulated, and the Residual Difference

There was a significant ($P = 0.06$) interaction between species and defoliation treatments for total dry matter yield harvested (Table 4.2, Fig. 4.5). In addition, both main effects were significant (Table 4.2). The TS treatment (defoliating from 3300 to 2400 kg DM ha$^{-1}$) had the lowest total yield (Table 4.3) among the four treatments evaluated. No significant differences were found among the TT, Hay, and V defoliation treatments and they yielded on average 22% more than TS. The species x defoliation treatment interaction was likely a result of variable response of the MIX, ORG, and TF across defoliation treatments while KBG yield remained static across treatments (Fig. 4.5). For example, treatment TS decreased the total forage yield of ORG and TF. This result might also have contributed toward ranking that defoliation treatment as the lowest total forage yield (Table 4.3). However, there was no reasonable biological explanation for this negative impact of defoliation treatment TS on yields of monocultures whilst the same was not observed in the MIX. In fact, this may have been a result of variation within replicates. For instance, one replicate of TF of defoliation treatment TS yielded 40% less than the average of the other replicates.

The lack of uniformity across experimental units may have resulted from the high population of weeds before the commencement of the experiment, which led to interspecies competition that lowered the stand density or vigor of the remaining plants. Overall, for the TF, ORG, and MIX the V treatment had the highest total dry matter yield which was similar to the Hay treatment. Among species, KBG consistently had the lowest yield (average = 2869 kg DM ha$^{-1}$). Furthermore, defoliation treatments had no effect on total herbage yield (Fig. 4.5). The lack of response of KBG to different
defoliation schemes can be related to the position of its growing points. In a vegetative sward of KBG, the growing points are found below or at the soil surface and usually within 5 mm the parent rhizome (Evans, 1949). Therefore, defoliation does not decrease yield due to removal of growing points. However, the yield can be negatively affected by self shading under harvest regimes which allow high accumulation of leaves in the sward. Bryan et al. (2000) reported no total herbage yield difference for KBG between defoliations of 14 to 7 cm and 15 to 7.5 cm; however, defoliating from 12 cm down to 6 cm resulted in the highest yield. In addition, they found no cutting height effect for average growth rate.

The total dry matter accumulation responded significantly to the main effect of species and the species x defoliation interaction, but no differences were found for the main effect of defoliation treatment (Tables 4.2, 4.3, Fig. 4.6). The effect of species and species x defoliation interaction showed the same qualitative results as for total dry matter harvested (Table 4.4). The difference between the final and initial stubble mass was only significant for defoliation treatment, with the V treatment (3600 to 1600 kg DM ha\(^{-1}\)) having the lowest residual difference (Table 4.3).

Comparisons among defoliation treatment studies are difficult because the criteria chosen to characterize treatments such as: interval between defoliation events, canopy height, or herbage mass, are not always measured or the measurement methods vary between studies. The use of herbage mass as a determinant of defoliation treatment has an advantage of being easily extrapolated for many different scenarios. Not only can the amount of herbage mass left after harvest impact dry matter production, but also the amount of dry matter removed will vary among defoliation treatments. The amount of
mass present after harvest is related to the photosynthetic capacity of the remaining leaves and consequently the rate of replacing the defoliated area. The proportion of the canopy removed has to do mainly with the capture of light by photosynthesis during the regrowth period. The use of height has been extensively used in the literature because it is assumed to be the most practical method to be assessed by farmers. However, few studies using height as treatment have reported the actual herbage mass, which makes it difficult to compare the results of this work with previous studies. For this reason the average RPM values for the initial and final herbage mass for each defoliation treatment across species were calculated:

1) TT, 3600 to 2800 kg DM ha\(^{-1}\): 15 to 12 cm.

2) TS, 3300 to 2400 kg DM ha\(^{-1}\): 13 to 9.5 cm.

3) Hay, 3600 to 1800 kg DM ha\(^{-1}\): 12.5 to 7 cm.

4) V, 3000 (4300 - 2000) to 1600 kg DM ha\(^{-1}\): 12 (14 - 7) to 5 cm

Burns et al. (2002) studied the impact of a range of frequency (sward height before grazing) and intensity (residual height) treatments on TF dry matter production. When comparing the intensity, they reported about 20% greater harvested yield by clipping to 5 cm (6030 kg DM ha\(^{-1}\)) than to 9 cm (4975 kg DM ha\(^{-1}\)). Voilesky and Anderson (2007), compared three stubble heights for ORG and found a 40% lower total dry matter yield for the 7 cm stubble (representing 80% of canopy removed) than for taller stubbles (14 and 21 cm). Likewise, Griffith and Teel (1965) found a decrease in the dry matter yield when ORG swards were mowed to a 5-cm stubble as compared with 10 cm. In contrast, Belesky and Fedders (1994) found a significant increase in total yield of ORG for more
severe harvests that removed about 75% of the canopy height compared with the more lenient 50% removal of the canopy. However, no significant difference was found when ORG was clipped from 10 or 20 cm down to a 5-cm stubble. Similar to our results, they reported the highest total herbage yield for the hay management treatment with an average yield of 6500 kg DM ha⁻¹. The variation in these results found in the literature might be a reflection of the amount of herbage mass present between harvests. It has been reported that pasture swards under severe and frequent harvest are under relatively constant full light. Conversely, in swards under less severe defoliation management (i.e., greater final target herbage mass), the self shading constantly increases over the regrowth period. Since shading can affect the carbon supply for the plant, the dry matter production can be negatively affected (Parsons et al., 1983).

The defoliation treatments in this study apparently did not represent sufficiently contrasting ranges of herbage mass removal to affect total dry matter accumulation, except between the TS and V comparison (Table 4.3). In addition, the period between defoliation events for treatments TT, TS, and V were very similar, about 30 days. This might have been enough time to allow the canopy to reestablish the leaf area and intercept almost all the incident radiation (Brougham, 1955; 1956) and restore water soluble carbohydrates reserves, which can impact the next regrowth cycle (Donaghy et al., 2008). Donaghy et al. (2008) reported a positive linear relationship between the leaf dry matter and the water soluble carbohydrate concentration in the stubble, which increased with increasing rest periods allowing restoration of the leaf tissue. However, along with the dry matter production, the impact of the length of regrowth period on forage quality should be also evaluated. Therefore, those authors concluded that the
minimum regrowth interval for TF is the appearance of two new leaves to a maximum of four new leaves, and beyond this interval there is a huge compromise to forage quality (eg. NDF > 630 g kg\(^{-1}\)). For ORG, Turner et al. (2006) found similar results.

