A DEGREE DAY MODEL OF SHEEP GRAZING INFLUENCE ON ALFALFA WEEVIL, *Hypera Postica*

by

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ABSTRACT

Alfalfa, *Medicago sativa* (L.), is produced on approximately 720,000 ha in Montana and is the foremost forage crop in many high, semiarid, intermountain states. Two biological stressors (insects and weeds) combined with poor field management are primarily responsible for reduced alfalfa production. In the U.S. alone, arthropods cause an estimated $260 million loss to alfalfa with the alfalfa weevil (AW), *Hypera postica* Gyllenhal, being the most damaging phytophagous pest in the United States. Using degree days as predictors for initiation and cessation of arthropod IPM programs is a common practice and on-line degree day calculators using regional temperature data are providing equal accuracy as on-site estimates.

Grazing is emerging as a legitimate IPM tactic however there is no published literature using degree days to implement an IPM based grazing systems. A degree day predictive model is needed, as a producer decision and support tool, to improve the effectiveness of strategic sheep grazing to manage alfalfa weevil.

Grazing treatments exclosures were established in a randomized complete block design at weekly intervals giving each treatment a unique degree day and stocking rate. Degree days calculated from both on-site and near-site data produced the same model accuracy. Therefore, the near-site model was selected to encourage use by producers.

Treatments meeting the selection criteria (G3, G4, G5) were 'modeled' together and a simple linear regression ($P < 0.01$) was calculated predicting AW larval populations based on stocking rate and degree day. Harvest sample treatment DM did not differ ($P > 0.16$). However, NDF, CP, and Yield differed ($P < 0.01$) between treatments. Due to an interaction ($P < 0.01$), ADF and TDN were separated by year and did not differ $P = 0.93$ during 2008, but did ($P < 0.01$) during 2009. Based on yield and nutritive differences between treatments, a simple regression ($P < 0.01$) of plant RGR was calculated to predict when yield and nutritive characteristics of the modeled and less extensively grazed 'alternative' (NG, G1, G2) treatments would equal. The equation predicted that producers would need to wait an average of four days for treatment harvest characteristics to equal.

INTRODUCTION

Alfalfa (*Medicago sativa* L.), is produced on approximately 650 thousand ha in Montana (NASS 2008) and economically the third most important crop in the U.S. being produced in many semiarid, intermountain states (Barnes 2007). Two biological stressors (insects and weeds) combined with poor field management are primarily responsible for reduced alfalfa production (Latheef et al. 1988). In the U.S. alone, arthropods cause an estimated $260 million loss to alfalfa (Leath et al. 1988) with the alfalfa weevil (AW), *Hypera postica* Gyllenhal, being the most damaging phytophagous pest (Blodgett et al. 2000).

Multiple tactics have been examined to manage AW populations and limit damage with varied results. Alfalfa weevil tolerant cultivars currently available to producers often do not provide sufficient protection from AW larval damage to justify their use (Blodgett et al. 2000). Biological agents have reduced weevil populations below economic thresholds in the eastern U.S. (Richardson et al. 1971); however, their impact has been marginal in the west (Van den Bosch 1982, Kingsley et al. 1993, Brewer et al. 1998, Radcliffe and Flanders 1998). Insecticides that target AW larvae are used on approximately 34% of the alfalfa acreage in the U.S. (Bailey 1994). However, insecticide use is costly and requires intensive field monitoring, by producers or consultants, to determine when a treatment is economically justifiable. Previous work published in Goosey et al. (2004) indicates that strategic sheep grazing is effective at managing in-field AW larval populations. However a method to standardize the grazing protocol across environments is needed.

Using degree days (DD) as predictors for initiation and cessation of arthropod integrated pest management (IPM) programs is a common practice (Guppy, 1974, AliNiazee 1976, Sevacherian et al. 1977, Peterson and Meyer 1995) and online DD calculators using regional temperature data prove equal to on-site estimates for AW sampling (Brewer 2002). Degree days are also used to predict rangeland plant responses to grazing (Frank and Hofman 1989) and plant developmental morphology (Mitchell et al. 1997). Alfalfa quality and yield are highly correlated with development (Fick and Mueller 1989, Cash et al. 1995) which is a function of relative growth rate (RGR) (Hutchings 1997) and can be estimated by DD.

Grazing is emerging as a legitimate IPM tactic (Walker 1992, Olson 1994, Clark 2004, Goosey et al. 2004,2005; Hatfield et al. 2007a,b) however no published literature exist expressing DD for initiation and cessation of IPM based grazing systems. A DD predictive model is needed, as a producer decision and support tool, to improve the effectiveness of AW control and encourage acceptance of the grazing system proposed by Goosey et al. (2004).

LITERATURE REVIEW

Alfalfa

Alfalfa or lucerne (*Medicago sativa* L.) is grown as a superior feed for livestock because it is relatively high in protein, high in cell solutes, quickly digested, and low in neutral detergent fibers (Conrad and Klopfenstein 1988). Alfalfa was harvested on approximately 8.5 million ha nationally in 2008 worth $10.8 billion. Montana 2008 harvest was 650 thousand ha worth $360 million (NASS 2008). As a forage crop, alfalfa is an integral component to the dairy and beef cattle (*Bos spp*.), sheep (*Ovis* spp.), horse (*Equus* spp.), swine (*Sus* spp.), and poultry (*Gallus* spp.) industries (Van Keuren and Matches 1988).

Alfalfa is recognized as the oldest plant grown solely for forage and it was likely cultivated prior to recorded history (Michaud et al. 1988). Common alfalfa probably originated in or around Asia Minor, Transcaucasia, Iran, and Turkministan (Whyte et al. 1953, Bolton 1962, Wilsie 1962, McWilliam 1968). Over 400 modern cultivars or brand names were available to growers in the U.S. and Canadian markets in 1983 (Miller and Melton 1983).

Alfalfa, a legume, is an extremely adaptable plant and can be grown under a wide range of soil and climatic conditions. Leguminous crops improve soil fertility through the addition of biologically fixed nitrogen (Pierzynski et al. 2005). Ideal soil textures to grow alfalfa are sandy, silty and clay loams with depths greater than 1.8 m. However, alfalfa will produce in loamy sand and silty clay soils with depths greater than 0.9 m. Soil chemistries suitable to alfalfa production are: pH 5.8-8.2, salinity ($EC_{e \text{ in mmho/cm}}$) 0-5, exchangeable sodium percentage 0-15, and boron (mg/L) 2-6 (Orloff 2008). Alfalfa produces best when grown under irrigation but can be raised, with out irrigation (dryland), in areas receiving greater than 30 cm of annual precipitation.

A diversity of arthropods can be found in an alfalfa stand, most of which have little or no impact on the crop itself. Van den Bosch and Stern (1969) estimated that approximately 1000 species of arthropods are linked with alfalfa in California's Central Valley. Pimentel and Wheeler (1973) sampled 591 arthropod species from alfalfa stands in upstate New York. Most of these arthropods do not cause damage to alfalfa but are present for the shelter it provides from the environment and natural enemies. Others are predators or parasitoids attacking alfalfa pests (Summers 1998).

Pest management can trace its origins to alfalfa (Summers 1998). The first entomologist hired to monitor alfalfa fields and make management recommendations regarding the alfalfa caterpillar *Colias eurytheme* Boisduval occurred in California in 1946 (Hagen et al. 1971). Other significant pests include eastern and western alfalfa weevil (AW), *H. ostica* (Gyllenhall), the Egyptian AW, *H. brunneipennis* (Boheman), and clover root curculio, *Sitona hispidulus* (F.). Important hemipterans are the pea aphid, *Acrthosiphon pisum* (Harris), blue alfalfa aphid, *A. kondoi* (Shinji), spotted alfalfa aphid, *Therioaphis maculate* (Buckton), cow pea aphid, *Aphis craccivora* (Koch), potato leafhopper, *Empoasca fabae* (Harris), threecornered alfalfa hopper, *Spissistilus festinus* (Say), and meadow spittlebug, *Philaneus spumarius* (L). Lepidopterans include armyworms, *Spodoptera* spp., and webworms, *Loxostege* spp. and *Achyra* spp. Collectively, these few significant pests, caused an estimated $260 million in crop damage in 1988 (Manglitz and Ratcliff 1988, Leath et al. 1988).

Alfalfa Weevil

The AW is indigenous to Europe, south central Asia, and northern Africa (Anonymous 1983). The AW was introduced into North America on three separate instances: in 1904 near Salt Lake City, Utah (Titus 1910), in 1939 near Yuma Arizona (Wehrle 1939), and in 1951 near Annapolis, Maryland (Poos and Bissel 1953).

Alfalfa Weevil Strains

Alfalfa weevil is found in all lower 48 U.S. states, parts of northern Mexico and southern Canada from Quebec west to British Columbia (Summers 1998). Cytogenetic and allozyme evidence indicates that only a few individuals contributed to the founding of three strains (western, eastern, and Egyptian) in North America (Hsiao 1993). Ranges of the western AW (introduced in Utah in 1904) and eastern AW (introduced in Maryland in 1951) first merged about 1971 (Klostermeyer and Manglitz 1979) and overlap in at least nine states (Radcliff and Flanders 1998). The Egyptian AW (introduced to Arizona in 1939) has expanded its range in hot, arid habitats by displacing populations of the western AW (van den Bosch and Dietrick 1959). Ranges of the Egyptian and western AW overlap in at least four states (Hsiao 1996).

Biologically, the three strains differ, but it is difficult to separate these differences from effects due to environment (Hsiao 1993). However, biological differences between strains have been reported (Davis 1967, Armbrust and Gyrisco 1982, van den Bosch et al. 1982). The western AW prefers to pupate in the ground litter, but the Egyptian and eastern AW prefer the above ground plant parts. The western and eastern AW hibernate by random dispersal in or outside fields where as the Egyptian strain aggregates under tree bark or in open crevices such as loose boards on buildings. The Egyptian AW thrives in hot climates, such as southern California, whereas the western AW prefers relatively colder climates. The western AW exhibits an extended pre-oviposition period that was significantly longer than in the eastern and Egyptian strains when reared under a non-diapause photoperiod regime (Rosenthal and Koehler 1968, Schroder and Steinhauer 1976). The rate of larval and pupal development of the eastern AW was also shorter than that of the western and Egyptian AW (Schroder and Steinhauer 1976). These examples indicate that AW strains differ in their seasonal phenology and diapause characteristics.

The Egyptian and eastern strains, which live in warmer climates, resume feeding and oviposition in the fall and begin a new generation during the winter and early spring months. These AW aestivate during the late spring and summer months. The western AW typically reproduces in the spring and produces one generation during the late spring and early summer months (Hsiao 1993). It then enters adult diapause in late summer and overwinters until the following spring (Blodgett 1996). Bundy et al. (2005) isolated strain geographic ranges in New Mexico and provides the most current U.S. AW strain distribution map (Fig. 1).

Until recently, the eastern and western strains were considered to represent distinct subspecies of *H. postica*, while the Egyptian AW was considered to be a different species (*H. bruneipennis*) (Summers 1998). The eastern and western populations are not isolated and differ in details of biology, (e.g., the eastern AW returns from summer aestivation sites to the alfalfa in the fall whereas the western AW does not return until spring). Entomologists now recognize that eastern and Egyptian AW are more closely related to each other than to western AW (Summers 1998). Comparison of isoenzymes

