Wheat yield estimates using multi-temporal AVHRR-NDVI satellite imagery
by Mari Patricia Henry

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Land Resources and Environmental Sciences
Montana State University

Abstract:
Crop condition monitoring and early season yield estimates could provide information for assessing crop stress, fertilizer demand, and productivity and assist in farm management decisions. I examined the application of the Advanced Very High Resolution Radiometer (AVHRR) Normalized Difference Vegetation Index (NDVI) for making crop yield estimates at regional, county, and farm levels in Montana. Seasonal growth profiles were examined to determine if yield and/or protein concentration could be accurately estimated prior to harvest.

Results are presented for six regions, thirty-nine counties, and five farms in Montana. Biweekly NDVI values were extracted to produce yearly growth profiles representing April through mid-September for the years 1989 through 1997. Wheat yield data were supplied from Montana Agricultural Statistics Service and from cooperating farmers. Protein concentration - NDVI parameter relationships were developed for four farm sites. NDVI values were integrated and summed in various ways across the growth profile to find the best model for wheat yield estimation. Sixteen NDVI growth profile parameters were computed at the region and county level whereas twenty-nine were computed at the farm level. A multiple linear regression model was used to determine overall relationships between NDVI parameters and yield or protein concentration.

. Regions, counties, and farms were included as indicator variables in the model, along with interaction terms, when significant (p-value = 0.05).

Results show correlation between yield and several NDVI growth profile parameters at the region, county, and farm level. Regions showed strong relationships between wheat yields and integrated NDVI over the entire growing season (adj. R2 = 0.753, p = 0.0001) and with late season NDVI parameters (summation period 7/6 - 8/30 adj. R2 = 0.686; summation through August adj. R2 = 0.745). Counties exhibited similar, yet weaker relationships between wheat yield and NDVI parameters. Farms revealed strong relationships between integrated NDVI over the entire growing season and. spring wheat yields (adj. R2 = 0.628) that improved when adjusted to the apparent growing -season (AGS) (adj. R2 = 0.688). Protein concentration was also strongly correlated with integrated NDVI when adjusted for AGS (adj. R2 = 0.789). Early season NDVI parameters showed weak relationships with spring wheat yields and percent protein content and thus, could not provide accurate yield and protein concentration estimates.

Results indicate a need for region, county, and farm-specific calibration of NDVI growth profiles and refinement of integration and summation periods to improve wheat yield and protein concentration estimates. The use of AVHRR-NDVI growth profiles at the regional level provided the best yield estimates. At the farm scale, the spatial resolution (1km^2) limited the certainty for accurate portrayal of field locations. However, our models provide a basis for further examination of time-series NDVI data with satellite/sensor systems with higher spatial and spectral resolution to be launched in the near future.

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Date 4-13-99

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ABSTRACT

Crop condition monitoring and early season yield estimates could provide information for assessing crop stress, fertilizer demand, and productivity and assist in farm management decisions. I examined the application of the Advanced Very High Resolution Radiometer (AVHRR) Normalized Difference Vegetation Index (NDVI) for making crop yield estimates at regional, county, and farm levels in Montana. Seasonal growth profiles were examined to determine if yield and/or protein concentration could be accurately estimated prior to harvest.

Results are presented for six regions, thirty-nine counties, and five farms in Montana. Biweekly NDVI values were extracted to produce yearly growth profiles representing April through mid-September for the years 1989 through 1997. Wheat yield data were supplied from Montana Agricultural Statistics Service and from cooperating farmers. Protein concentration – NDVI parameter relationships were developed for four farm sites. NDVI values were integrated and summed in various ways across the growth profile to find the best model for wheat yield estimation. Sixteen NDVI growth profile parameters were computed at the region and county level whereas twenty-nine were computed at the farm level. A multiple linear regression model was used to determine overall relationships between NDVI parameters and yield or protein concentration. Regions, counties, and farms were included as indicator variables in the model, along with interaction terms, when significant (p-value = 0.05).