**Fiber Concentration**

The neutral detergent fiber concentration was significantly affected by defoliation treatment \((P = 0.04)\), species \((P < 0.001)\) and the defoliation x species interaction \((P < 0.008)\) (Fig. 4.7). The ranking among species for NDF was: KBG (606 g kg\(^{-1}\)) > MIX (578 g kg\(^{-1}\)) = ORG (588 g kg\(^{-1}\)) > TF (558 g kg\(^{-1}\)) (LSD = 16.8). Temperate perennial grasses have been recognized as high quality forages, which can produce as much milk as legume based diets if they are harvested as young growth (Cherney and Cherney, 2004). The NDF concentration was significantly lower for the hay treatment (572 g kg\(^{-1}\)) treatment, whilst the TT (584 g kg\(^{-1}\)), TS (584 g kg\(^{-1}\)) and V (591 g kg\(^{-1}\)) treatments did not differ (LSD = 11.4). That result was not expected, because the Hay treatment had a much longer regrowth interval (Table 4.3). The plant content of cellulose, hemicellulose and lignin increases with plant maturity, which in this case would be the period of days between defoliation events. The final NDF value was weighted among all harvested events and the last harvest in October presented the lowest NDF values for all defoliation treatments. The Hay treatment had only three harvest events while other defoliation treatments had five or four. Although there was a significant species x defoliation treatment interaction, there was no a consistent pattern of response within species to defoliation management and the differences were relatively small. Cherney and Cherney
(2005) studied the changes in nutritive value of ORG, TF and reed canarygrass (*Phalaris arundinacea* L.) at three stubble heights: 10 to 15 cm, 15 to 20 cm and 20 to 25 cm. For ORG and TF, an increase of 2.5 cm in stubble height corresponded to a decrease of 0.30 percentage unit in NDF concentration.

**Model Validation**

Model validation was accomplished by simulating the 16 species x defoliation treatment combinations to compare the values of standing herbage mass (HM) of observed values (Y) with the model output values (X) (Gauch et al., 2003). Additionally, regressions by harvest, by species, and the overall fit were conducted (Table 4.4). The amount of variation explained by the regressions of observed on predicted values ranged from 0.48 to 0.88 and 11 out 25 regressions presented no significant difference for slope = 1 and intercept = 0.

The overall fit (across all 16 species x defoliation treatments) had the lowest difference between the observed (4922 kg DM ha$^{-1}$) and the predicted harvested yield (4576 kg DM ha$^{-1}$); however it found $m$ and $c$ were significantly different from 1 and 0, respectively, suggesting the presence of a bias in our model.

Among harvest treatments, the model did not show a constant relationship with the measured data (Table 4.4). For treatments Hay and V, the model underestimated the mean standing herbage mass by 975 and 2152 kg DM ha$^{-1}$, respectively. In contrast, the model overestimated the mean yield for treatments TT (763 kg DM ha$^{-1}$) and TS (976 kg DM ha$^{-1}$). The weekly predicted values of standing herbage mass tended to be slightly
higher than the measured RPM values throughout the experimental period for those treatments (Fig. 4.8, 4.9); however, two periods should be pointed out as having greater differences between observed and predicted values. The first was between 26 June and 7 July, during which period precipitation was 2.3 cm, 8.6 cm less than the long term average. The second period occurred during the month of October, which reflected the large differences between observed and modeled yield at the last harvest. October had double the precipitation (12.6 cm) of the long term average and a monthly mean temperature of 10 °C, so it is not clear why the observed herbage accumulation was lower than the model. Those periods of overestimation by the model were not observed for the Hay and V treatments.

A limitation of the model was observed with the Hay and V treatments, which may have contributed to the low predicted harvested yield. When the initial herbage mass was at or below 1600 kg DM ha^{-1}, it appeared that the model predicted very low rates of herbage accumulation throughout the entire growing period. Clearly, the model did not perform well when the starting herbage mass was near the limits of the calibration data used for developing the model parameters. A hypothesis would be that the standing herbage mass can influence the rate at which mass is accumulated if above a certain amount of standing herbage mass. It may be supported by the fact that when clipping lower than a certain standing mass, the results is a small proportion of leaves in the sward. Under that condition, it is known that plants rely on carbohydrate reserves to drive regrowth until enough leaf area is restored to make photosynthesis supply the demand for carbon. A solution for this model constraint would be to include a sub-model which would be able to accurately predict the rate of accumulation when initial mass was at or
below 1600 kg DM ha\(^{-1}\). Additional experiments are needed to investigate not only the accumulation rate when stubble mass is below 1600 kg DM ha\(^{-1}\), but the factors contributing to herbage accumulation during that period. In addition to the constraint cited above, greater differences between observed and predicted values were found for defoliation treatments Hay and V were observed during the month of September, when in a year with good rainfall distribution there is a second small seasonal peak of dry matter production of cool-season grasses. Although our calibration plots and validation plots were at the same site and being conducted simultaneously, the parameters from the calibration plots were extrapolated based on the 2008 model. The 2008 experimental period was characterized as drier than 2009, so the peak of forage production was not observed in September 2008. Therefore, when extrapolating the 2009 parameters based on 2008, the new 2009 parameters did not account for the increase in forage production that actually occurred. Another explanation for the discrepancy between observed and predicted values might be due to the high variability within the experimental area. Additionally, unfortunate randomization might have placed calibration plots in worse areas (subjected to weed competition) which may have contributed to lower yields than in the validation plots.

Among the defoliation treatments, treatment TT had the smallest difference between predicted and observed values; however the Hay treatment (3600 – 1800 kg DM ha\(^{-1}\)) was the only treatment with a slope not different from 1 and an intercept not different from zero (Table 4.4). Among species, the model underestimated values for TF, ORG, and MIX; whilst overestimated for KBG. All species regressions had an intercept different from zero and a slope different (\(P < 0.10\)) from 1.
The model accuracy differed among species and defoliation treatment combinations (Table 4.4, Fig. 4.8 – 4.11). The slope equal to 1 and intercept equal to 0 for TF and Hay in treatments TT, TS, and Hay and for ORG in treatments TT, Hay, and V. Among all possible combinations, KBG had the lowest $r^2$'s and had a slope equal to 1 and an intercept equal to 0 only for treatment V.

The variability between the predicted and observed values for standing herbage mass described above is in part due to error associated with data measurement and plot to plot variability. The standing herbage mass was assessed using the RPM which requires calibration between height and the mass under the plate. This process has some error, mainly when collecting the hand clipped forage or choosing the place to take calibrations. In addition, the RPM sometimes estimated lower herbage mass in a given week than the previous week; which might have contributed to more scattered and less correlated data. Although the data used to calibrate the present model was collected at the same site as the validation and under the same conditions (weather, fertility, species), some considerations should be made in future studies in order to improve the process of parameter calibration. For instance, use a larger number of plots (dates of initiation of herbage accumulation) for developing Gompertz curves and its time independent form. From this, it would be possible to determine the actual seasonal variations of the Gompertz equation parameters at the same site and for the same species. An additional comparison between this and the 2008 parameters could be conducted to investigate the effect of climate and location.
CONCLUSIONS

The model showed promise in predicting the effect of defoliation on subsequent herbage accumulation rate; however, some refinement is required in parameter calibration and especially for predicting herbage accumulation when the residual herbage mass < 1600 kg DM ha\(^{-1}\). The use of previous year parameters may have contributed to the bias in our model and thus further study is necessary for accurate parameter calibration. Besides basing the parameters on the Gompertz accumulation curves, the values of the parameters in the model could be also adjusted by weather variables such as rainfall and temperature. Error associated with data measurement and plot to plot variability likely contributed to the variability between predicted and observed values for standing herbage mass. This model can easily provide a predictive scenario in the short term by running as a spreadsheet and requiring simple inputs, which may be attractive for its use by farmers. In future studies it may be worthwhile to include a senescence sub-model, since defoliation modifies the green and dead tissue flux in the sward.
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</table>

*May growing period had two replicates.