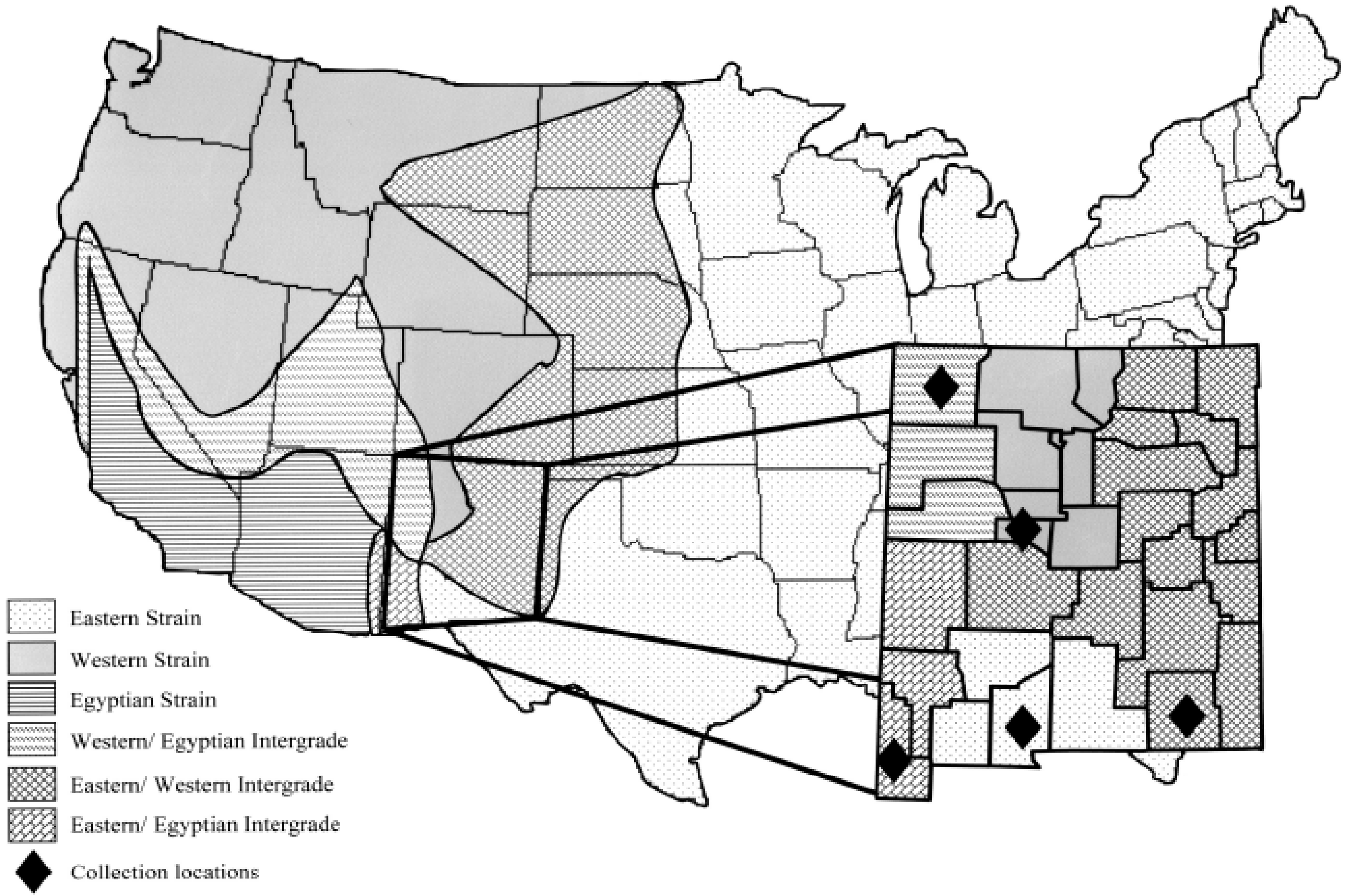

Fig. 1. Strain distribution of alfalfa weevil in the United States (adapted from Bundy et al. 2005)

(Hsiao 1993) tends to support this view and historically the AW is an arthropod that has a broad range of distribution, occurring from Scandinavia to Egypt and Iran. Therefore, it is not surprising that distinct biotypes exist (Radcliffe and Flanders 1998).

Life Cycle

In Montana and other U.S. locations above 40° to 42° N latitude, the western and eastern strains overwinter in the adult stage in leaf litter or around alfalfa crowns (Blodgett 1996, Radcliffe and Flanders 1998). In southerly locations below 38° to 40° N latitude, eggs, larvae, and pupae of the eastern and Egyptian strains can survive the relatively milder winters (Armbrust et al. 1969). Alfalfa weevil is univoltine (Helgesen and Cooley 1976) however there can be a distinct second generation in more southerly (below 40° N latitude) locations (Michelbacher 1943, White et al. 1969, Loan et al. 1983). Locations where AW is univoltine oviposition occurs during spring. The majority of oviposition occurs during fall and winter in locations with multivoltine populations (Berberet et al. 1980).

Adult-Egg: The adult AW is about four mm long, varying in color from brown to almost black with faint lighter markings on the abdomen (Summers 1998). Adult AW become active when daytime temperatures reach or exceed 15.5 °C with adult females being highly fecund laying upwards of 4000 eggs in a lifetime (Coles an Day 1977). Females chew holes in alfalfa stems and then insert clusters of 5-20 eggs (Litsinger and Apple 1973).

Egg-Larvae: After 7-14 days, eggs hatch into larvae which molt three times through four larval instars and attain a length of approximately nine mm at maturity. Mature larvae have a black head, green body, and a dorsal white stripe down the middle of the back with fainter parallel stripes on each side. Young AW larvae (first and second instar) are strongly phototrophic and migrate into alfalfa stem terminals shortly after hatching and feed on folded leaves. As the larva matures (third and fourth instar), it moves to fully formed leaves and feeds until pupation. Typically, AW larvae complete development in three to four weeks, but if prevailing temperatures are below average, development can take six weeks or longer to reach pupation. Larvae can usually be found in Montana alfalfa fields from mid-May to early July. Peak populations in Montana occur about the time of first cutting, in early- to mid-June (Blodgett 1996, Blodgett et al. 2000).

Larvae-Pupae-Adult: Fully developed larvae drop to the ground and construct a loose, lace-like cocoon to for pupation (Blodgett 1996). Adults emerge 10-12 days later, feed on alfalfa foliage for a short time before leaving the field to aestivate (Prokopy et al. 1967). Adults will also break aestivation and feed for a short time in fall before hibernating. Alfalfa weevils in northerly climates overwinter as adults and break hibernation in the spring to start the cycle again.

Damage

The AW is an annual pest of first-growth alfalfa (Flint and Clark 1981, Blodgett and Lenssen 2004). Under irrigated or high rainfall conditions, multiple hay crops can be harvested from an alfalfa field. First-growth alfalfa is defined as the first annual growth within any one field. Initial crop damage, which is not very visible, is caused by first and second instar larvae feeding inside developing alfalfa terminals. Mature third and fourth instars feed on more exposed plant leaves resulting in more visible damage (Radcliffe and Flanders 1998). Alfalfa weevil larvae cause indirect damage by feeding on and removing the highly digestible, cell solute portion of the alfalfa, which is intended for livestock, while leaving the less digestible more fibrous cell wall structures (Summers 1998). As AW larvae numbers increase, cell solute content and forage digestibility decrease (Berberet and McNew 1986).

Direct AW damage is caused by adults and larvae feeding on the growing tips, leaves, and buds of alfalfa which removes crop biomass and lowers harvested yield. Extensive feeding by AW can give alfalfa a frosted appearance (Blodgett 1996). If significant numbers of adults and/or larvae survive the harvest process, they can damage stems and crown buds, retarding regrowth (Fick 1976, Blodgett and Lenssen 2004). Severe damage can reduce plant vigor, resulting in diminished stand density and relatively lower yields in subsequent harvests (Fick and Liu 1976).

Methods of Control

Integrated pest management (IPM) is a pest control strategy which manages pests through a combination of control practices rather than reliance on a single tactic. Tactics include mechanical and physical devices, altering pest and host genetics, introduction and enhancement of biological control agents, improving management through cultural practices, and the use of pesticides. Many strategies are available for management of pests associated with alfalfa making it an ideal crop for an IPM program.

<u>Biological Control:</u> Biological control of the western AW was first attempted in Utah between 1911 and 1914 with the introduction of 10 parasitoid and egg predator species (Chamberlin 1924a,b). However, only *Bathyplectes curculionis* (Thompson), an ichneumonid endoparasitoid of AW larvae was established (Chamberlin 1926). *Bathyplectes curculionis* also parasitizes Egyptian AW yet introductions have not been effective due to the hot and dry habitats preferred by Egyptian AW (Summers 1998). Additional releases of *B. curculionis* have been made in California (1933-1936) (Michelbacher 1940a,b), Arizona and southern California (McDuffie 1941), and the northeastern U.S. (Puttler et al. 1961) with limited success (Summers 1998). *Bathyplectes curculionis* populations have been moderately effective at controlling the eastern AW (Radcliffe and Flanders 1998).

The National AW biological control project (1957 to 1980), released 12 exotic biological control species, in the northeastern U.S., of which six, all Hymenoptera, became established: three Ichneumonidae, *B. curculionis, B. anurus* (Thompson), *B. stenostigma* (Thompson), an Eulophidae, *Oomyzus incertus* (Ratzenburg), and two Braconidae, *(Microctonus aethiopoides* (Loan) and *M. colesi* (Drea) (Radcliffe and Flanders 1998).

In the eastern U.S., current key biological control agents are: 1) *B. curculionis*, 2) *B. anurus*, 3) *M. aethiopoides*, 4) *O. incertus*, and 5) *Zoophthora phytonomi* (Arthur) (Phycomycetes: Entomophthoraceae). *Zoophthora phytonomi* is a fungal pathogen that kills large numbers of AW. It was first identified from AW larvae in Ontario in 1973 (Radcliffe and Flanders 1998). Success of *M. aethiopoides*, which is considered to be the most important parasitoid of the eastern AW (Day 1981), is largely attributed to reduced insecticide rates used for potato leaf hopper (PLH) (*Empoasca fabae* Harris) management. Potato leaf hopper and the AW often occur temporally and spatially in late spring and early summer in the northeastern US (Hower and Davis 1984). Insecticides, applied to manage PLH, often disrupt populations of *M. aethiopoides,* a parasitoid of the adult AW. Subsequently, Hower and Davis (1984) determined that the pupal stage of *M. aethiopoides* was far less susceptible to insecticides than the adult wasp and developed an insecticide application strategy for leafhoppers using lower than recommended insecticides rates. These lower rates, while producing adequate leafhopper suppression, minimized *M. aethoipoides* mortality.

Biological agents that parasitize AW larvae and adults have reduced populations below economic thresholds in the eastern U.S. (Yeargan 1985). Success depends on upon ecological adaptation of the established biological control agents to their particular habitats and to a lesser extent on their biological adaptation to indigenous AW strains (Hsiao 1993, 1996). The impact of biological control has been marginal in the western U.S. (Al Ayedh et al. 1996, Radcliffe and Flanders 1998) possibly due to relatively dry and/or cold conditions limiting is adaptability to western AW habitats.

<u>Insecticides:</u> Insecticides are an integral component of an AW IPM program, and in some situations, the only effective option available to producers to minimize economic losses. Insecticides do have negative impacts relative to target and non-target arthropods (e.g., disruption of natural enemy populations, resistance, and secondary pest outbreaks). These impacts can be moderated by using economic thresholds for treatment guidelines,

use of selective insecticides when available, proper timing of application (e.g., at peak or damaging pest stages), and application rate (Summers 1998).

Summers and Cothran (1972a,b) found that Egyptian AW could be managed effectively in most years by a single, early winter application of carbofuran timed to coincide with adult AW returning to fields following their summer aestivation but prior to ovipositon. Application timing had no negative impacts on beneficial *Nabis* spp., *Orius* spp., *Crysopa* spp. and Coccinellidae (Summers and Cothran 1972b). Davis (1970) also recorded that early season treatments with carbofuran had no negative impacts on AW larval parasitoid *B. curculionis*. Roberts et al. (1987) demonstrated that a 12 to 21 m insecticide swath applied, in the fall, around the perimeter of an alfalfa field immediately after all adults had returned from summer aestivation was effective in controlling AW.

<u>Cultural Practices:</u> Harvesting has been used alone and in combination with other strategies to manage numerous arthropod pests. Early harvest of the first alfalfa crop was recommended as early as 1918 in Utah to reduce losses from AW (Hagan 1918). Casagrande and Stehr (1973) observed 100, 73, and 53% mortality of AW larvae in Michigan alfalfa fields harvested prior to, at, and after the larval peak, respectively. Many larvae were killed by desiccation or starvation and the eggs, which are normally laid in the stems, were removed along with the forage. Timing is crucial however, since cutting before peak oviposition resulted in injury to the second crop regrowth by larvae hatching from eggs that remained in the stubble below cutter bar height. Similar results were obtained in New York (Koehler and Gyrsco 1989) and Alberta (Harper et al. 1990). Blodgett et al. (2000) reported early harvest followed by raking reduced AW larval

numbers in post harvest stubble by 43% compared to early harvest alone. Raking, if undertaken at less than 30% plant moisture, can result in 60% crop leaf loss which comprises 70% of the nutritive value of alfalfa hay (Cash and Bowman, 1993). Essig and Michelbacher (1933) also reported early spring harvest can remove the majority of *H. postica* eggs and young larvae, thus reducing subsequent damage. However, repeated early harvesting of regrowth typically has a negative impact on yield and stand longevity (Cash and Bowman 1993).

Schoner and Norris (1975) noted that larvae of the Egyptian AW, that were not mechanically killed by harvesting, were concentrated in the alfalfa windrow and made their way to the underside where they were protected from excessive heat and drying. If baling the hay was delayed, larvae could continue feeding on regrowth under the windrow severely weakening alfalfa plants causing subsequent yield losses (Schoner and Norris 1975). Blodgett and Lenssen (2004) reported similar findings when swath row dry matter approximated 40%; approximately 90% of AW larvae were located either within or under the swath row. As the swath row dried and percent dry matter increased, AW larvae migrated out of swaths to location between rows to feed.

Flaming with liquid propane to burn alfalfa plant biomass and expose AW to harsh environmental conditions has been used successfully to control AW (Hanson and Simpson 1969, Scheibner 1969, Harris et al. 1971, Hower 1975). This tactic also has the added advantage of killing many weeds (Hanson and Simpson 1969). Although effective, this technique was generally abandoned in the 1970s when the price of petroleum products rose beyond the costs of effectiveness of the method (Summers 1998).