Results show correlation between yield and several NDVI growth profile parameters at the region, county, and farm level. Regions showed strong relationships between wheat yields and integrated NDVI over the entire growing season (adj. R^2 = 0.753, p = 0.0001) and with late season NDVI parameters (summation period 7/6 – 8/30 adj. R^2 = 0.686; summation through August adj. R^2 = 0.745). Counties exhibited similar, yet weaker relationships between wheat yield and NDVI parameters. Farms revealed strong relationships between integrated NDVI over the entire growing season and spring wheat yields (adj. R^2 = 0.628) that improved when adjusted to the apparent growing season (AGS) (adj. R^2 = 0.688). Protein concentration was also strongly correlated with integrated NDVI when adjusted for AGS (adj. R^2 = 0.789). Early season NDVI parameters showed weak relationships with spring wheat yields and percent protein content and thus, could not provide accurate yield and protein concentration estimates.

Results indicate a need for region, county, and farm-specific calibration of NDVI growth profiles and refinement of integration and summation periods to improve wheat yield and protein concentration estimates. The use of AVHRR-NDVI growth profiles at the regional level provided the best yield estimates. At the farm scale, the spatial resolution ($1km^2$) limited the certainty for accurate portrayal of field locations. However, our models provide a basis for further examination of time-series NDVI data with satellite/sensor systems with higher spatial and spectral resolution to be launched in the near future.

CHAPTER 1

GENERAL INTRODUCTION

Montana is largely an agricultural state within the northern Great Plains region. Agriculture accounts for over 30% of the state's basic industry employment, labor income, and gross sales (Montana Agricultural Statistics, 1997). Approximately 61% of Montana land is either farmed or ranched, with nearly 30% in cropland and an average farm size of 1040 ha. Wheat (spring, winter, and durum) is the primary crop, with barley ranking second (Montana Agricultural Statistics, 1997). Agricultural production in this region is characterized by risk due to weather, international markets, and consumer preference (Seielstad, 1995). While risk can never be eliminated, it can be minimized with access to timely information that would allow farm and ranch managers to monitor crop condition and make better, more informed management decisions.

Since the early 1970's, satellite remote sensing has been promoted as a potentially valuable tool for agricultural monitoring because of its frequent synoptic coverage and ability to "see" in many spectral wavelengths (Hinzman et al., 1986; Quarmby et al., 1993). Numerous studies have shown the possibilities of remotely monitoring phenological and physiological change in crop canopies at the global-, regional-, and farm-scales using various satellite, airborne and ground sensors (Pinter et al., 1981; Benedetti & Rossini, 1993; Fischer, 1994; Reed et al., 1994; Blackmer et al., 1996). In particular, spectral vegetation indicies, which reduce multi-band observations to a single number, have been used to monitor crop development and estimate final yields (Weigand

& Richardson, 1990; Rasmussen, 1992; Groten, 1993; Quarmby et al., 1993; Doraiswamy & Cook, 1995). With several years of remotely sensed data now available, multi-temporal analyses of spectral data is developing as an exciting research area (Moran, 1996).

Presently, AVHRR-NDVI satellite imagery has relatively low spatial resolution ($1km^2$) but is available on a daily, weekly, or biweekly basis. This relatively high temporal resolution might allow for a near real-time monitoring and assessment of crop condition that is crucial in farm management. While AVHRR-NDVI might not be appropriate for assessing yield differences within fields due to low spatial resolution, a time-series of image data can provide a historical and near real-time record of crop performance of a region within a growing season. This information, used in conjunction with managers' knowledge of their own land, could prove to be beneficial not only to farm and ranch managers in assessing crop or rangeland performance, but also to providers of remote sensing services eager to find ways of ground-truthing their data. Together these two groups can advance the science and applications of remotely sensed data in agricultural production.

This study investigates the potential of the Normalized Difference Vegetation Index (NDVI) produced from the Advanced Very High Resolution Radiometer (AVHRR) for regional and farm-scale monitoring of wheat production in Montana. The goal was to determine whether AVHRR-NDVI time-series profiles could be used to estimate wheat productivity (yield) and quality (protein concentration) at the regional and/or farm scale and determine if early estimates of wheat yield and protein concentration would be useful to farmers and land managers.