Table 4.1. Parameters $Y_A$, $Y_{\text{min}}$, ‘a’ and ‘b’ of the Gompertz curves for growing periods April, May and June for tall fescue (TF), orchardgrass (ORG), Kentucky bluegrass (KBG), and the three species mixture (MIX) with their respective maximum herbage accumulation rate and the days of regrowth needed to reach it.
Table 4.2. Sources of variation of ANOVA and their respective standard error (SE) and denominator degree of freedom (df) for total dry matter harvested, total dry matter accumulation and the residual difference.

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Total dry matter accumulation</th>
<th>Total dry matter harvested</th>
<th>Residual difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Defoliation†</td>
<td>NS</td>
<td>**</td>
<td>**</td>
</tr>
<tr>
<td>SE</td>
<td>395.7</td>
<td>388.92</td>
<td>124.4</td>
</tr>
<tr>
<td>df</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Species†</td>
<td>**</td>
<td>**</td>
<td>NS</td>
</tr>
<tr>
<td>SE</td>
<td>258.7</td>
<td>244.8</td>
<td>66.7</td>
</tr>
<tr>
<td>df</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Defoliation x species††</td>
<td>*</td>
<td>*</td>
<td>NS</td>
</tr>
<tr>
<td>SE</td>
<td>597.8</td>
<td>575.4</td>
<td>169.8</td>
</tr>
<tr>
<td>df</td>
<td>24</td>
<td>24</td>
<td>24</td>
</tr>
</tbody>
</table>

† NS = not significant, * significant and ** highly significant at α = 0.05.

†† NS = not significant and * significant at α = 0.15.

Table 4.3. Defoliation treatments and their respective number of harvest events, average regrowth period in days, total dry matter harvested, total dry matter accumulation and the residual difference (total accumulated – total harvested).
<table>
<thead>
<tr>
<th>Treatment combination</th>
<th>( r^2 )</th>
<th>RMSE</th>
<th>Mean harvested yield</th>
<th>Prob</th>
<th>Prob</th>
<th>Prob</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Observed kg DM ha(^{-1})</td>
<td>Predicted</td>
<td>m</td>
<td>SE(_m)</td>
</tr>
<tr>
<td>Overall fit</td>
<td>0.674</td>
<td>373.3</td>
<td>4922</td>
<td>4576</td>
<td>0.81</td>
<td>0.031</td>
</tr>
<tr>
<td>3600 - 2800 kg DM ha(^{-1}) (TT)</td>
<td>0.675</td>
<td>292.9</td>
<td>4807</td>
<td>5570</td>
<td>0.81</td>
<td>0.062</td>
</tr>
<tr>
<td>3300 - 2400 kg DM ha(^{-1}) (TS)</td>
<td>0.735</td>
<td>220.9</td>
<td>4116</td>
<td>5092</td>
<td>0.76</td>
<td>0.049</td>
</tr>
<tr>
<td>3600 - 1800 kg DM ha(^{-1}) (Hay)</td>
<td>0.670</td>
<td>370.3</td>
<td>5164</td>
<td>4191</td>
<td>1.03</td>
<td>0.083</td>
</tr>
<tr>
<td>3000 - 1600 kg DM ha(^{-1}) (V)</td>
<td>0.766</td>
<td>348.7</td>
<td>5603</td>
<td>3451</td>
<td>1.47</td>
<td>0.094</td>
</tr>
<tr>
<td>Tall Fescue (TF)</td>
<td>0.690</td>
<td>372.2</td>
<td>5711</td>
<td>4857</td>
<td>0.86</td>
<td>0.063</td>
</tr>
<tr>
<td>Orchardgrass (ORG)</td>
<td>0.566</td>
<td>437.0</td>
<td>5552</td>
<td>5021</td>
<td>0.75</td>
<td>0.073</td>
</tr>
<tr>
<td>Kentucky bluegrass (KBG)</td>
<td>0.742</td>
<td>232.3</td>
<td>2870</td>
<td>3461</td>
<td>0.70</td>
<td>0.046</td>
</tr>
<tr>
<td>Mixture (MIX)</td>
<td>0.671</td>
<td>398.5</td>
<td>5559</td>
<td>4965</td>
<td>0.82</td>
<td>0.063</td>
</tr>
<tr>
<td>TF x TT</td>
<td>0.724</td>
<td>267.1</td>
<td>5765</td>
<td>5663</td>
<td>0.86</td>
<td>0.125</td>
</tr>
<tr>
<td>TF x TS</td>
<td>0.758</td>
<td>220.0</td>
<td>4566</td>
<td>5277</td>
<td>0.80</td>
<td>0.101</td>
</tr>
<tr>
<td>TF x Hay</td>
<td>0.838</td>
<td>279.9</td>
<td>6105</td>
<td>4777</td>
<td>1.26</td>
<td>0.135</td>
</tr>
<tr>
<td>TF x V</td>
<td>0.888</td>
<td>273.8</td>
<td>6409</td>
<td>3709</td>
<td>1.59</td>
<td>0.140</td>
</tr>
<tr>
<td>ORCH x TT</td>
<td>0.760</td>
<td>315.2</td>
<td>5516</td>
<td>6471</td>
<td>0.94</td>
<td>0.121</td>
</tr>
<tr>
<td>ORCH x TS</td>
<td>0.707</td>
<td>223.1</td>
<td>4248</td>
<td>5514</td>
<td>0.69</td>
<td>0.099</td>
</tr>
<tr>
<td>ORCH x Hay</td>
<td>0.598</td>
<td>425.5</td>
<td>5838</td>
<td>4267</td>
<td>1.01</td>
<td>0.196</td>
</tr>
<tr>
<td>ORCH x V</td>
<td>0.662</td>
<td>456.0</td>
<td>6606</td>
<td>3833</td>
<td>1.52</td>
<td>0.264</td>
</tr>
<tr>
<td>KBG x TT</td>
<td>0.328</td>
<td>196.3</td>
<td>3039</td>
<td>4320</td>
<td>0.36</td>
<td>0.119</td>
</tr>
<tr>
<td>KBG x TS</td>
<td>0.602</td>
<td>211.6</td>
<td>2689</td>
<td>3970</td>
<td>0.69</td>
<td>0.126</td>
</tr>
<tr>
<td>KBG x Hay</td>
<td>0.484</td>
<td>192.1</td>
<td>2905</td>
<td>3347</td>
<td>0.43</td>
<td>0.104</td>
</tr>
<tr>
<td>KBG x V</td>
<td>0.527</td>
<td>254.4</td>
<td>2843</td>
<td>2221</td>
<td>0.82</td>
<td>0.184</td>
</tr>
<tr>
<td>MIX x TT</td>
<td>0.644</td>
<td>327.1</td>
<td>4909</td>
<td>5827</td>
<td>0.77</td>
<td>0.131</td>
</tr>
<tr>
<td>MIX x TS</td>
<td>0.765</td>
<td>240.3</td>
<td>4960</td>
<td>5607</td>
<td>0.81</td>
<td>0.101</td>
</tr>
<tr>
<td>MIX x Hay</td>
<td>0.664</td>
<td>380.5</td>
<td>5809</td>
<td>4372</td>
<td>1.06</td>
<td>0.177</td>
</tr>
<tr>
<td>MIX x V</td>
<td>0.846</td>
<td>326.7</td>
<td>6557</td>
<td>4054</td>
<td>1.58</td>
<td>0.151</td>
</tr>
</tbody>
</table>