Host Plant Resistance: Host plant resistance is a major component of many IPM programs. The greatest success in developing insect resistant alfalfa cultivars has been against the pea aphid, *A. pisum* (Harris), blue alfalfa aphid, *A. kondoi* (Shinji), and the spotted alfalfa aphid, *T. maculate* (Buckton) (Neilson and Lehman 1980, Manglitz and Ratcliffe 1988, Sorensen et al. 1988). Multiple cultivars with AW resistance (‘Team’, ‘Arc’, ‘Liberty’ ‘Weevilchek’ and ‘Cimmaron SR’) have been released in the U.S. over the past 25 years. Currently, available cultivars do not have sufficient AW resistance to be the single management tactic (Blodgett et al. 2000).

Livestock Grazing: Livestock producers often rely on fall regrowth of alfalfa as a source for fall and winter grazing. Fall regrowth is also utilized as overwintering habitat by the adult AW (Dively 1970, Dowdy et al. 1986), which hibernates in leaf litter or around plant crowns (Blodgett 1996). Dowdy et al. (1992) reported a 67% reduction in AW eggs and 25% reducing in spring larval numbers in grazed compared to non-grazed plots in Oklahoma. In northern latitudes, temperatures restrict early spring AW activity oviposition (Blodgett et al. 2000). Therefore, these researchers speculated that winter/spring grazing would have no impact on spring AW larval populations. Spring populations that damage first cut alfalfa in northern latitudes hatch from eggs oviposited that spring (Blodgett 1996). Goosey et al. (2004) reported winter and spring sheep grazing in Montana reduced AW larvae 40-70% in grazed vs. non-grazed plots and kept populations below the economic threshold without impacting first cut alfalfa quality or quantity.

Alfalfa Grazing

Grazing alfalfa stands with sheep is not a common practice in the U.S. (Schlegel et al. 2000). However, fall regrowth of alfalfa can be used as suitable pasture without negatively impacting harvest quantity or quality (Mitchell et al. 1991, Goosey et al. 2004). Since alfalfa stands are not maintained under continuous stocking (Van Keuren and Matches 1998), a rotational stocking system must be implemented. The advantages to these types of rotational grazing systems are recycled animal waste nutrients, improved animal health, consumer preference, sustainability of agricultural systems, and on-farm economic benefits.

Economically, incorporating some level of alfalfa grazing into a production system is beneficial. Marten et al. (1987) studied whether palatability differences among alfalfa and three nonbloat-inducing alternative legumes would influence performance of grazing heifers (*B. taurus*). Mean average daily gains during two years of study were 0.67, 0.81, 0.80, and 0.42 kg for alfalfa, birdsfoot trefoil, sainfoin, and cicer milkvetch, respectively. Heifer production per hectare was influenced more by daily gains than by legume carrying capacity and daily gains.

In an additional study, Marten et al. 1990 reported the opposite regarding lamb production. Lamb production per hectare was influenced more by legume carrying capacity than by daily gains. Lambs were confined to cicer milkvetch, alfalfa, birdsfoot trefoil or red clover. Mean average daily gains were 0.22, 0.23, 0.22, and 0.22 kg for alfalfa, birdsfoot trefoil, red clover, and cicer milkvetch, respectively. Researchers concluded that legume nutritive value variation had no consistent significance for lamb performance.

McClure et al. (1994) compared rotational grazing of orchardgrass, ryegrass, or alfalfa to an all-concentrate diet fed in drylot. Performance of lambs grazing alfalfa approached that recorded for the drylot diet and was better then either grass forage. Better performance was attributed to more crude protein (CP) and less neutral detergent fiber (NDF) and acid detergent fiber (ADF) in alfalfa; indicating that rotational grazing systems offered economic benefits to production by allowing sheep to harvest their own forage.

Additional benefits such as pest insect and weed management make strategic sheep grazing an attractive alternative to traditional practices. Hatfield et al. (2007a). recorded sheep grazing reduced wheat stem sawfly populations below no-input control, tilled, and burned plots. In the same study, sheep grazing also reduced weed density below that recorded in control, tilled, or burned treatments (Hatfield et al. 2007b). Similar results were reported by Goosey et al. (2005).

Degree Days (DD)

Temperature controls the developmental rate of many organisms. Plants (Mooney and Ehleringer 1997) and invertebrate animals, including insects (Romoser and Stoffolano 1998), require a certain amount of heat to develop from one point in their life cycles to another. This measure of accumulated heat is known as physiological time and theoretically provides a common reference for the development of poikilothermic organisms. The amount of heat required to complete an ectotherm’s development does not vary; the combination of temperature (between thresholds) and time will always be the same (Zalom et al. 1983). Physiological time is often expressed and approximated in degree day units.

Using DD as predictors for initiation and cessation of arthropod IPM programs is a common practice (AliNiazee 1976, Sevacherian et al. 1977, Peterson and Meyer 1995). Sevecherian et al. (1977) described a method of heat accumulation using only daily maximum and minimum temperatures. The procedure was used to predict when 50-70% of the *Lygus* bug nymph population in safflower would be in the third to fifth stages. This procedure enabled growers to apply a single area wide insecticide treatment to their safflower fields before *Lygus* dispersed to other crops. The treatment was attributed to largely eliminating the *Lygus* threat to cotton on the west side of the San Joaquin Valley.

Peterson and Meyer (1995) present a technique for determining the dates of AW egg eclosion by correlating DD with calendar dates. They used historical climate data to calculate the median date a DD was reached. This technique gave dates when egg hatch was likely to occur throughout the north central U.S. Their reason for this was to augment existing decision criteria for initiation sampling programs for AW and subsequent management recommendations.

Harcourt (1981) reports cumulative DD requirements for AW development at 155 (oviposition), 197 (1^{st} instar), 239 (2^{nd} instar), 285 (3^{rd} instar), 343 (4^{th} instar), 382 (prepupa) and 462 (pupa) (base 9 °C). Guppy et al. (1974) reports AW peak occurrences (base 10 °C) at 109 DD (1^{st} instar), 148 DD (2^{nd} instar), 186 DD (3^{rd} instar), and 227 (4^{th} instar). Blodgett (1996) reports peak DD values (base 9 °C) in Montana at 172 (1^{st} instar), 236 (2^{nd} instar) 306 (4^{th} instar), and 472 (Adult emergence).

Summary

Alfalfa is produced on approximately 650 thousand ha in Montana (NASS 2008) and is the foremost forage crop in many high, semiarid, intermountain states (Bailey 1994, Al Ayedh et al. 1996). Two biological stressors (insects and weeds) combined with poor field management are primarily responsible for reduced alfalfa production (Latheef et al. 1988). In the U.S. alone, arthropods cause an estimated $260 million loss to alfalfa (Leath et al. 1988). The AW is considered the most damaging alfalfa phytophagous pest in the U.S. (Blodgett et al. 2000).

Tolerant alfalfa cultivars often do not provide sufficient protection from AW to justify their use (Blodgett et al. 2000). Biological agents that parasitize AW larvae and adults have reduced populations below economic thresholds in the eastern U.S. (Yeargan 1985). However, their impact has been marginal in the western U.S. (Al Ayedh et al. 1996, Radcliffe and Flanders 1998) possibly due to relatively dry and/or cold conditions. Insecticides that target larvae were used on approximately 34% of the alfalfa acreage in the U.S. during 1994 (Bailey 1994). Insecticides are an integral IPM tool and under certain circumstances, the only viable management option. However, insecticide use is costly and can disrupt natural enemy populations causing secondary pest outbreaks (Summers 1998).

Cultural management of AW includes late fall (Dowdy et al. 1992) and early spring harvest (Essig and Michelbacher 1933, Harper et al. 1990), burning (Hanson and Simpson 1969, Harris et al. 1971, Hower 1975), early harvest with raking (Blodgett et al. 2000), and grazing (Dowdy et al. 1992, Goosey et al. 2004). Late fall harvest as practiced by Dowdy et al. (1992) reduced AW eggs by 55% in fall regrowth but: 1) did not reduce spring larval numbers and 2) is not practical in Montana because AW are not actively ovipositing during fall months. Cold northern U.S. temperatures restrict later fall through early spring AW activity and oviposition (Blodgett et al. 2000) resulting in only one generation per year. In Montana, larvae that damage the first cutting of alfalfa hatch from eggs oviposited that spring (Blodgett 1996).

Burning fall regrowth, during winter months, has been used effectively to keep AW larvae below ET in Pennsylvania, Maryland, and Colorado (Hanson and Simpson 1969, Harris et al. 1971, Hower 1975) but was generally abandoned in the 1970s do to rising petroleum product costs (Summers 1998).

Blodgett et al. (2000) reported early harvest followed by raking reduced AW larvae in post harvest stubble by 43% compared to early harvest alone. Raking, if undertaken at less than 30% plant moisture, can result in 60% crop leaf loss and leafs comprise 70% of the nutritive value (Cash and Bowman 1993). Essig and Michelbacher (1933) also reported early spring harvest can remove the majority of AW eggs and young larvae, thus reducing subsequent damage. Dowdy et al. (1992) reported a 67% reduction in AW eggs and 25% reduction in spring larvae in grazed compared to non-grazed plots in Oklahoma. Goosey et al. (2004) reported winter and spring sheep grazing, in Montana, reduced AW larvae 40-70% in grazed vs. non-grazed plots and kept populations below the economic threshold without impacting first cut alfalfa quality or quantity.

Insecticides and early harvest with raking (Blodgett et al. 2000) are both remedial measures that require AW to reach the economic threshold prior to implementation.

Sheep grazing is preventative and causes a disruption of AW habitat and life cycle. However, the application of sheep grazing is limited by the variability of environments under which alfalfa is grown in Montana. For producers to use sheep grazing, the system timing needs to be expressed in units that are universal across environments. Alfalfa weevil life cycle events vary substantially across Montana when based on calendar dates. However, prediction of these same events with DD establishes a universal calendar based on accumulated temperatures (Fig. 2). This universal calendar allows producers to apply management practices at optimal times increasing their overall effectiveness

Using DD to initiate IPM programs is a common practice and on-line websites make calculations relatively easy. Grazing is emerging as a legitimate IPM tactic (Walker 1992, Olson 1994, Clark 2004, Goosey et al. 2004, 2005; Hatfield et al. 2007a,b) however no published literature exist expressing DD for initiation and cessation of IPM based grazing systems.

The main question this research set out to answer was can this grazing system be expressed as a DD predictive model? Therefore the objective of this research was to develop a model by identifying sheep stocking rates and associated DD which keep AW equal to or below the economic threshold (ET) of 1.5 larvae/stem but do not reduce alfalfa growth rates.

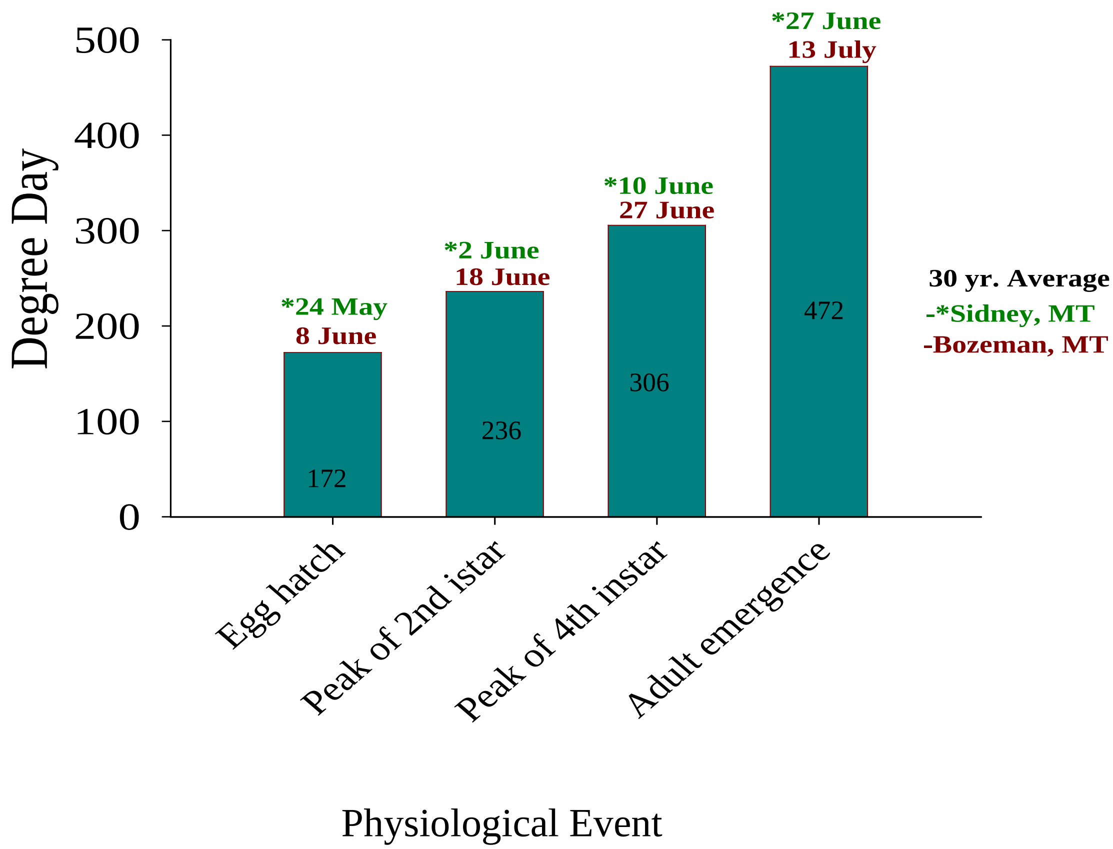

Fig. 2. Alfalfa weevil physiological life cycle events expressed as DD and calendar dates (30 year averages) at Sidney and Bozeman, MT (Blodgett 1996).