Chapter 1 provides a literature review on the use of remotely sensed data for studying vegetation dynamics and, in particular, the use of AVHRR-NDVI satellite imagery for estimation of crop yields. Chapter 2 describes AVHRR-NDVI time series and wheat yield relationships at the regional and county scale. At these scales, regional patterns of productivity can be seen and addressed with AVHRR-NDVI. In Chapter 3, the capability of AVHRR-NDVI time series profiles for estimating wheat yields and protein concentration at the farm scale is examined.

Literature Review

Traditional methods of monitoring crops throughout the growing season include climatic or plant process models such as Growing Degree-Days (GDD) or the Crop Environment Resource Synthesis (CERES) Wheat model (Wiegand and Richardson, 1990). These process models use weather, soils, and other environmental data as response functions to describe development, photosynthesis, evapotranspiration, and yield for a specific crop. Though based on strong physiological and physical concepts, these models are poor predictors when spatial variability in soils, stresses, or management practices are present or when simultaneous, multiple variables affect yields (Wiegand, 1984; Wiegand & Richardson, 1990).

Weigand and Richardson (1990) recognized that plant development, stress response, and yield capabilities are expressed in plant canopies and could be observed using spectral analysis of various spectral vegetation indicies. Spectral vegetation indicies (VIs) are typically a sum, difference, or ratio of two or more spectral wavelengths

(Wiegand et al., 1991). VIs are often produced by ratios or combinations of red (R) and near-infrared (NIR) spectral bands (Wiegand & Richardson, 1990). Plant chlorophyll absorbs incident radiation in the visible red (0.6 - 0.7μm) and thus reflects very little in this wavelength (10%), while plant mesophyll causes strong reflectivity (40-60%) due to scattering in the near infrared (0.75 – 1.35μm) (Knipling, 1970). VIs are highly correlated with photosynthetic activity in non-wilted plant foliage and have been shown to be good predictors of plant canopy biomass, vigor, or stress (Tucker, 1979). VIs have been correlated to canopy development and used to quantify canopy responses and measure the amount of photosynthetically active plant tissue present (Hatfield, 1983; Wiegand et al., 1986b). Tucker et al. (1981) found that red and infrared spectral data measured with a hand-held radiometer were highly related ($r^2 = 0.86$) to canopy vigor (dry matter accumulation) of winter wheat and suggested that measurements taken from satellite systems could be used to monitor plant growth and development. Wiegand & Richardson (1990) found the Normalized Difference Vegetation Index (NDVI) to be a good measure of absorbed photosynthetically active radiation (APAR), and its relative magnitude and rate of change during maturation an indication of the relative number of fruit or seed to expect per unit area.

When sequential VI observations are taken frequently over a season, profiles can be developed that show the progression of crop canopy emergence, maturity, and senescence, which are factors that reflect crop performance and are related to crop yields (Pinter et al., 1981; Malingreau, 1989; Benedetti & Rossini, 1993). The integration of VIs over time should reveal the productive history of the canopy and tell us, by inference, about vegetation production (Malingreau, 1989). Seasonal growth profiles have been related to specific physiological changes in crop canopies. Agronomic variables such as ear water concentration (EWC), crop senescence rates, early crop emergence, and final grain yields have been estimated using multi-temporal VI (Idso et al., 1980; Boissard et al., 1993; Benedetti & Rossini, 1993). Examination of crop cycles over many growing seasons and identification of critical times in crop growth cycles have been identified recently as potential research areas that could provide a basis for crop monitoring and prediction of final grain yield (Moran, 1996).

Studies that derived pre-harvest yield estimates typically correlated final grain yield with a single VI observation or time-integrated VI over a specific period (Idso et al., 1980; Weigand et al., 1991; Benedetti & Rossini, 1993; Quarmby et al., 1993; Doraiswamy & Cook, 1995). Grain yields have been found to be correlated with time of maximum NDVI (Barnett & Thomson, 1983), with time-integrated NDVI during the reproductive phase (Rasmussen, 1992), with crop senescence rates (Idso et al., 1980), and with phenological stages from anthesis-to-maturity (Boissard et al., 1993). Yield estimations made by examining early periods in the crop growth profile would be more useful for early season management. Yield predictions made by Rudorff and Batista (1991) correlated the Ratio Vegetation Index (RVI) at a period 50 – 60 days after wheat crop emergence (end of stem elongation and beginning of heading stage) and found that it could be used to explain 64% of the yield variability. Hershenhorn (1992) reported that end of May and end of June AVHRR NDVI were highly correlated with relative spring wheat yield, winter wheat yield, and range condition in the northeastern Montana region for 1985 through 1988. She hypothesized that if data became available in “real-time”, regional yield predictions based on NDVI could be made available in early season.