Table 4.4. Parameters of the regression of measured standing herbage mass on the predicted standing herbage mass for cool-season grass species subjected to four harvest schedules at South Charleston, OH in 2009.
Figure 4.1. Parameters a) ‘b’ and b) $Y_\Delta$ for tall fescue. Open squares and discontinuous fitted line represent the data collected at South Charleston in 2009, closed symbols and solid line represent the data collected at Columbus and Coshocton in 2008.
Figure 4.2. Parameters a) ‘b’ and b) $Y_\Delta$ for Kentucky bluegrass. Open squares and discontinuous fitted line represent the data collected at South Charleston in 2009, closed symbols and solid line represent the data collected at Columbus and Coshocton in 2008.
Figure 4.3. Parameters a) ‘b’ and b) $Y_\Delta$ for orchardgrass. Open squares and discontinuous fitted line represent the data collected at South Charleston in 2009, closed symbols and solid line represent the data collected at Columbus and Coshocton in 2008.
Figure 4.4. Parameters a) ‘b’ and b) $Y_\Delta$ for a three-species grass mixture. Open squares and discontinuous fitted line represent the data collected at South Charleston in 2009, closed symbols and solid line represent the data collected at Columbus and Coshocton in 2008.
Figure 4.5. Total herbage dry matter harvested for each defoliation x species treatment; KBG = Kentucky bluegrass, MIX = mixture of the three species, ORG = orchardgrass, and TF = tall fescue.

Figure 4.6. Total herbage accumulation for each defoliation x species treatment; KBG = Kentucky bluegrass, MIX = mixture of the three species, ORG = orchardgrass, and TF = tall fescue.
Figure 4.7. Neutral Detergent Fiber for each defoliation x species treatment; KBG = Kentucky bluegrass, MIX = mixture of the three species, ORG = orchardgrass, and TF.
Figure 4.8. Predicted (line) and measured values (symbols) for herbage mass for consecutive (open and closed) growing periods for tall fescue (a), orchardgrass (b), Kentucky bluegrass (c) and mixture (d) subjected to defoliation from 3600 to 2800 kg DM ha$^{-1}$ (TT).
Figure 4.9. Predicted (line) and measured values (symbols) for herbage mass for consecutive (open and closed) growing periods for tall fescue (a), orchardgrass (b), Kentucky bluegrass (c) and mixture (d) subjected to defoliation from 3300 to 2400 kg DM ha$^{-1}$ (TS).
Figure 4.10. Predicted (line) and measured values (symbols) for herbage mass for consecutive (open and closed) growing periods for tall fescue (a), orchardgrass (b), Kentucky bluegrass (c) and mixture (d) subjected to defoliation from 3600 to 1800 kg DM ha$^{-1}$ (Hay).
Figure 4.11. Predicted (line) and measured values (symbols) for herbage mass for consecutive (open and closed) growing periods for tall fescue (a), orchardgrass (b), Kentucky bluegrass (c) and mixture (d) subjected to defoliation from 3000 to 1600 kg DM ha\(^{-1}\) (V).
CHAPTER 5:
SEASONAL VARIATION IN THE RISING PLATE METER CALIBRATION FOR FORAGE MASS

ABSTRACT

Many methods of measuring forage mass have been evaluated to find reliable and fast measurements that can be conducted easily over extensive pasture areas. The indirect method of using a rising plate meter (RPM) has potential to meet those demands; however it requires careful calibration to provide reliable yield estimates. Potential variation in RPM calibration equations within and across seasons and locations has not been thoroughly examined in the Midwest USA. The objective of this research was to investigate the variation in weekly calibration coefficients of the RPM for estimating forage dry matter mass in five Ohio environments: Columbus 2008 (COL08) and 2009 (COL09), two sites at Coshocton (COSH1, COSH2) in 2008 and South Charleston in 2009 (SCH09). Calibration data were analyzed to investigate differences in the linear model due to environment, calendar week (15 to 43) and environment x week interactions, and at SCH09 for the effect of grass species on herbage mass using RPM as a covariate in the analysis. There was an effect of RPM ($P < 0.0001$), week ($P = 0.0021$), environment ($P < 0.0001$), environment x week ($P < .0001$), and at SCH09 species ($P = 0.0078$). Most (84%) calibration equations of herbage mass regressed on RPM height had an intercept equal to zero. Slope coefficients decreased rapidly during
the first few weeks of the season then increased steadily to the end of the season in all environments, suggesting the existence of underlying processes responsible for the seasonal changes. We recommended that RPM calibration samples be made frequently and possibly by species to maximize accuracy of forage mass prediction from RPM.
INTRODUCTION

The efficiency of pasture based animal production systems is sensitive to changes in the amount of forage supply over the season. Monitoring the amount of available forage mass is essential for managing stocking rates for optimal pasture utilization and profitable animal production. Documentation of available forage mass is critical to most pasture research, as it informs the extrapolation and analysis of animal performance results across different studies and environments. Therefore, accurate forage mass estimations are important both to producers and researchers alike.

Many methods of measuring forage mass are cited in the literature (Ganguli et al., 2000; Paruelo et al., 2000; Sanderson et al., 2001; Hill et al., 2004) and are usually classified into direct and indirect methods. The direct method of harvesting above ground biomass from a known area and determining the dry weight is considered the most reliable method (Cauduro et al., 2006). Nevertheless, this is a laborious and time-consuming method that limits its application among producers for making dynamic pasture management decisions. For on-farm monitoring, there is a need for reliable methods allowing fast measurement that can be carried out easily over extensive areas. The indirect method of using a rising plate meter (RPM) has potential to meet these demands allowing 100 readings in five minutes (Earle and McGowan, 1979).

The RPM relates the compressed sward height to the herbage mass below the plate (Sanderson et. al, 2001). An equation was developed to relate the RPM height to dry weight per unit area of hand-clipped forage samples. But this calibration process is also considered too laborious for producers to conduct and they usually do not have drying equipment to determine the actual dry weight of calibration samples collected. Usually
producers use a single calibration equation for the whole season that researchers or extension personnel have developed for their region. Such an approach assumes the relationship between the RPM and forage mass does not change over time, within a region, and among forage species. Harmoney et al. (1997) concluded that the relationship between the RPM measurement and forage mass may be affected by sward species composition.