Research hypotheses:

Alfalfa weevil and growth rate hypotheses were as follows.

Alfalfa Weevil

H_o: Sheep grazing as an IPM tactic against AW can not be modeled in DD units

H_a: A relationship does exist and can be modeled in DD units.

Alfalfa Plant Growth Rates

H_o: The AW modeled grazing system will not reduce alfalfa growth rates.

H_a: The AW modeled grazing system will reduce alfalfa growth rates.

MATERIALS AND METHODS

Site Description

Research was conducted during 2 study years, 2008 and 2009, 2.4 km east of Lavina in central Montana (N 46° 17.401, W 108° 54.811, Elevation: 1039 m) in a 2 (2008) or 3 (2009) yr old, 10 ha field of 'Magnum V' alfalfa. The field soil type is a clay loam and was flood irrigated both study years. The alfalfa crop, since seeding in 2005, has not been treated chemically with, insecticides, fungicides, fertilizers. The experimental 10 ha field was located within a larger (21 ha) cropped area. The 11 ha not cropped to alfalfa was seeded annually each spring to corn and sugar beets. Each spring, sugar beets were seeded along with a granular insecticide Counter 20 CR to reduce sugarbeet root maggot damage. During non-cropped periods, this area was fallowed with tractor and plow after fall harvest and repeatedly until spring seeding the following year. Repeated tillage reduced above ground biomass to minimal amounts and so sheep spent their time, during the grazing period, on the 10 ha experimental field. Cattle (*B. tarus*) grazed the experimental field each fall from 15 October to 15 November 2008 and 15 October to 22 November 2009 at stocking rates of 128 to 136 cow d per ha.

Plot Description

The experimental design was a randomized complete block (3 blocks) with plot as the experimental unit. A four m^2 non-grazed plot was randomly established in each of three blocks prior to sheep being introduced to the experimental field. Non-grazed plots were fenced on 15 February 2008 and 8 January 2009. Grazed plots were established weekly, in the same field (one per block) by fencing off four m^2 portions of the experimental field during the sheep grazing period (Figs. 3 and 4). Fenced plots or 'exclosures' were established to keep sheep from grazing within the fenced area. Exclosures established in 2009 did not occur on the exact same locations as in 2008. Rather exclosures were nested within year. Sheep had free access to the entire field, including water, with the exception of the exclosures. This fencing process, which continued until sheep were removed from the experimental field, established grazing treatments with specific stocking rates and DD.

In both 2008 and 2009, seven treatments were established: Non-grazed (NG), Grazed 1 (G1), Grazed 2 (G2), Grazed 3 (G3), Grazed 4 (G4), Grazed 5 (G5) and Grazed 6 (G6). The number indicates the week that grazing each treatment was established. In both study years, sheep were removed from the experimental field prior to establishing the G5 and G6 treatments (Table 1). These treatments were grazed by sheep to 11 May 2008 and 15 May 2009 and had additional grazing simulated using a Stihl Model FS 45-Z Autocut weed eater (Stihl Inc., Norfolk, VA) by clipping alfalfa plants in treatment plots to less than 5 cm in height. Clipped forage was then raked and discarded away from the exclosures.

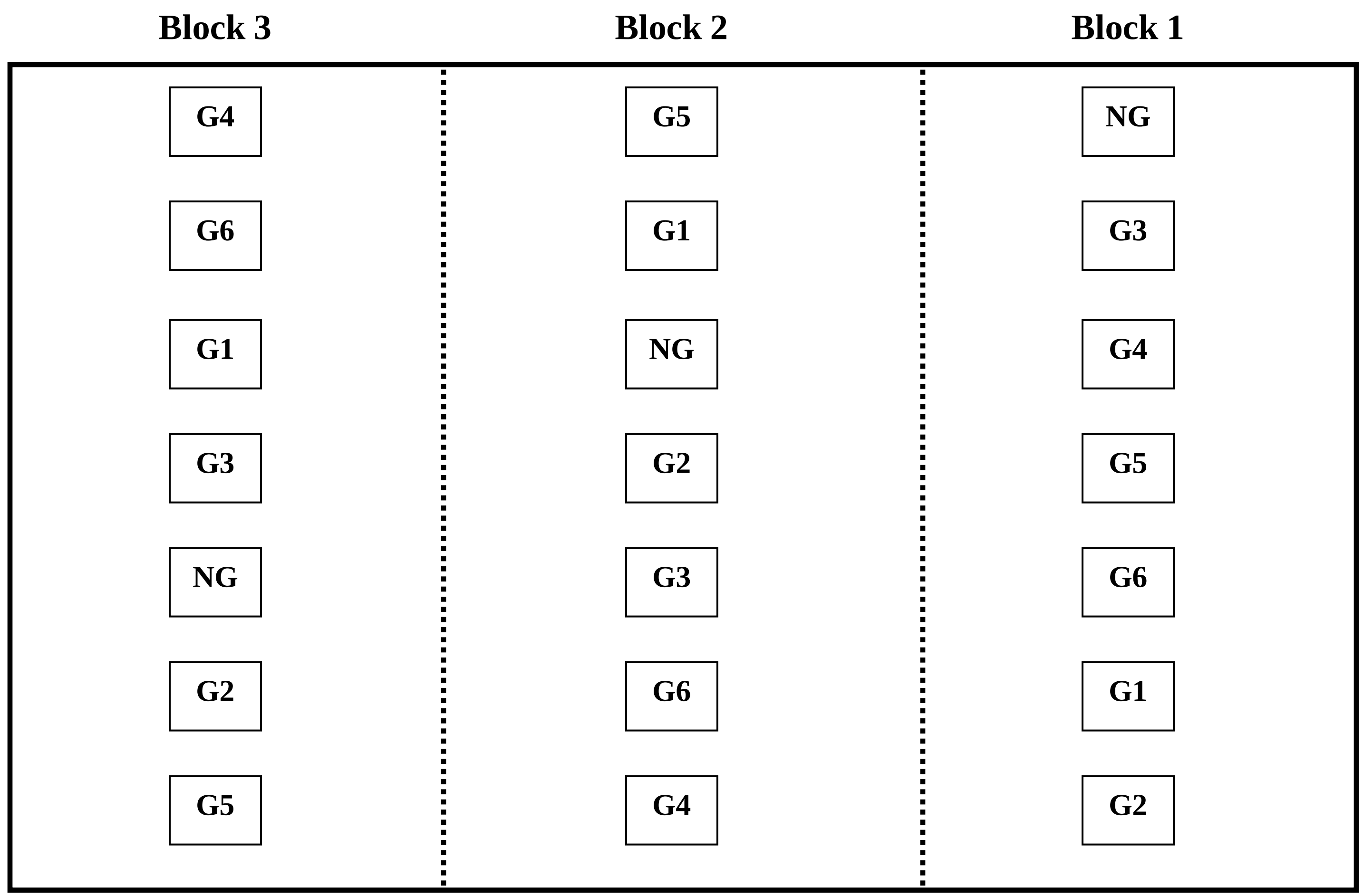

Fig. 3. Plot map of 2008 treatment arrangement in the experimental field (10 ha) near Lavina, MT where G1 through G6 denote grazing treatment and NG denotes a non-grazed no input control.

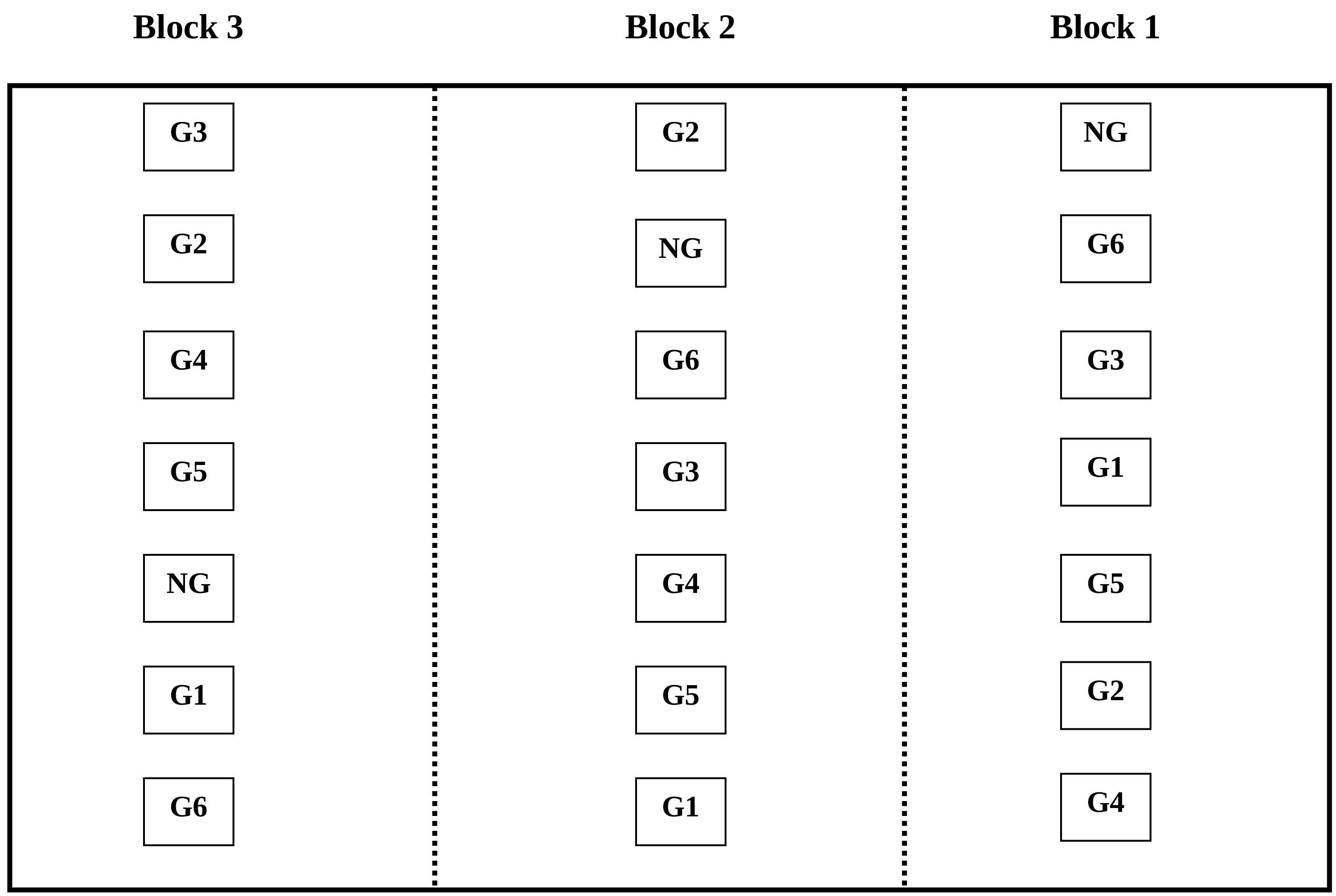

Fig. 4. Plot map of 2009 treatment arrangement in the experimental field (10 ha) near Lavina, MT where G1 through G6 denote grazing treatment and NG denotes a non-grazed no input control.

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Table 1. A timeline of grazing, treatment establishment, stocking rate, and DD 2.4 km east of Lavina, MT

		2008			2009		
	Experimental Event	Date	Stocking Rate[w]	DD[x]	Date	Stocking Rate[w]	DD[x]
NG	Non-grazed fenced[t]	15 Feb	0	2.0	10 Jan	0	0.8
---	Sheep grazing begins	7 April	0	34.1	16 April	0	63.4
G1	1st treatment fenced[t]	14 April	80	34.1	21 April	86	83.2
G2	2nd treatment fenced[t]	22 April	171	41.7	1 May	257	93.3
G3	3rd treatment fenced[t]	29 April	251	57.7	6 May	343	106.7
G4	4th treatment fenced[t]	6 May	355	75.0	15 May	497	125.4
---	Sheep grazing ends	11 May	440	85.3	15 May	497	125.4
G5	5th treatment[t,y]	13 May	475 (34[z])	89.2	20 May	583 (86[z])	159.7
G6	6th treatment[t,y]	20 May	595 (154[z])	147.4	27 May	703 (206[z])	200.5
---	Harvest Samples	23 June	---	314.4	24 June	---	374.4

[t]A grazed treatment consists of 3 fenced plots (4 m^2) in a RCB design.
[w]Stocking rate calculated: *[Sheep numbers(head) * grazing duration (days)/Field size (ha)]*
[x]DD calculated using the single sine method with AW lower (9°C) and upper (31°C) development thresholds.
[y] Additional grazing simulated both study years with Stihl Model FS 45-Z Autocut weed eater.
[z]Simulated additional stocking rate was calculated by using the ending sheep numbers of the respective year.