Another approach is to integrate the area under the seasonal growth profile and correlate this value with final grain yield. In this approach, assessment of the efficiency of the vegetative phase (accumulated biomass) using the integrated NDVI during the first phase of the development curve can be made and then yields adjusted as the NDVI evolves thereafter (Hatfield, 1983). In general, larger areas under the curve should correspond with more photosynthetic activity and biomass and result in larger yields. This has been shown to be particularly true for fodder crops, in which final yield is made of the entire above ground production (Malingreau, 1989; Benedetti & Rossini, 1993). However, for cereal crops whose yield depends on the efficiency of their leaves to assimilate CO^2 into storage organs, the VI link with yield is indirect and more difficult to measure (Benedetti & Rossini, 1993). One of the critical periods for wheat is grain-fill (flowering to physiologic maturity). During this period, the upper two leaves are the most actively photosynthesizing part of the plant and produce the majority of the substances stored in the grain (Benedetti & Rossini, 1993). Consequently, events (such as drought, rain, or fertilization) that occur during this time can greatly affect final grain production. For example, the addition of N fertilizer just prior to grain-fill has been shown to increase grain protein concentration in N deficient plants (Westcott et al., 1997). In Montana, N deficiency is frequently observed in years when growing season moisture is favorable for maximum plant growth resulting in depletion of available N. However, if crop growth is impeded due to moisture stress, N deficiency is less likely to occur and a mid-season application of N will not be cost effective. Close examination of VI profiles during this time would be important for understanding crop performance and estimating final grain yields and quality.

A few researchers have looked at integration of vegetation indicies during critical periods of plant growth. Doraiswamy & Hodges (1991) found the area under the NDVI profile between silking and maturity was correlated with regional corn yields reported by the National Agricultural Statistics Service (NASS) (r^2 of 0.72). An integrated AVHRR-NDVI used by Benedetti & Rossini (1993) from the third week in April through mid June (flowering to physiologic maturity) was correlated with wheat yield in Italy ($r^2 = 0.515$). Use of comparative VI profile observations in early-season combined with examination of profiles during critical periods might be useful in the formation of crop yield estimates.

If VI growth profiles are used throughout a growing season for crop yield assessment, the only operational satellite/sensor-system currently capable of providing data with adequate frequency is the National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) (Rassmussen, 1992). Satellite data from the AVHRR has been used in numerous environmental modeling and global change studies because of its extensive global coverage, high temporal frequency (twice daily coverage), and low cost (Box et al., 1989; Soriano & Paruelo, 1992; Gutman et al., 1994; Wagner, 1998). However, the spatial resolution of AVHRR data is low at 1.1km^2 at nadir for Local Area Coverage (LAC). Low spatial resolution complicates the separation of crops from other land cover types when dimensions of fields are small (Fischer, 1994).

The AVHRR sensors are carried aboard the NOAA 11, 12, 14, and 15 polar orbiting satellites. The sensor collects data in five spectral bands ranging from visible red to thermal. One product produced from the data is the Normalized Difference Vegetation Index (NDVI), which is a normalized ratio of the red ($R = 0.58 - 0.68\mu m$) and near infrared (NIR = 0.725 – 1.1μm) spectral wavelengths. NDVI is a unitless value defined as:

$$NDVI = (NIR - R) / (NIR + R).$$

NDVI is expressed in a range of –1 to 1, where increasing positive values are related to increasing green vegetation. Negative NDVI values indicate non-vegetated surface features such as water, clouds, or snow that have high red reflectance relative to infrared reflectance. Positive NDVI values near zero indicate rock and bare soil, which have similar reflectance in both the visible and infrared wavelengths (EDC, 1995; Lillesand & Keifer, 1994). A ratio of the vegetation index reduces the effects of changing illumination conditions, surface slope and aspect, and atmospheric perturbations while emphasizing varying vegetation density (Holben et al., 1986). NDVI data supplied from EROS Data Center are linearly re-scaled to byte data range values of 0 to 200, where the original NDVI value – 1.0 is equal to 0, NDVI value 0.0 is equal to 100, and NDVI value 1.0 is equal to 200 (EDC, 1995). The 1.1km pixels are resampled to 1km pixel resolution.

Atmospheric conditions can severely affect the amount of reflected radiation that reaches a satellite sensor. Haze from water vapor, clouds, and cloud shadows can diminish or scatter reflected radiation and introduce 'static' into NDVI data. To compensate, NDVI data are compiled biweekly and an algorithm is applied that retains the maximum NDVI value for each image pixel from that two-week period. Maximum Value Composite (MVC) NDVI imagery is used to create a relatively cloud-free data set by choosing NDVI pixels from days when radiance interference is lowest and sun angle is highest with the assumption that the selected pixel is most representative of actual ground reflectance (EDC, 1995; Holben, 1986).

Composite, multi-temporal imagery requires registration to a common map projection to ensure that, from image to image, each 1km pixel represents the same ground location (EDC, 1995). The Lambert Azimuthal Equal Area Projection is used for the AVHRR-NDVI data set distributed by the EROS Data Center. Images are registered to a hydrography base map developed from a U. S. Geological Survey 1:2,000,000-scale digital line graph (DLG). The base map is registered by using 250 ground control points with a root mean square error (RMSE) of less than one pixel, and registration is performed through image-to-image correlation (EDC, 1995).

Use of AVHRR-NDVI data in agricultural studies has been extensive. Methods for deriving phenological metrics have been devised that estimate the rate of green-up and senescence, time of onset of growing season, duration of growing season, and maximum NDVI in relation to agricultural monitoring (Reed et al., 1994; Idso et al., 1980; Badhwar, 1980). Techniques for discerning different agricultural crops within AVHRR's coarse pixels have been proposed (Fischer, 1994; Benedetti & Rossini, 1993). Multi-temporal measurements made from AVHRR-NDVI have been used to estimate and predict crop yields over large and small regions (Benedetti & Rossini, 1993; Doraiswamy and Cook, 1995; Quarmby et al., 1993; Rassmussen, 1992). While AVHRR-NDVI has inherent limitations, it is an inexpensive and readily available source of remotely sensed data that has provided much of the basis for monitoring land resources with spectral radiance measurements.

CHAPTER 2

REGIONAL AND COUNTY SCALE WHEAT YIELD ESTIMATION USING MULTI-TEMPORAL AVHRR-NDVI SATELLITE IMAGERY

Introduction

Techniques for quickly monitoring and estimating agricultural production during the growing season would be useful for land managers whose decisions depend on timely and accurate information (Rudorff & Batista, 1991). Satellite remote sensing is a promising tool that provides periodic coverage of land resources and has been highly correlated with many agronomic variables (Quarmby et al., 1993). These data not only provide information about vegetation condition over extensive regions during the growing season, but also provide volumes of historic data that could be used to compare to present conditions. Monitoring crop performance and making early season yield estimates could provide farm managers and consultants with a new method for assessing and comparing fertilizer demand, drought stress, or productivity among regions.

Agencies interested in world regional grain production have used satellite remote sensing to increase the accuracy of crop production predictions (Wagner, 1998). In particular, the AVHRR data have been used extensively due to their large ground coverage and timely acquisition. In some parts of the world, it is often the only data available. NDVI has gained most of the attention because it is correlated with agronomic variables such as live biomass, leaf area index, and stand density when normalized for the effects of some atmospheric and ground conditions not associated with vegetation condition (Tucker, 1979; Weigand et al., 1991; Thoma, 1998). (For more detail on NDVI, see Ch. 1.) Growth profiles produced from NDVI data represent plant growth responses for the season and should provide an indirect estimate of final grain yield (Malingreau, 1989). Many studies have examined AVHRR-NDVI imagery as a tool for estimating final yields at the county or regional level (Rasmussen, 1992; Benedetti & Rossini, 1993; Groten, 1993; Quarmy et al., 1993; Doraiswamy & Cook, 1995). In most of these studies, a single NDVI value or an integrated NDVI over a period during the growing season has been correlated with final grain yield over a single season or a few years. Few researchers have examined long-term relationships of the NDVI seasonal growth profile and grain yield.