A wealth of data is available in the literature evaluating the accuracy and pattern of RPM calibration on ryegrass swards (Mitchell, 1981; Mitchell and Lange, 1983); however, there is a need for developing reliable RPM calibrations for estimating yield of forage species grown under Midwestern USA conditions. Most published research on the RPM method has addressed the accuracy of forage mass estimation (Laca et al, 1989; Harmoney et al, 1997) or has different indirect and direct methods of measuring forage mass (Sanderson et al., 2001). An investigation changes in RPM calibration over the growing season has not been thoroughly examined. Therefore, the objective of this research was to investigate the variation in weekly calibrations of RPM for estimating forage mass across the growing season in five pasture environments in Ohio and in different cool-season grass species.
MATERIALS AND METHODS

To investigate the seasonal pattern of the RPM calibration equations for estimating total aboveground forage mass, hand-clipped calibration samples were collected from cool season grass pastures once a week in five Ohio environments (location and year combinations): Columbus 2008 (COL08) and 2009 (COL09), Coshocton I (COSH1) and Coshocton 2 (COSH2) in 2008 and South Charleston in 2009 (SCH09). In the COL09, COSH1 and COL08 the RPM calibrations were collected from plots of an existing study evaluating the pattern of herbage mass accumulation with different dates of initiation of mass accumulation in the absence of animal grazing (Barker et al., 2010). The COSH2 samples were taken from permanent pastures under grazing. Calibration samples at the SCH09 site were collected from plots under different mechanical defoliation treatments. Therefore, on most dates in each environment it was possible to calibrate the RPM using forage samples representing a wide range of standing herbage mass, which is assumed to improve calibration and yield prediction.

The COL08 and COL09 environments were located at The Ohio State University Don Scott Airport (40°04’ N, 83°05’ W) in a established mixed sward comprised predominantly of tall fescue [Schedonorus phoenix (Scop.) Holub, formerly Festuca arundinacea Schreb.] (73%) and Kentucky bluegrass (Poa pratensis) (15%) mixed sward. The soil was a Kokomo silty clay loam (a fine, mixed, superactive, mesic Typic Argiaquolls). In 2008, nitrogen in the form of urea fertilizer was applied on 9 Apr at 47 kg N ha\(^{-1}\) and on 3 June at 56 kg N ha\(^{-1}\). At COSH1 and COSH2 the soil was a Gilpin silt loam (mixed, active, mesic Typic Hapludults). Nitrogen in the form of urea was applied on 16 April and 5 June at 47 and 80 kg N ha\(^{-1}\), respectively. At SCH09 the soil was a tile
drained Kokomo silty clay loam (fine, mixed, superactive, mesic Typic Argiaquolls). Nitrogen was applied as urea at a rate of 55 kg N ha\(^{-1}\) on 25 September 2008 and in 2009 it was applied at 78 kg N ha\(^{-1}\) on 30 March and 56 N ha\(^{-1}\) on 20 August. The evaluation of RPM calibration equations was conducted in plots (32 m\(^2\)) from 6 April to 30 October 2008 at COL08. Both COSH1 and COSH2 environments were located at the USDA North Appalachian Experimental Watershed (40°21’51” N, 81°46’56” W) near Coshocton, OH; however, they consisted of two distinct experimental areas. Before commencement of the present study the COSH1 area was managed as a hay field and grazed pasture in alternated years. This area consisted of predominantly tall fescue (76%) with a small percentage of Kentucky bluegrass (4%) and white clover (\textit{Trifolium repens}) (10%). In contrast, the COSH2 environment had been part of a 4 yr study aiming to evaluate the effect of intermittent and continuous stocking on water runoff, soil erosion and nutrient leaching. Botanical composition in the COSH2 pasture site was 50% tall fescue, 27% Kentucky bluegrass, 10% orchardgrass (\textit{Dactylis glomerata}), 5% white clover and 8% of other species. The mixed cool grass pasture treatments of COSH2 were grazed from late April to late August at an average stocking rate of 3.2 cows/ha, with RPM calibration samples collected from 24 April to 29 August 2008. The SCH09 environment consisted of monoculture stands of tall fescue, Kentucky bluegrass, and orchardgrass and a mixture of those same species. The plots (11 m\(^2\)) were located at the Western Research Station of the Ohio Agricultural Research and Development Center (39° 85’ 29” N, 83° 84’ 09” W) located near South Charleston, OH and had been seeded in August 2008 in rows spaced 15 cm apart. Samples for RPM calibrations were collected from 20 May to 30 October 2009.
In order to standardize time across environments, sample dates were allocated to the appropriate calendar week of the year (Week 1 being the first week in January). Thus, samples were collected from Weeks 15 (early April) to Week 43 (end of October). Calibrations samples were collected by the same operator in all environments in 2008 and at SCH09 in order to minimize data bias due to operator effect (Rayburn et al., 2007); however, calibration samples at COL09 were collected by a different operator. The number of calibration samples collected for each evaluation day varied among environments, although the average was six samples. The RPM (Ashgrove Pasture Plate, Ashgrove Industries, Ashhurst NZ) used in this study consisted of an ascendant disc with an area of 0.1 m$^2$ and weighing 0.3 kg. It measures the compressed sward height in 5-mm increments (using a mechanical counter). After recording the RPM height, the forage under the plate was clipped to ground level within a 0.1 m$^2$ quadrat, after which the sample was dried at 55°C to constant weight to determine the dry weight. At SCH09, the RPM was always placed between two rows and calibration samples were collected for each monoculture grass species and the mixture.

The PROC MIXED procedure of SAS (Littell et al., 1996) was used to test the effect week, environment, and the week x environment interaction on forage mass of the hand-clipped samples, with the RPM height measurement included as a covariate in the model statement. For each environment x week combination, the RPM height was used to estimate herbage mass (kg DM ha$^{-1}$) by developing a linear regression equation, in which herbage mass of the hand-clipped samples was regressed on the corresponding RPM height data using the PROC REG procedure of SAS (SAS for Windows v. 9.1.3, SAS Institute Inc., Cary, NC). To describe the seasonal pattern of the slope coefficient of RPM
calibration equations, the RPM calibration coefficients (slope ‘b’values from the regression of yield on RPM) were fitted to a 4-parameter equation using PROC NLIN in SAS (SAS for Windows v. 9.1.3, SAS Institute Inc., Cary, NC) using Method=Newton. For each model \[ y = a + (b*\exp (-c*x)) + d*x^2 \], the coefficient of determination \((r^2)\), root mean square error (RMSE), model probability (Pr>F), parameter estimates and their standard errors from the PROC NLIN procedure were reported. At SCH09, an additional analysis of variance was conducted to evaluate the effect of grass species, week, and the species x week interaction on forage mass, with RPM height included as a covariate in the model statement. The RPM height was used to estimate herbage mass by developing a linear regression equation for each species, in which herbage mass of the hand-clipped samples was regressed on the corresponding RPM height data using the PROC REG procedure of SAS.