All fences, once established, remained standing throughout the grazing period. Rambouillet ewes were introduced to the experimental field on 16 April of each study year. In 2008, 240 ewes grazed from 7 April to 2 May. An additional 120 ewes were added on 3 May, totaling 360, which grazed until 11 May. In 2009, 360 ewes grazed from 16 April to 15 May. Stocking rates were unique to each treatment of each study year (Table 1) with total stocking rates of 595 (2008) and 703 (2009) sheep d/ha. Stocking rates were calculated as: *[(Sheep numbers * d)/ha]* where *d* = days spent grazing. Simulated stocking rates of G5 and G6 were calculated by the same equation. For example 360 ewes grazed from 16 April to 15 May 2009 equaling a stocking rate of 514 sheep d/ha. These treatments during 2009 experienced 514 sheep d/ha from real sheep grazing and 86 and 206 sheep d/ha from simulated grazing (Table 1). The simulated stocking rates were calculated with the assumption that sheep numbers (i.e., 360 ewes) remained constant if grazing continued during the entire experimental period.

Degree Day Calculations

Temperature and relative humidity data were collected, from 15 February to 23 June 2008 and 10 January to 24 June 2009, one m above the soil surface using a HOBO® H8 Pro Series (Onset, Pocasset, Massachusetts) Temp/RH data logger. The methods of Sevacherian (1977) were used to calculate on-site DD with the exception that a 30 min, instead of 12 hr, interval was used to provide the greatest calculation accuracy (Raworth 1994, Brewer and Hoff 2002). On-site DD were calculated by fitting a straight line between successive temperature readings and summing the area between the line and AW lower development threshold Sevecherian (1977). The DD calculation process was completed using customized Microsoft Excel® spreadsheet (Microsoft, Redmond, Washington). Near-site DD were calculated using an on-line calculator (Coop 2002), which uses regional temperature data to estimate DD. Alfalfa weevil development thresholds used to calculate both on-site and near-site DD were: Lower = 9 °C; Upper = 31°C (Harcourt 1981). Regional temperatures data was accessed from the 'ROUNDUP KRPX NCAWOS' weather station (46.4750 °N; 108.5431 °W; 1,064 m) approximately 32 km from the Lavina study site. Both on-site and near-site calculation data were used to run separate regressions of AW and relative growth rate (RGR) data to generate the most accurate models.

Sample Size Equation

The sample size equation (Southwood 1978) was used to calculate statistically appropriate sample sizes of alfalfa stem biomass and AW larval numbers. Data collection of tiller biomass was initiated on the day each grazing treatment was established. For example, on 14 April 2008 samples were only collected from the NG and G1 treatments because they were the only ones established. However, the following sampling date (22 April), the G2 treatment was established and so sampling encompassed the NG, G1, and G2 treatments. This process continued until all grazing treatments were established at which time all treatments were sampled on each sampling date (Table 1).

Alfalfa weevil larval sampling began after all grazing treatments (NG and G1 to G6) were established. Samples were taken from each treatment weekly over 4 sampling dates during both study years: 2008 (date 1 = 3 June, date 2 = 10 June, date 3 = 17 June, date 4 = 24 June) 2009 (date 1 = 3 June, date 2 = 10 June, date 3 = 17 June, date 4 = 24 June).

The sample size equation $N = S^2 / mean^2 * E$ (N = sample size, S^2 = sample variance, $mean^2$ = sample mean squared, E = 0.15, a predetermined level of accuracy) requires the inclusion of both variance and mean values. Initially on sampling date 1, a preset number of 10 alfalfa stems/plot (30 stems/treatment) were collected to determine treatment variance and mean values for each treatment variables. These data were entered into the equation for each variable and used to calculate appropriate sample sizes for the second sampling date. Once collected and calculated, data from the second sample date were used to calculate appropriate and specific treatment sample sizes for the third date. This process continued throughout the entire sampling period of both study years and was conducted for AW and biomass sampling.

Treatment Biomass and Relative Growth Rate (RGR)

Treatment RGR was determined from weekly random stem collections. Alfalfa stems were clipped and bagged weekly from each plot, taken to the MSU campus, dried for 72 h at the Plant Growth Center on the MSU campus in a plant drying room set at 48°C. Samples were weighted on a Mettler BB2400 scale (Mettler Inc., Hightstown, NJ.) to determine dry matter (DM) biomass expressed in grams (g). Plotting natural log dry biomass vs. DD (physiological time), for each treatment yielded stocking rate adjusted linear RGR values. The slope of each line represents treatment RGR. Sample sizes were determined by the sample size equation.

Alfalfa Growth and Regrowth

Yield was determined by hand harvesting one 0.5 m^2 quadrat per plot by cutting and bagging all above ground biomass. Forage samples were dried at 48°C for 72 h to determine DM yield. Fifteen stems were collected at harvest and bagged separately for nutrient analyses at the MSU Oscar Thomas Nutrition Center. Samples were oven dried and ground to pass a 1.0 mm sieve using a Wiley Mill (Thomas Scientific, Swedesboro, NJ). Crude protein (CP) was determined using the AOAC Leco combustion method 990.03 (AOAC International 1999) and acid (ADF) and neutral (NDF) detergent fibers were calculated using methods of Van Soest et al. (1991). Total digestible nutrients (TDN), as a percent of DM, was calculated as: *TDN (% DM) = [82.38 – (0.7515 * ADF%)]* (Shewmaker et al. 2008)

Mean stage by weight (MSW) values were calculated from mean stage by count (MSC) values where *MSW=0.456 + 1.153 * MSC* (Fick and Mueller 1989). MSC is the average of the individual stage categories present in the herbage sample, weighted for the number of stems at each stage. To determine MSC, 15 stems per plot were visually inspected to determine growth stage at harvest using the criteria of Fick and Mueller (1989).

Alfalfa Weevil

Mean AW larval numbers were determined weekly from each plot by using the shake bucket method (Hoff et al. 2002) which more accurately detects smaller larvae compared to sweep net sampling. Larval sampling dates for 2008 were June 3, 10, 17, and 23 June. Sampling dates for 2009 were June 3, 10, 17, and 24. Sample sizes were determined weekly from the sample size equation.

Statistical Analyses

Analysis of Variance Assumptions

Linearity of the regression function was assessed by plotting the residuals vs. the independent (X) data. Homogeneity of variances for selected variables was determined by plotting residual vs. predicted values and by analyzing the absolute value of the residuals as the dependent variable and block and treatment as class variables using PROC MIXED (SAS 2002). Independence of error terms were assessed by plotting the residuals vs. time. The distribution of data was tested to be normal using normal probability plots where data was considered normally distributed when residual vs. Z-score plots were linear.

Relative Growth Rate

Plant biomass was transformed using the natural logarithm function. These transformed values were fitted against treatment DD and linear regressions were calculated for each grazing treatment. The slope coefficient of each regression analysis represents individual RGR values for each grazing treatment. Proc GLM was used to test the interaction between grazing treatment and DD accumulations, both on-site and near-site. A significant interaction indicates that not all grazing treatment slope coefficients are equal. The GLM procedures were used to determine treatment slope differences from zero and contrasts were calculated to compare treatment slope coefficients (SAS 2002).

Alfalfa Growth and Regrowth

The MIXED procedures (SAS 2002) were used to compute least squared means to make comparisons of grazing treatment yield, DM, CP, ADF, NDF and TDN. Year by treatment interactions were tested using the GLM procedures (SAS 2002).

Alfalfa Weevil Model

Grazing treatment data that were entered in the regression model were collected from grazing treatments meeting two criteria. Criteria one was keeping AW larvae equal to or below the ET of 1.5 larvae/stem and criteria two was not reducing yield. First, AW larval numbers, by treatment, were plotted vs. sample date. Treatments that satisfy criteria one are those stocking rates which kept AW larvae below the ET of 1.5 AW larvae/stem (Blodgett et al. 1996). Secondly, PROC Mixed procedures of SAS (SAS 2002) were used to compute differences in yield ($p < 0.05$) between grazing treatments selected by criteria 1. Data that met the selection criteria were tested for homogeneity of slope using PROC GLM to produce slope contrasts, a preliminary step in the analysis of covariance. The predicative model was built using PROC REG procedures of SAS by fitting simple linear regressions of biweekly AW vs. both on-site and near-site DD.

The best fit of AW larval data was determined by comparing the coefficient (R^2) and adjusted coefficient (Adj. R^2) of determination sum of squares (SS), root mean square error (RMSE), coefficient of variation (CV), and prediction sum of squares (PRESS) values of the on-site and near-site analyses. The model which maximized R^2 and minimized SS, RMSE, CV, and PRESS values was considered to be the most accurate.

RESULTS

Alfalfa Weevil

During both 2008 and 2009 grazing treatments G3, G4, G5, and G6 kept AW larvae below the numerically selected ET of 1.5 larvae per stem (Blodgett 1996) and therefore met the first selection criteria (Table 2; Figs. 5 and 6). Yield measurements of G3, G4, G5, and G6 were then subjected to a mean comparison with results indicating that yields of G3, G4, and G5 did not differ ($P > 0.17$) while the mean yield of G6 was lower ($P < 0.03$) (Table 2). Therefore treatments G3, G4, and G5 but not G6 met the second selection criteria (Table 2) and were used to develop the degree day based regression model. Visual analysis of plots confirmed the model assumptions of regression function linearity and independence and normality of error term variances. The assumption of homogeneity of variance was met across block (F = 0.84; df = 2, 67; $P = 0.4378$) and treatment (F = 0.75; df = 2, 67; $P = 0.4747$). From this point forward when 'modeled grazing treatments' is referenced, this indicates the pooled data from grazing treatments G3, G4, and G5.

No treatment by year interaction was detected (F = 0.06; df = 2, 23; $P = 0.9396$) and therefore modeled treatment data was combined across year. Modeled grazing treatment slope coefficients were contrasted and found to be equal for on-site (F = 0.00; df = 2, 23; $P = 0.9985$) and near-site (F = 0.01; df = 2, 23; $P = 0.9934$) analyses so modeled treatment data were combined into one regression analysis specific to temperature data collection site (i.e., on-site or near-site). Modeled grazing treatment AW numbers were fitted against both on-site and near-site DD and linear regressions were computed for

Table 2. Mean 2008 and 2009 treatment AW larvae/stem, yields, and treatments included in the regression model

Treatment	Larvae/stem 2008[x]	AW larvae/stem 2009[x]	Yield 2008[x] MT/ha	Yield 2009[x] MT/ha	Modeled TRTS
NG	2.1	3.0			
G1	1.6	2.9			
G2	1.8	2.5			
G3	1.1[y]	1.5[y]	3.5a[z]	3.2a[z]	X
G4	0.9[y]	1.5[y]	3.0a[z]	3.4a[z]	X
G5	0.8[y]	1.5[y]	2.8a[z]	2.7a[z]	X
G6	0.7[y]	1.3[y]	1.7b	1.3b	
S.E.	NA	NA	0.5	0.4	NA
P-value	NA	NA	<0.01	<0.01	NA

Means in columns followed by the same letter grouping are not significantly different (*P*>0.05); least squared means/least significant difference (Proc Mixed; SAS 2002).

[x]23 June 2008; 24 June 2009.

[y]Grazing treatments meeting 1st selection criteria : keeping AW larvae below the Montana economic threshold of 1.5 larvae/stem (Blodgett et al. 1996).

[z]Grazing treatments meeting 2nd selection criteria: no differences in yield; means in columns followed by the same letter grouping are not significantly different (*P*>0.05); least significant difference (Proc Mixed; SAS 2002).

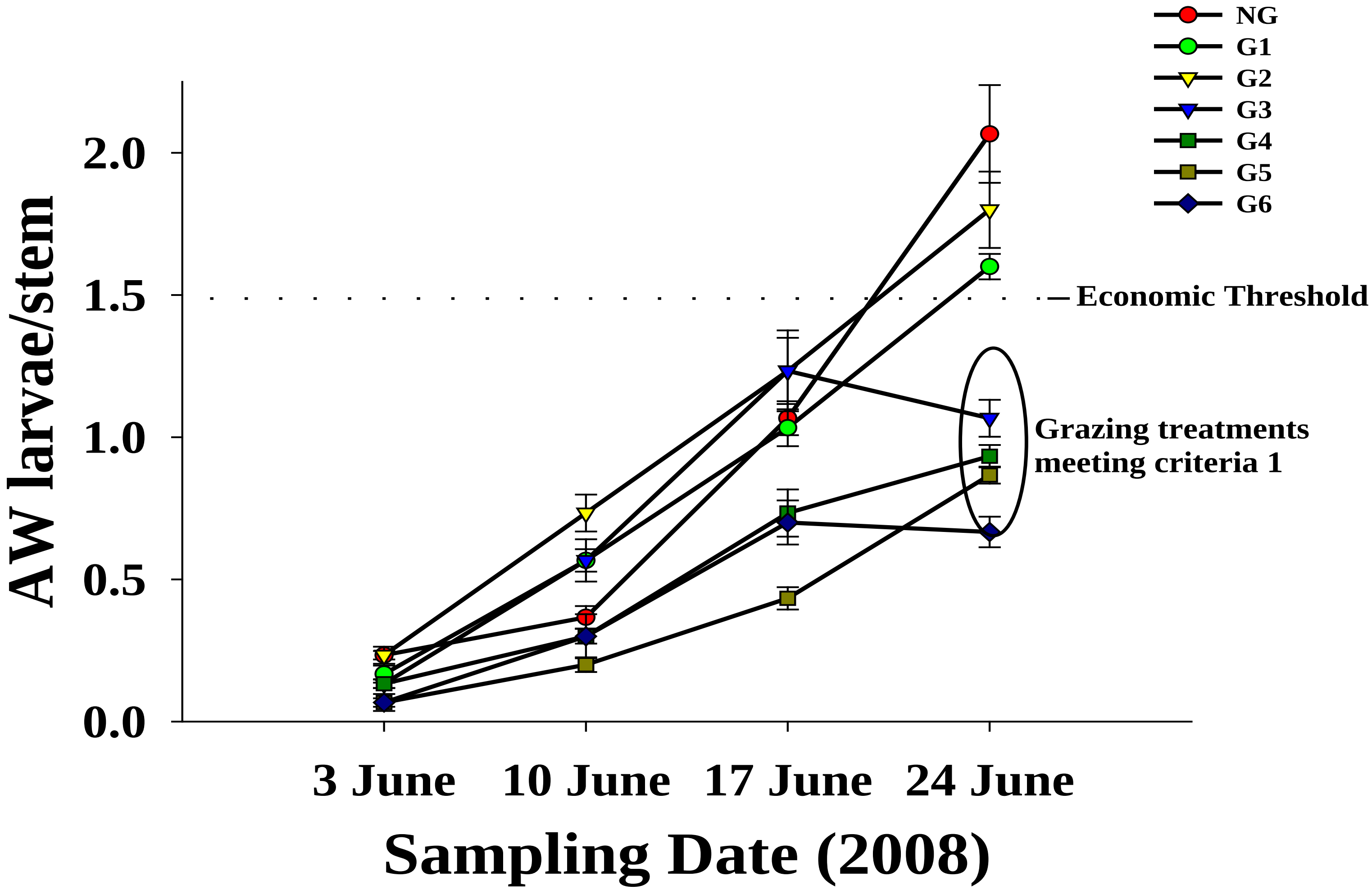

Fig. 5. Results of larval alfalfa weevil shake bucket samples taken across four sampling dates during 2008 in one non-grazed and six sheep grazed plots.

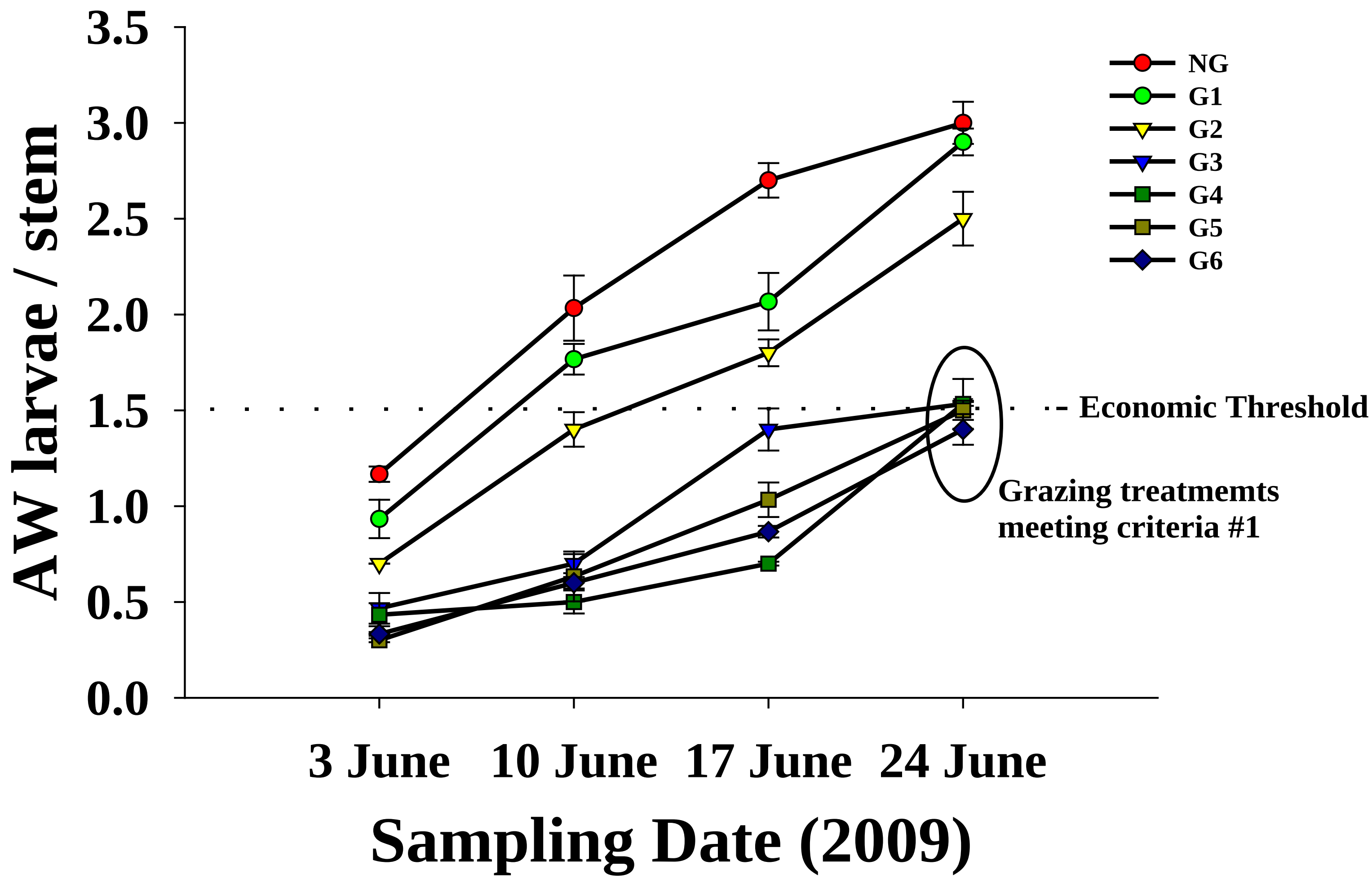

Fig. 6. Results of larval alfalfa weevil shake bucket samples taken across four sampling dates during 2009 in one non-grazed and six sheep grazed plots.

each. The purpose of this comparison was to determine which temperature data, either on-site or near-site, and subsequent degree day calculations produced the best fit and most accurate model. The best fit and most accurate model will maximize R^2 and Adj. R^2 while minimizing PRESS, SS, CV, and RMSE (Table 3). The near-site model was selected, the slope coefficient differed from zero (F = 105.24; df = 1, 23; $P < 0.0001$) and the resulting simple regression model is presented in Fig. 7.

Analysis of all AW larval data collected from each treatment over two years of study indicates that increased stocking rate and DD decrease AW larvae (F = 44.65; df = 1, 167; $P < 0.0001$). This suggests that as spring grazing proceeds and DD accumulate the larger the impact on subsequent AW larvae populations. The model *Larvae = -1.31693 + 0.00751DD* was built on data collected from stocking rates ranging between 251 to 584 sheep days/ha and indicates that if stocking rates are within this target range, strategic sheep grazing will keep AW larvae below the ET.

Alfalfa Growth and Regrowth

Model assumptions of regression function linearity and independence and normality of error term variances were met through visual analysis of appropriate plots. The model assumption of homogeneity of variance was met for variables DM (F = 1.33; df = 6, 33; $P = 0.3698$), NDF (F = 1.98; df = 6, 33; $P = 0.10$), CP (F = 2.57; df = 6, 33; $P = 0.0371$), and Yield (F = 0.53; df = 6, 33; $P = 0.7795$) across year and ADF (2008: F = 0.76; df = 6, 12; $P = 0.6176$), (2009: F = 0.69; df = 6, 12; $P = 0.6640$) and TDN (2008: F = 0.76; df = 6, 12; $P = 0.6131$), (2009: F = 0.69; df = 6, 12; $P = 0.6648$) within year.

Table 3. A comparison of on-site and near-site regression model slope, y-intercept, and best fit selection parameters

	Model	
Parameter	On-site	Near-site
y-intercept	-1.531	-1.317
slope	0.0079	0.0075
r^2	0.829	0.827
Adj. r^2	0.821	0.819
CV %	26.46	26.57
RMSE	0.196	0.196
PRESS	0.947	0.954
Sum of Squares		
Model	4.062	4.056
Error	0.841	0.848
Total	4.904	4.904

No grazing treatment x year interaction was detected for DM (F = 0.64; df = 6, 41; *P* = 0.69), NDF (F = 1.99; df = 6, 41; *P* = 0.11), CP (F = 0.67; df = 6, 41; *P* = 0.68), and yield (F = 0.68; df = 6, 41; *P* = 0.67). A year x treatment interaction was detected for ADF (F = 3.5; df = 6, 41; *P* = 0.01) and TDN (F = 3.5; df = 6, 41; *P* = 0.01). ADF and TDN are presented by year in Table 4 and combined over year in Table 5.

ADF (F = 0.28; df = 6, 12; *P* = 0.93) and TDN (F = 0.28; df = 6, 12; *P* = 0.93), during 2008, did not differ (Table 4). In 2009, ADF (F =15.4; df = 6, 12; *P* < 0.0001) decreased while levels of TDN (F = 15.36; df = 6, 12; *P* < 0.0001) increased as stocking rate increased from NG to the most extensively grazed G6 (Table 4).

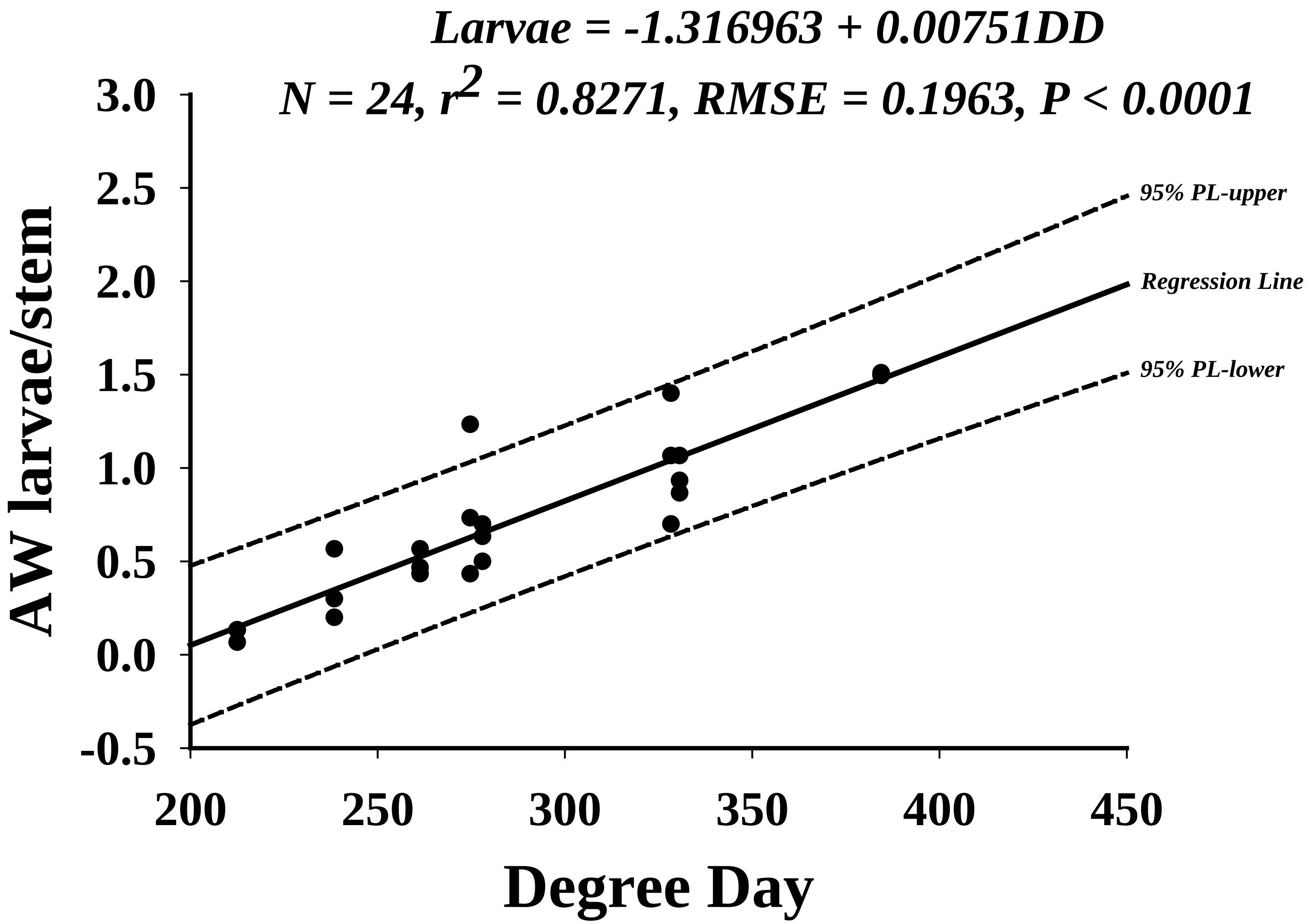

Fig. 7. Degree day model (developed from 2008 and 2009 AW larval data collected in treatments G3, G4, and G5) of sheep grazing influence on alfalfa weevil populations.