Of interest for extension applications, an analysis was carried out to evaluate the possibility of combining the RPM calibration across different sites within the same region. For this, validation tests were analyzed using different RPM calibration coefficient models (the model fitted across time within each environment specific, environment and species specific and combined across three environments). The validation tests were performed by comparing herbage mass estimated by the RPM (using the different calibration approaches just described) to yields measured with a forage plot harvester on 18 June, 21 August, and 5 November in 2008 at Columbus (COL08); on 20 June, 3 July, 14 and 29 August, and 6 November 2008 at Coshocton (COSH1); on 30 September and 27 October 2009 at South Charleston SCH09). The small plot harvester was used to collect fresh forage from a 1 x 9 m area. A 300-g subsample was collected to
determine dry matter content and used to convert the fresh wt to dry wt. Harvested yield was estimated with the RPM by taking the difference between the RPM measurement before and after harvesting and multiplying it by the appropriate calibration coefficient for that date and location. A number of parameters were used in evaluating the relationship between plot harvester and RPM estimated yield. The regression of forage harvester yield on the RPM estimated yield was evaluated with $r^2$ and root mean square error (RMSE), and tested for intercepts at the origin (y-intercept = 0) and unitary slope coefficient (slope = 1). In addition, mean squared deviation (MSD) and its components were calculated and evaluated as described by Gauch et al. (2003). The MSD reflects discrepancy between a model and the data and is a direct measure of predictive success. The MSD components of squared bias (SB), nonunity slope (NU), and lack of correlation (LC) provide further insight into model performance. The three components have distinct meanings and simple geometric interpretation, with SB relating to translation, NU relating to rotation, and LC relating to scatter.
RESULTS AND DISCUSSION

Herbage mass for the hand-clipped calibration samples was affected by RPM height (covariate), week, environment, and the week x environment interaction (Table 5.1). The RPM height was linearly related to dry matter yield in all environment x week combinations, which has long been accepted as the best type of fit for calibrating RPM height to herbage mass (Scrivner et al., 1986; Laca et al., 1989). The intercept was different ($P > 0.05$) from zero only in 19 out of 118 week x environment combinations. Thus, we forced the model through zero ($Y= bx$) in all cases. Using the RPM height to predict herbage yield based only on the slope coefficient (0 intercept) provides more direct comparisons and extrapolation across studies and locations. The slope coefficients of RPM calibration for forage mass ranged from 83 to 304 among all environments with a mean of 133 for COL08, 134 for COSH1, 130 for SCH09, 176 for COL09 and 157 for COSH2.

Herbage mass was significantly affected by week across all five environments and in the analysis for each individual environment, suggesting that the use of a single RPM calibration for yield over the entire season is unlikely to accurately predict herbage mass. The effect of date on RPM calibration has been observed by others (Scrivner et al., 1986; Laca et al, 1989). However, most have analyzed the RPM calibration data by month instead of considering possible differences over a shorter time scale.

Individual t-tests among environments demonstrated that mean yields (adjusted for RPM height as a covariate) at COL08, COSH1 and SCH09 were similar, indicating it might be possible to combine those environments when developing calibration equations for converting RPM height to forage dry matter yield. The rank for mean herbage mass
adjusted for RPM height for the main effect of environment was: COL08 (2473 kg DM ha\(^{-1}\)) = COSH1 (2550 kg DM ha\(^{-1}\)) = SCH09 (2615 kg DM ha\(^{-1}\)) < COL09 (3187 kg DM ha\(^{-1}\)) < COSHII (4138 kg DM ha\(^{-1}\)). Despite a significant environment effect, in the covariate analysis of yield, all environments had a similar general pattern of the slope coefficient of the RPM calibration equations across time, illustrated by fitted non linear responses across time (Fig. 5.1, Table 5.2). The mathematical relationship between parameters of the nonlinear model fitted to the slope coefficients across time provides a description of the responses observed (Sheehy and Johnson, 1983). The phase of decreasing slope coefficients at the beginning of the season was primarily described by parameter ‘b’ of the nonlinear equation, while parameter ‘d’ seemed to describe the increasing trend observed later in the season, especially during the latter half of the experiments. At the beginning of the growing season, the slope coefficients were high and decreased sharply during the first few weeks and then increased throughout the remainder of the season. The RPM slope coefficients for COL09 were higher than the other environments and in the COSH2 environment the slope coefficients increased after wk 22 more sharply than in the other environments (Fig. 5.1). The different late season pattern at COSH2 was likely due to drought stress at that site, which was located on a south-west-facing slope in a pasture that was continuously stocked by cattle. In fact, sampling did not continue in that pasture after wk 30 because pasture growth had ceased and the animals were moved to another pasture.

The higher values for COL09 compared with the other environments may have been confounded with an operator effect, because one person performed calibration sampling at COL08, COSH1 and SCH09 while a different people performed calibration
sampling at COL09. An operator effect has been reported to be an important source of variation for many indirect methods for measuring forage yield (Aiken and Bransby, 1992; Rayburn et al., 2007). Differences among operators can occur through differences in the force applied to push the rod through the canopy so it touches the ground surfaces, which can be more accentuated in very dense swards. Operator can also affect how close to the ground the sample is cut and how much of the stubble residue inside the quadrat is collected after cutting. The effect of operator should be carefully considered for grazing management decisions, especially in grazing research, and it is important to train operators in standardized sampling protocols in order to reduce the variation in RPM calibration caused by operator.

Silva and Cunha (2003) and Braga et al. (2009), working with grazed tropical pastures, reported high calibration coefficients at the beginning of the growing season as we found in this study. They suggested that the high initial values were a consequence of accumulation of dead material in the canopy, because dead material contributed to herbage mass but exerted lower resistance to the plate compression than green material. The same may have been the case in our experiments. At the commencement of the experimental period (wk 15), the pastures at COL08 and COSH1 had ~850 g kg\(^{-1}\) dead material, at wk 17 it was 550 g kg\(^{-1}\), and at wk 18 it was 450 g kg\(^{-1}\). In addition, the canopy architecture can contribute to variation in RPM calibration over the growing season (Stockdale and Kelly, 1984; Gonzalez et al., 1990). A seasonal pattern in the slope coefficient was also observed by Mitchell (1982) in a grazed ryegrass and white clover mixed pasture. He reported relatively constant values for the slope coefficient during
winter and spring, whilst in summer the coefficients varied. In similar work, Mitchell and Lange (1983) reported higher values of the slope coefficient during summer than spring.

A second phase in the RPM calibration pattern occurred in our studies when the slope coefficient steadily increased from wk ~19 to 21 (depending on environment) until the end of the experiment. This consistent pattern of increase in the RPM calibration coefficients across environments has not been reported in the literature and suggests there may have been important factors driving that phenomenon. The accumulation of nonstructural carbohydrates in grasses occurs primarily in the pseudostem and can contribute up to 200 g kg\(^{-1}\) of the dry weight present (Parsons et al., 1983). Many have reported a seasonal pattern in nonstructural carbohydrate storage in the shoots of temperate grasses (Parsons et al., 1983). Generally, the nonstructural carbohydrate content of C3 grasses increases with low night temperatures when carbon loss by respiration declines (Fulkerson and Donaghy, 2001). Those authors reported high levels of nonstructural carbohydrates during the reproductive phase, autumn and winter with decreased levels in early spring. Lower concentrations during early spring were a consequence of high carbohydrate demand to produce new tissues (mobilization) (Poloc and Jones, 1979; Steen and Larson, 1986). However, Griggs et al. (2005) reported higher total nonstructural carbohydrate concentrations during the month of June than August. Therefore, if the seasonal pattern in nonstructural carbohydrates can partially explain the increasing trend in the slope coefficients found in this work after early to mid-June, it may be that other factors cause the lower values in June and further investigation is warranted to understand this. As the RPM correlates the herbage mass to canopy architecture, changes in the components that characterize the spatial distribution of the
sward could affect the RPM calibrations. For example, the onset of reproductive
development during the spring may have caused the slope coefficients to decrease
indicating a decline in the density of grass mass, followed by increasing density of the
mass the remainder of the season.