Table 4. Grazing treatment mean ADF and TDN during 2008 and 2009

	ADF(%)[x]		TDN[xy]	
Treatment	2008	2009	2008	2009
NG	27.7a	32.7a	61.56a	57.81a
G1	29.2a	31.9a	60.43a	58.41a
G2	28.8a	33.1a	60.74a	57.51a
G3	28.4a	32.3a	61.04a	58.12a
G4	28.1a	27.4b	61.22a	61.79b
G5	26.9a	28.6b	62.16a	60.89b
G6	27.3a	22.1c	61.86a	65.76c
S.E.[z]	2.23	1.43	1.76	1.13
P-value	0.93	<0.01	0.93	<0.01

Means in columns followed by the same letter grouping are not significantly different (P>0.05); least significant difference (Proc Mixed; SAS Institute 2002).

[x]Year x treatment interaction was detected (P <0.01).

[y]TDN (% of DM) = 82.38-(0.7515 x ADF%).

[z]Least significant difference test standard error.

Table 5. Grazing treatment mean DM, NDF, CP, ADF, TDN, MSW and yield combined across study year

Treatment	DM(%)[t]	NDF(%)[t]	CP(%)[t]	ADF[w]	TDN[wy]	MSW[t]	Yield[tx]
NG	94.21a	43.13ab	20.78a	30.22ab	59.67ab	5.1a	4.61a
G1	94.45a	43.08ab	19.07a	30.55ab	59.42ab	5.0ab	4.15a
G2	94.41a	42.84ab	19.77a	30.95a	59.12a	4.8b	3.96ab
G3	94.67a	43.41ab	20.86a	30.28ab	59.62ab	4.0c	3.30bc
G4	94.65a	45.66a	21.52ab	27.76b	61.52b	4.0c	2.21c
G5	94.46a	39.07bc	22.67bc	27.74b	61.53b	4.0c	2.76c
G6	94.47a	34.49c	23.66c	24.71c	63.81c	2.2d	1.51d
S.E.[z]	0.68	2.86	0.88	1.66	1.21	0.09	0.35
P-value	0.99	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

Means in columns followed by the same letter grouping are not significantly different (P>0.05); least significant difference (Proc Mixed; SAS Institute 2002).

[t]Year x treatment interaction was not detected (P > 0.11).

[w]Year x treatment interaction was detected (P < 0.01).

[x]Yield: Metric Tons/Hectare.

[y]TDN (% of DM) = 82.38-(0.7515 x ADF%).

[z]Least significant difference test standard error.

Combined over year, only DM did not differ between treatments (F = 0.1; df = 6, 33; *P* = 0.99). NDF (F = 3.37; df = 6, 33 ; *P* = 0.01), ADF (F = 3.73; df = 6, 33; *P* = 0.0061), TDN (F = 3.73; df = 6, 33; *P* = 0.0061), MSW (F = 213.33; df = 6, 33; *P* < 0.0001), and Yield (F = 16.91; df = 6, 33; *P* < 0.0001) decreased while CP (F = 6.55; df = 6, 33; *P* = 0.0001) increased as stocking rate increased from NG to the most extensively grazed G6 (Table 5).

Relative Growth Rate

No treatment x year interaction was detected (F = 0.37; df = 13, 107; *P* = 0.8980). A contrast of treatment RGRs indicates they do not differ (F = 0.55; df = 6,108; *P* = 0.7671) between treatment. Contrasts of NG, G1, and G2 vs. modeled treatment yield and MSW were conduced to compare the pooled data across treatments. From this point forward the pooled data for the NG, G1 and, G2 grazing treatments will be referred to as the ‘alternate treatments’.

Modeled grazing treatments pooled yield (F = 31.59; df = 1,33; *P* < 0.001) and MSW(F = 282.4; df = 1,33; *P* < 0.0001) were lower than the pooled yield and MSW of the alternative treatments. Test for homogeneity of variance across treatment were met (F = 0.98; df = 2, 37; *P* = 0.3842) and visual tests confirmed the regression function linearity and independence and normality of error terms. No year by treatment interaction was detected (F = 0.12; df = 2, 39; *P* = 0.8835) so data were combined across years. The individual RGR slope coefficients of the NG, G1, G2, G3, G4 and G5 treatments were contrasted and found to be equal (F = 0.55; df = 6, 108; *P* = 0.7671) and were combined, by contrast group, for comparison of RGRs between alternative and modeled grazing treatments.

Contrast recorded that the RGR of the alternative and modeled treatment were equal (F = 0.00; df = 1, 96; *P* = 0.9949); indicating that plants were developing at the same rate in the alternate and modeled treatments. Further, this also indicates that a simple linear regression of the modeled grazing treatment biomass vs. DD accumulation will produce a predictive equation of when, based on RGR as a function of DD, the modeled treatments would yield equal to the alternate treatments (Fig. 8). The model was built on stem biomass data collected from 40 weekly samples taken over two years of study. Two research hypotheses were presented earlier. Research rejected the AW null hypothesis indicating a relationship does exist between sheep grazing as an IPM tactic and DD. Furthermore, the alfalfa plant growth rates null hypothesis was accepted indicating that the grazing system presented here did not alter plant growth rates.

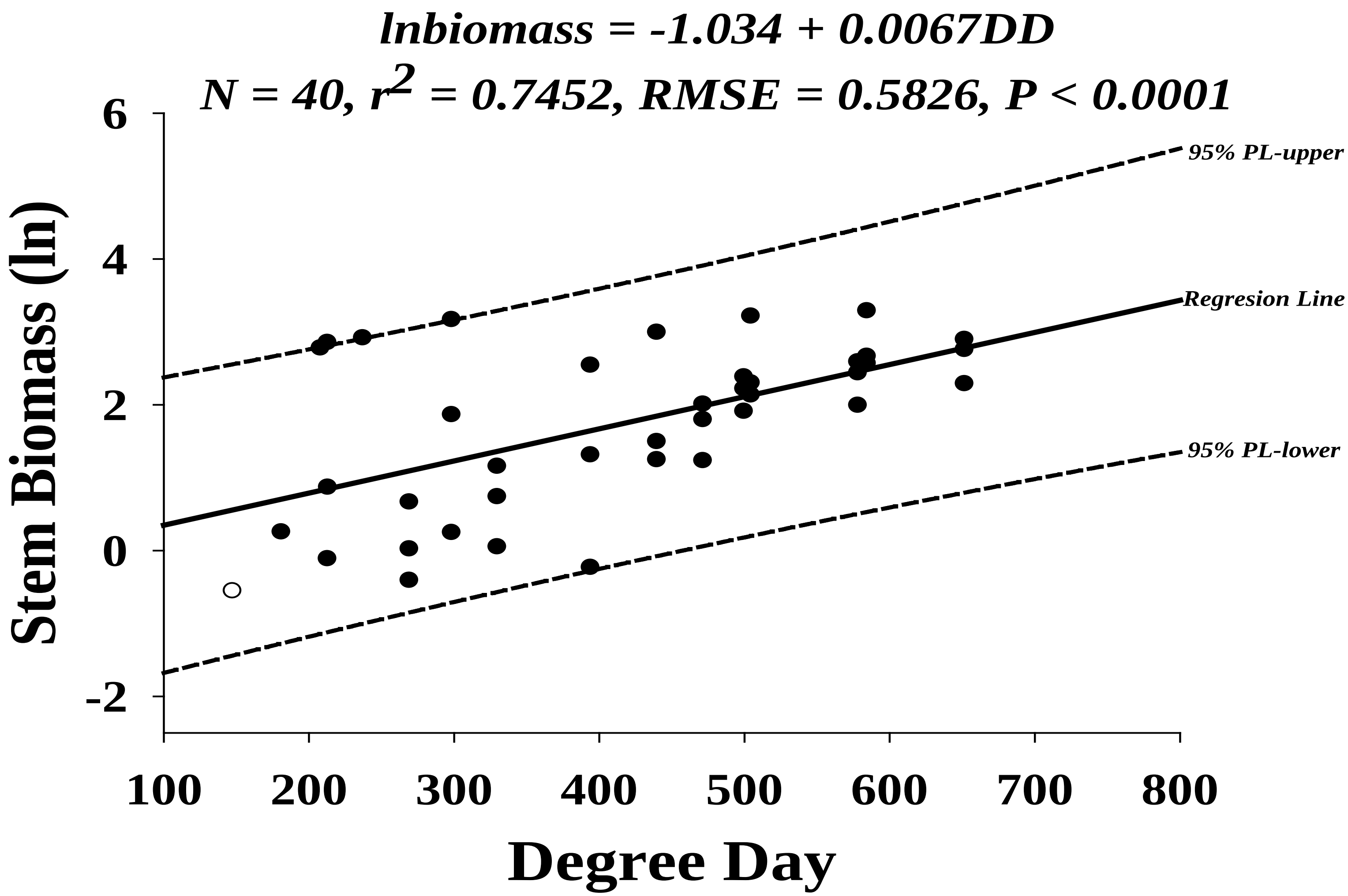

Fig. 8. Results of 2008 and 2009 pooled RGR used to predict yield equivalency between alternative and modeled treatments (lower threshold 5 °C)

DISCUSSION

Livestock producers often rely on fall regrowth of alfalfa as a source of fall and winter livestock pasture. Fall regrowth of alfalfa is also utilized as overwintering habitat by the adult AW (Dively 1970, Dowdy et al. 1986), which hibernates in leaf litter or around plant crowns (Blodgett 1996). Dowdy et al. (1992) reported a 25% reduction of AW larvae in grazed compared to non-grazed plots with stocking rates of 168 to 315 cow d/ha. This work was conducted in Oklahoma where AW actively oviposit during winter months. Oviposition does not occur in Montana during winter (Blodgett et al. 2000).

In northern latitudes above 40° N, spring sheep grazing reduced AW larvae by 40-70% between grazed and non-grazed plots. At the research site, fall regrowth was allowed to accumulate and sheep were stocked at 363 to 469 sheep d/ha on the field in January of each study year (Goosey et al. 2004). However there is no peer reviewed literature utilizing DD as a method to predict the best times to graze. Grazing would need to take place in the spring during the alfalfa green-up and AW oviposition periods to reduce AW larvae in northern latitudes (Goosey et al. 2004). This shift to spring grazing would occur at the same time as AW oviposition and peak occurrence of first instar larvae. When these two events coincide, grazing sheep either directly consume and/or trample AW adults, larvae, and/or eggs located on growing alfalfa plants. Indirect mortality to AW larvae could occur through changes in plant biomass affecting relative humidity and/or temperature in the field.

Degree days calculated from both on-site and near-site temperature data produced the same model coefficients and accuracy level (Table 3). Brewer and Hoff (2002) recorded that regional and near-site temperature was as accurate as on-site data when used to calculate DD for the purpose of initiation and cessation of IPM programs. Based on this similarity, near-site temperature data were chosen to build the model because the purpose of this research was to build a 'producer ready' predictive model. Online near-site temperature data are much more accessible to the producer and they do not require the use of monitoring equipment.

The model was built using grazing treatments which kept AW populations below the ET (1.5 larvae/stem). This was an intentional conservative approach because the published Montana ET is 1.5-2 larvae/stem (Blodgett 1996). Solving for DD in the equation *Larvae = -1.31693 + 0.00751DD* indicates that two larvae/stem would be reached at 442 DD. Upper level prediction intervals indicate that two larvae/stem is reached at 380 DD. Peak of AW 4th instar, the most damaging stage, occurs at approximately 306 DD (Harcourt 1981, Blodgett 1996). Fifty percent of larvae have cocooned at approximately 335 DD (Harcourt 1981). Both of these values are below the 380 DD mark suggesting that the scenario of AW larvae exceeding the two larvae/stem ET will not be reached. This predictive equation is the first published attempt to link DD and sheep grazing in an IPM program.

Results indicate a decrease in NDF, ADF (2009), TDN (2009), and yield and an increase in CP with time (Table 4) with delayed grazing. Generally, it can be concluded that alfalfa in later grazed treatments was more digestible and nutritious but yielded less. First, the physical act of spring grazing keeps plants at a younger growth stage by removing plant tissues which minimize maturation causing the plant to react with compensatory growth (Briske and Richards 1994). Younger plants are generally more digestible and nutritious but are generally smaller when compared to relatively older plants (Orloff and Putnam 2008). So these results are expected. However, during 2008 ADF and TDN did not differ between treatments. Total digestible nutrients are calculated from ADF and so the lack of variation in 2008 is a function of ADF. Therefore, the discussion will relate only to ADF values. Why then did treatment ADF values not differ in 2008?

First, AW larval numbers were not as high in 2008 (Fig. 5) as recorded in 2009 (Fig. 6) and feeding AW populations cause economic losses by consuming plants leaves, which are high in cell solubles (i.e., sugars) and leaving plant stems, that are higher in structural carbohydrates (i.e., acid and neutral detergent fibers). It is possible that ADF values in 2008 did not differ based on AW populations differences.

Second, and possibly the most plausible explanation is revealed by examining DD which accumulated more slowly in 2008 than in 2009 (Table 1). For example, the G4, G5, and G6 treatments were established at 75, 89.2, and 147.4 DD in 2008 but at 125.4, 159.7, and 200.5 in 2009 (Table 1). Treatment establishment occurred 1.73 times later in 2009 compared to 2008. This is reflected in the ADF values. ADF approximately measures the cellulose, lignin, and cutin components, or the least digestible components of the cell wall. Even though grazing had proceeded for 43 calendar days (9 simulated) in 2008, it only extended to 147.4 DD compared to 200.5 DD in 2009. Essentially, there was not sufficient DD between grazing treatment establishment to be reflected in the ADF (digestibility). Why then were these differences not also reflected in NDF and CP values?

Both NDF and CP relationship to mean score by weight (MSW), a measure of plant maturity, are curvelinear while ADF relationship is linear (Fick and Mueller 1989). The same change in plant maturity produces greater changes in NDF and CP than ADF (Fick and Mueller 1989) and so the data suggests that DD were sufficient to produce differences in CP and NDF in 2008 but not ADF and TDN values. Mean stage by weight values in this study decreased as stocking rate increased (Table 5). This indicates that as stocking rate and DD increase, alfalfa maturity degreases (Table 5).

In general these results agree with Mitchell et al. (1991) who reported no detrimental effects on subsequent alfalfa production in fields grazed by sheep. Paddocks (20.11 m^2) were continuously grazed with 5 to 7 month old lambs for 60 sheep days during winter months in the Sonoran Desert. Yields reported from grazed paddocks were 5.4 percent greater than yields collected from mowed or control paddocks. Yield increases with grazing occurred but yields did not differ among the NG, G1 and G2 treatments in this study. Pelton et al. (1988), who stocked paddocks in northern California at 137 and 69 sheep per ha for 2.5 to 3 days in the fall, also reported no yield differences among non-grazed and partial and severe grazed treatments. These results are supported by Allen et al. (1986) who reported when grazing reduced biomass below 161.93 kg/ha the alfalfa regrowth was negatively impacted and none of the grazing treatments here reduced biomass below this level. Allen et al. (1986) also reported that the time to yield maturation did not differ between grazed and non-grazed alfalfa. Results of the present study indicate that time to maturation was increased with grazing pressure (Table 5) however I report stocking rates of 0-704 sheep d/ha compared to 171-411 sheep d/ha reported by Allen et al. (1986). Allen et al. (1986) does not report what criteria were used to assess maturation and so the differences in stocking rate impact on time to maturation of grazed alfalfa may be reflected in those criteria. It is vital to note that experiments comparing grazing and clipping vary greatly depending on trampling effects, sward characteristics, animal species, season, location, grazing, and defoliation severity and maintenance of sufficient soil water infiltration rate (Mitchell et al. 1991).

Yield, NDF, 2009 ADF and TDN were lower and CP was greater in the modeled compared to the alternative grazing treatments. These data suggest that plants in the modeled treatments were younger than those in the alternative treatments which is supported by differences in treatment MSW. This difference leads to the question of when would the modeled grazing treatments yield equal to the combined alternate treatments?

In 2008 and 2009, the pooled yields of the alternate treatments were 4.13 and 4.35 metric tons/ha and the natural log of stem biomass for each of these samples was 3.35 and 3.71 g/15stems, respectively. During 2008, based on the equation $lnbiomass = -1.034 + 0.0067DD$ when solving for DD, the modeled treatments would yield equal to the alternative treatments at 654 alfalfa DD (lower threshold 5 °C)in 2008 and 708 DD in 2009. These DD accumulations translate into calendar dates of 28 June 2008 and 27 June 2009, 5 and 3 d after when harvest samples were taken, respectively.

Stocking rate and DD for the grazing period did not alter RGR between treatments. According to the grazing optimization hypothesis, three plant responses can be observed in response to livestock grazing (Hilbert 1981). Primary production may 1) increase with increasing grazing intensity to an optimal level and the decrease, 2) remain unaffected until intermediate levels of grazing intensity are attained and then decrease, and 3) decrease with increasing grazing intensity (Detling 1988). Based on treatment RGR being equal, alfalfa in this study remained unaffected from grazing (number two above). Previous research reported that grazed and non-grazed plots yielded equal and therefore grazed plants expressed an accelerated growth rate (Goosey et al. 2004). Results presented here appear to contrast these earlier findings. Degree days offer an explanation. Previous research investigated where sheep graze the experimental field until 3 May 2002 and 15 May 2003 of which the DD were 40.0 and 57.3, respectively. In the current research, during 2008, grazing treatments G2 and G3 were established at 41.7 and 57.7 DD. Yields between the NG and G2 and G3 plots were statistically similar during 2008. This indicates that the results presented here are in agreement with those published in earlier work.

The grazing intensity necessary to induce a decrease in primary production is difficult to establish definitively as is supported by these findings (Hilbert 1981). It is important to recognize that much of the data collected in support of the grazing optimization hypothesis were derived from grazed systems where herbivore density and movement were not directly regulated by humans. In these systems, primary production and herbivore density fluctuate widely in a series of continuous feedback loops in response to climatic variation (Sinclair 1975, Walker et al. 1987). Conversely herbivore density and movement are rigidly restricted in managed systems and consequently the grazing intensity in many if not all managed systems may frequently exceed the intensity required to consistently stimulate primary production as indicated by the optimization hypothesis (Hilbert 1981).

The results presented here are a continuation of earlier work and provide a producer ready DD based predictive model to encourage use of grazing to manage AW across environments. Management of pests and conservation of beneficial insects associated with grazing has been investigated primarily in rangelands (O'Neill et al. 2003, O'Neill et al. 2008, Onsager, 2000, Sjodin 2007) but literature does exist for croplands as well (Dowdy et al. 1992, Goosey et al. 2004, Pelton et al. 1988). However, little relevant published literature exists from annual and perennial cropping systems.

The recommendation this research makes to producers is as follows. Stock alfalfa fields in the spring prior to 34 cumulative degree days with rates between 251 and 583 sheep d/ha. Sheep should be allowed to graze to a minimum of 106 and maximum of 150 DD before removal. The minimum number ensures that grazing has proceeded far enough into the spring to manage the weevil and the maximum is the point where grazing must be stopped to ensure that the model predicting equal stem biomass and yields is accurate. At the central MT site where this research was conducted, 106-150 degree days historically falls between the 6th and 18th of May. Since the weevil hibernates in northern latitudes we only expect this model to work in the same environments.

Finally, the above recommendation and predictive DD model (Fig. 7) were preliminarily validated using data from previous research conducted north of Dillon, MT in 2002 and 2003. This research (Goosey et al. 2004) reported a 40-70% reduction in AW larvae in grazed vs. non-grazed treatments. Sheep were introduced to the experimental field in January or February, prior to 34 DD, of each year and continuously grazed for 95 d (2002) and 98 d (2003) during winter and spring. This produced stocking rates ranging between 363 and 469 sheep d/ha. Sheep grazed to 146 (2002) and 151

(2003) DD before being removed. The above stocking rates and DD fall within the recommended ranges of 251 and 584 sheep d/ha and 106-150 DD produced from this research. Additionally, AW larval numbers were economical in non-grazed plots during 2003 however numbers were kept below the ET in grazed plots which is also consistent with results of this research. Acid and neutral detergent fibers (kg/ha) were greater in non-grazed compared to grazed treatments during both study years and percentage of plants blooming (an indicator of treatment growth stage and maturity) was greater in non-grazed alfalfa during 2003. These results are consistent with the results of the current research in that grazed plants were less mature (2003) and more nutritious (2002 and 2003) in grazed vs. non-grazed treatments. However, yield did not differ between treatments like that recorded in the current research which may be reflected in methods used to estimate yield. Small quadrat sampling of alfalfa may not be the preferred methods of true yield estimation.

This is one step toward model validation but further applications of the model are needed to ensure accuracy in differing environments. Additional competitive research funds have been secured to further validate this model by collecting new data. Collections sites are Bozeman and Terry, MT; Hettinger, ND; and Belle Fourche, SD, with research to begin in spring 2010. Validation at the Terry, MT and Bell Fourche, SD sites will entail establishing non-grazed plots prior to grazing. Stocking rates will be intentionally set to range between the recommended 251-584 sheep d/ha. Grazing will begin prior to 34 DD and continue to between 106 and 150 DD. Regional temperature from the nearest weather stations will be used to calculate DD. Managerial decisions will be based entirely on DD. Alfalfa weevil larvae, stem biomass, yield, ADF, NDF, CP and

MSW values will be determined from grazed and non-grazed alfalfa at harvest. These values will be compared to those of the current study to assess validation.

Validation at the Bozeman, MT and Hettinger, ND sites will involve all the above methods with incorporation additional grazing exclosures. From these additional exlcosures, the same samples at harvest will be taken. This process will establish a gradient of stocking rates and DD, similar to the current research, from which the above samples will be taken.

Data collected from each site will be used to re-estimate the model form. Regression coefficients and characteristics of the newly fitted model will be compared for consistency to those of the model produced from the current research. Consistency will be determined using Proc Mixed (SAS 2002) with the level of significant set at $P = 0.05$. Mean square prediction error (MSPR) will be calculated to assess the actual predictive capability of the regression model. If MSPR is close to mean square error (MSE) based on the regression fit to the model-building data set, then MSE for the selected regression model is not seriously biased and gives and appropriate indication of the predictive ability of the model. Finally, the predicted residual sum of square (PRESS) value will be compared to error sum of squares (SSE). A PRESS value close to SSE supports the validity of the fitted regression model and of MSE as an indicator of the predictive capability of the model.

IMPLICATIONS

Experimental grazing research embodies a fundamental tradeoff between a robust assessment of ecological processes and the ability to mimic the response associated with the adaptive management. Research protocols require that grazing experiments be structured in a manner that minimizes both ecological and managerial variability to effectively test hypotheses that enhance our understanding of critical ecological processes operating in grazed ecosystems. Developing degree day based grazing models is a very effective method to account for ecosystem variability and these models then can easily be adapted to varying climates and environments in which alfalfa is grown.

The focus of integrated systems revolves around bringing crops and livestock into an interactive relationship with the expectation that the partnered enterprises will benefit more together than apart in terms such as overall productivity, indices of environmental quality, and conservation of renewable and non-renewable resources. Application of sound ecological science is greatly needed in agriculture since in the US alone, 50% of the land area is either cropped, grazed or both (Robertson and Swinton 2005). Agriculture is the world's largest industry, and with population growth, fueling basic protein requirements, there is a great need for an ever more productive agriculture that protects and promotes sustainability (NRC 2003). Many solutions will be crop- and region-specific, although the principles on which individual solutions are based will be universal.

Since current management practices have been designed to meet the high demands for nutrients and pest protection, producers have been highly dependant on technologies that satisfy these requirements efficiently and in a timely manner (Roberston and Swinton 2005). Integrated systems research requires time and is expensive to establish and conduct (Allen et al. 2007). However, integrating crop and livestock production, such as the grazing system presented here, is one method of improving both the environmental capacity of and the sustainability within agriculture. One potential stumbling block of these integrated crop-livestock systems would be failing to recognize and consider the time required for ecosystems to adjust to changes in management regimes. Several years may be required for soil/plant/primary consumer variables to adjust and show a response to the new management regime. Research experiments that operate for short periods may only capture the period of system adaptation and underestimate the long-term potential of grazing systems as a whole (Briske et al. 2008). As the world's attention focuses increasingly on the need to feed a growing global population, there must be a parallel concern for the sustainability of that food production. There will be no single solution rather there must be an integration of parts to create a site and time specific integrated system. Utilization of DD to integrate crop and livestock production is one such method. Monoculture plant and animal systems have spurred major technological advances which in turn have spurred economies world wide, but increasingly are extracting a non-sustainable cost on global resources. Some of the solutions to the sustainability issues in agriculture can be found in integrated crop-livestock agriculture and within this arena, implementing strategic grazing as an integrated pest management tool has an important role to play.

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