Slope coefficients and intercepts (when significant) of RPM calibrations are
affected by time of the year, which can reflect sward condition (Laca et al, 1989),
operator (Earl and McGowan, 1979), morphological sward stage, changes in sward
species composition over time (Michel and Robert, 1987) and grazing management
(Mitchell and Lange, 1983). In addition, differences in calibration values can be affected
by time of the day calibration samples are collected due to changes in dry matter content
(Earl and McGowan, 1973). Although some periods had more scattered values for the
slope coefficient, the presence of a repeatable pattern over environments provides a focus
for further investigation than the values per se.

At SCH09, RPM, week and cool-season grass species had an effect on herbage
mass (Table 5.3). The species effect on herbage mass with RPM used as a covariate was
primarily due to the three species mixture: KBG 2911 kg DM ha\(^{-1}\), TF 2911 kg DM ha\(^{-1}\),
ORG 2762 kg DM ha\(^{-1}\), MIX 2652 kg DM ha\(^{-1}\) (LSD=166.6, \(P = 0.05\)). Silva and Cunha
(2003) reported the need to use different RPM calibration equations even for cultivars of
*Cynodon* sp. The use of specie-specific RPM calibration equations is supported by
differences in canopy architecture, volumetric density and growth habit among species.
On a farm where pasture paddocks are fairly consistent in species composition, it is
unlikely that different calibration equations will be necessary. Monitoring the botanical
composition can provide information of when paddock specific calibration equations should be developed (Baker et al., 1981; Karl and Nicholson, 1987).

Since no significant difference was found among COL08, COSHII and SCH09 for mean herbage mass (using RPM height as a covariate) and machine harvest of yield were performed on several dates at those sites, three validation scenarios were analyzed in order to evaluate the accuracy of herbage yield prediction using different levels of specificity in the RPM calibration. Forage yield determined with a small plot harvester was compared with the harvested yield as estimated from RPM measurements taken before and after clipping. The difference in RPM measurements before and after clipping was multiplied by the slope coefficient predicted for each specific harvest date using three scenarios: (1) the RPM slope coefficient was calculated from the model fitted across all three-environments (Table 5.2, 3-environments), (2) the RPM slope coefficient was calculated from the model fitted to each specific environment (Table 5.2), and (3) the most specific scenario using environment and species specific calibrations, calculated using calibration samples specific to each environment x week x species combination (Table 5.5)(3) (Table 5.2). For all scenarios the method of Gauch et al. (2003) showed that most of the variation was due to scatter (LC, 95 to 98%) and the most specific (3) presented the highest MSD (407881). The goodness of fit was quite similar among the three scenarios for determining the RPM coefficients (Table 5.4). Using the environment and species-specific fitted RPM calibration did not improve the herbage yield predictions compared with using the calibration as estimated from the model fitted across environments or fitted to each environment. RPM calibration coefficients from the model fitted across the three environments resulted in the highest $r^2$ and the lowest error overall.
Furthermore it has practical advantages over the environment specific models. For extension purposes, a seasonal pattern of RPM calibration could be developed for a region, as long as similar species are being used. However, as illustrated before, the operator can have a significant effect on the RPM calibration equations. Therefore, to avoid differences in RPM calibrations when making comparisons among environments, it is suggested that the same operator collect calibration samples from the different sites to develop the seasonal pattern of RPM calibration for a given region. Alternatively, multiple operators could be involved in sampling, but they would each have to collect an equal number of samples on any given date at a specific site or sites, using the same protocol, in order to have their individual sampling differences equally represented in the calibration sample set.

An assessment of available herbage mass is very useful for guiding producers in making grazing management decisions, but taking weekly calibration samples is not likely to be an appealing or practical procedure on a farm. Nevertheless, our results show that at the beginning of growing season, weekly changes in calibration coefficients were drastic and failing to make weekly calibrations of the RPM would likely result in large errors in estimates of available forage. In contrast, after about wk 20, the slope coefficients increased steadily but at a fairly slow rate in all but the COSH2 experiment, so monthly calibrations may be adequate on farms during the summer under normal growing conditions for the region, although yield estimates would be underestimated at an increasing rate as the time from the date of calibration lengthened. A practical compromise may be for producers, consultants, or extension personnel to conduct RPM calibrations every two weeks rather than relying on monthly calibrations or a calibration
for the entire season. In research, RPM calibrations derived from samples collected over two week periods would provide an averaging effect over a short time period and help smooth RPM yield predictions from one week to another due to variation and errors that might occur between consecutive weeks.

The existence of patterns in the RPM calibration coefficients may provide practical solutions to the dilemma of RPM calibration for producers. Daily herbage mass estimation could be calculated by using adjustments to a standard model for RPM calibration over time (developed through research as presented in this study). The adjustments would be based on the differences between the model predicted coefficient and less frequent performed on-farm calibrations. This method requires further investigation.
CONCLUSION

We recommend that RPM calibrations be made frequently and possibly by species to increase accuracy of forage mass prediction. The significant difference in RPM calibration coefficients across weeks suggests that researchers should conduct calibrations on each sampling date to minimize errors in their yield estimates obtained from a RPM, especially early in the spring. In contrast, producers are probably not willing or able to conduct RPM calibrations on a frequent basis because it can be a time consuming activity and proper equipment for drying forage samples may not be available on many farms. Our results demonstrate that the use of a monthly calibration or a single calibration for the whole season is likely to result in low accuracy of available herbage mass. Errors in estimating herbage mass could be especially great during the early spring when calibration coefficients decline rapidly, but even later in the season we observed a steady change in the calibration coefficients over time, suggesting fairly frequent calibrations are needed. There was an effect of species, week, and environment, although the species effect was much smaller than the week and environment effects, and the environment and operator effect in two environments may have been confounded. In practice, different operators should be trained to a standardized calibration protocol. The error of estimating herbage mass with the RPM would be reduced if the same operator collects calibration samples and measures the pasture with the RPM. The repeatable seasonal pattern of the slope coefficients found both in defoliated and non-defoliated pastures suggests the existence of an underlying process responsible for the seasonal changes in the slope coefficient values.
Figure 5.1. Fitted nonlinear models for the slope coefficients of rising plate meter (RPM) calibrations for herbage mass across the growing season in five environments in Ohio, Coshocton II (1), Columbus 2009 (2), Coshocton I (3), South Charleston 2009 (4) and Columbus 2008 (5). Parameters and statistics for the models are presented in Table 5.2.
Table 5.1. Analysis of variance of the effect of environment, annual calendar week, and their interaction on total above ground forage mass using the rising plate meter (RPM) as a covariate in the analysis.

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>df</th>
<th>F value</th>
<th>Pr &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPM</td>
<td>1</td>
<td>535.72</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Week</td>
<td>5</td>
<td>3.84</td>
<td>0.0021</td>
</tr>
<tr>
<td>Environment</td>
<td>4</td>
<td>38.04</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Week x environment</td>
<td>20</td>
<td>6.25</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Error</td>
<td>322</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.2. Parameters (a, b, c and d) and regression statistics for the nonlinear models fitted to the slope coefficients describing the relationship between rising plate meter height to herbage mass over the time, as shown in Fig. 5.1.
<table>
<thead>
<tr>
<th>Source of variation</th>
<th>df</th>
<th>F value</th>
<th>Pr &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPM</td>
<td>1</td>
<td>438.26</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Week</td>
<td>22</td>
<td>13.69</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Species</td>
<td>3</td>
<td>4.03</td>
<td>0.0078</td>
</tr>
<tr>
<td>Week*species</td>
<td>66</td>
<td>0.86</td>
<td>0.7667</td>
</tr>
</tbody>
</table>

Table 5.3. Analysis of variance of the effect of annual calendar week, forage species and their interaction on total above ground forage mass using the rising plate meter (RPM) as a covariate, at South Charleston, OH in 2009.
Table 5.4. A comparison of harvested yield regressed on yield predicted by the rising plate meter (RPM) using three methods of calibrating the RPM in three environments (Columbus 08, Coshocton I and South Charleston). The RPM coefficients used to estimate yield were determined from a model fitted across all three environments, fitted to each specific environment, and using environment x week x species specific calibration samples. Intercept (a), slope (b), standard error (SE), mean standard error (MSD) and its components (SB = squared bias; NU = nonunity of slope; LC = lack of correlation), and number of observations (N) for each model is presented.
APPENDIX A

SAS Program Statements Used To Test The Variables Total Dry Matter Accumulation, Total Dry Matter Harvested, Residual Difference and Neutral Detergent Fiber.

data anova;
input plot rep sp$ trt $ VARIABLE; *VARIABLE is the variable being analyzed;
cards;
101 1 tf 1 7712
102 1 k 1 3541
103 1 m 1 5948
104 1 o 1 6479
105 1 m 4 8415
106 1 k 4 3451
107 1 tf 4 8574
108 1 o 4 8095
109 1 m 3 7412
110 1 tf 3 6633;
proc mixed;
class rep trt sp;
model VARIABLE = harv sp trt*sp;
random rep rep*trt;
lsmeans trt sp trt*sp/pdiff;
run;
APPENDIX B

SAS Program Statements Used To Test Dry Matter Yield Using RPM as a Covariate and Develop the RPM Calibration Equations Over the Growing Season for Four Species.

data calwars;
input week sp $ rpm DWkgha;
cards;
15 t 11 3676
15 t 14 4058
15 t 12 3582
15 o 7 1730
15 o 13 2395
15 o 12 2259
;
run;

proc mixed;
class week sp;
model DWkg= rpm week|sp/ddfm=satterth;
lsmeans week sp week*sp/ pdiff;
run;

proc sort; by week sp;
proc reg; by week sp;
model DWkg=rpm/noint;
run;
APPENDIX C

SAS Program Statements Used To Test Dry Matter Yield Using RPM as a Covariate and Develop RPM Calibration Equations Over the Growing Season for Five Environments.

data calall;
input week env rpm DWkg ha;
cards;
15 1 11 3676
15 1 14 4058
15 2 12 3582
15 2 7 1730
15 2 13 2395
15 3 12 2259
15 3 16 2645
15 3 13 2333
15 3 14 1989;
run;

proc mixed;
class week env;
model DWkg= rpm week|env;
lsmeans week env/pdiff;
run;

proc sort; by week env;
proc reg; by week env;
model Dwkg=rpm/noint;
run;
APPENDIX D

SAS Program Statements Used To Fit a Model to the Slope Coefficient of RPM Calibration Equations Over the Growing Season.

data;
input x y;
cards;
15 241
16 187
17 128
18 110
19 108
20 88
21 88
22 106
23 104
24 99
25 125
26 107
27 108
28 103
29 118
30 118
;
proc print;
proc nlin best=20 method=newton;
parms
a=50 to 200 by 50
b=200000
c=0 to 1 by 0.01
e=0 to 1 by 0.1
;
model y=a + (b*exp(-c*x)) + e * x**2;
der.a=1;
der.b=exp(-c*x);
der.c= b * exp(-c*x);
der.e=x**2;
;
run;
APPENDIX E

SAS Program Statements Used To Fit Gompertz Growth Curves.

```sas
data Gompertz curves;
input x y;
cards;
0 1308
10 1991
15 1781
23 1719
30 2144
37 2310
44 2325
52 2679
59 3339
65 3469
72 3478
81 3648
85 3810
94 4377;
proc print;
proc nlin best=20 method=newton;
parms a=5500 to 6000 by 50
  b=2 to 4 by 0.01
  c=0 to 0.05 by 0.01
;
model y=a*exp(-b*exp(-c*x)) + lowest mass measured;
der.a=EXP(-b*exp(-c*x));
der.b=exp(-c*x)*a*EXP(-b*exp(-c*x));
der.c= x * exp(a*(exp(-b * exp(-c*x))))*log(1/EXP(-b * exp(-c*x))));
run;
```
APPENDIX F

SAS Program Statements Used To Fit the Reverse Gompertz Equation.

data reverse gompertz;
input x y;
cards;
3522 60.0
3344 65.9
3740 69.3
3226 59.7
2604 73.1
2905 74.0
;
proc print;
proc nlin best=20 method=newton;
parms
  a=4000 to 7000 by 5
  c=0.01 to 0.02 by 0.005
  d=0 to 2000 by 10
;
model y=c*(x-d)* log(a/(x-d));
der.a= c*((x-d)/a);
der.c=(x-d)*log(a/(x-d));
der.d= c - c * log(a/(x-d));
run;
APPENDIX G

SAS Program Statements Used to Test the Hypothesis That All the Parameters of Regrowth and New Gompertz Growth Curves are Equal.

```sas
data gompertz;
input group x y d1 d2;
cards;
1 0 1785 1 0
1 8 1881 1 0
1 15 2013 1 0
1 22 2086 1 0
1 29 2220 1 0
1 37 2358 1 0
1 44 2929 1 0
1 50 3280 1 0
1 57 3304 1 0
2 0 1813 0 1
2 8 2100 0 1
2 15 1978 0 1
2 22 2033 0 1
2 29 2033 0 1
2 37 2285 0 1
2 44 2534 0 1
2 50 3073 0 1
2 57 2974 0 1
;
proc print;
proc nlin best=20 method=newton;
parms a= "estimated initial values"
b= "estimated initial values"
c= "estimated initial values"
;
model y=d1*(a*exp(-b*exp(-c*x))+ "lowest mass measured1") + d2*(a*exp(-b*exp(-c*x))+ "lowest mass measured2")
;
run;
```
Chapter 1


Chapter 2


135


Parsons, A.J., I.R. Johnson and A. Harvey. 1988b. Use of a model to optimize the interaction between the frequency and severity of intermittent defoliation and to provide a fundamental comparison of the continuous and intermittent defoliation of grass. Grass Forage Sci. 43:49-59.


Chapter 3


Parsons, A.J., I.R. Johnson, and A. Harvey. 1988. Use of a model to optimize the interaction between the frequency and severity of intermittent defoliation and to provide a fundamental comparison of the continuous and intermittent defoliation of grass. Grass Forage Sci. 43:49-59.


Chapter 4


Chapter 5