The objectives of this study were to (1) determine if region and county level AVHRR-NDVI growth profiles were related to the wheat grain yields reported by state agencies, (2) identify times in the growing season when useful yield estimations could be made using AVHRR-NDVI yearly growth profiles.

Methods and Materials

Montana physiography and climate

Montana is a region of extreme physiographic and climatic diversity. It is part of the Great Plains and the Middle and the Northern Rocky Mountain physiographic provinces, which have been affected by glacial and volcanic activity (Montagne et al., 1982). It is characterized by smooth to extremely dissected plains in the eastern part of the state, while high mountains and inter-mountain valleys dominate western regions. Montana's climate is primarily influenced by cold, dry continental air masses originating in the Arctic, and cool, wet air masses coming from the Pacific Ocean in the west (USDA Soil Conservation Service, 1982). The plains east of the Continental Divide experience extreme seasonal temperature fluctuations while the mountains and valleys west of the continental divide have a more mild, maritime climate. Embedded in these areas are pockets of microclimates associated with local topography and aspect (Montagne et al., 1982).

Growing season duration across the state ranges from less than 32 days to more than 135 days depending on elevation, aspect, and humidity (USDA Soil Conservation Service, 1982; MAPS, 1990). Precipitation increases towards the west and with increasing elevation. In most of the mountains and western valleys precipitation averages from 300 to more than 1000mm annually while in the semiarid plains east of the Divide, annual precipitation ranges from 300 to 400mm. Soils west of the Divide are diverse due to variable topography. Mollisols are primarily associated with the valley regions where there is crop production, whereas Alfisols and Inceptisols dominate in the forested hills and in some valleys in the Northwest. Soils of the semiarid plains region are primarily Mollisols with ustic moisture regimes, high available water capacity, and high suitability for dryland grains (USDA Soil Conservation Service, 1982). However, the semiarid plains are prone to periods of drought, which cause severe economic impact (Hershenhorn, 1992). These great physiographical diversities and climatic fluctuations play a large part in vegetation density, composition, and ultimately the reflective response that is received by satellite sensors.

Montana non-irrigated agricultural lands

The majority of wheat in Montana is grown under dryland conditions (90+%) (Montana Agricultural Statistics Service, 1997). Hence, only dryland acres within Montana were selected for this study. A 1973 land use polygon coverage of Montana delineating dryland agricultural lands was extracted from the Montana Agricultural Potentials System (MAPS, 1990). The coverage was imported into Arc/Info™ GIS software and converted to an Arc/Info™ GRID format. The grid cells produced from the dryland agriculture coverage were approximately 20.7km^2 in size. The coverage was converted to a Lambert Azimuthal Equal Area (LAEZA) projection to correspond to the projection of the NDVI imagery. The dryland agriculture grid was used as a mask to extract corresponding AVHRR-NDVI grid cells from each NDVI biweekly image so that only NDVI data from predominantly dryland agricultural lands would be included in the study (Figure 1). This procedure created a subset of only dryland acres from each NDVI biweekly period. Furthermore, only regions and counties with at least 100 pixels (100 km^2) of dryland agriculture were included in the study to avoid excess "pixel-mixing" in small areas and image geometric correction. Pixel-mixing is defined as having an NDVI response from other types of vegetation or objects that are contained in the area of interest. Regions were delineated as the Montana Agricultural Statistics Districts used by the Montana Agricultural Statistics Service (Montana Agricultural Statistics Service, 1997). Regions and their associated counties are presented in Figure 2. Counties and number of acres within each county included in this study are presented in Table 1.

Figure 1. MAPS Atlas coverage of areas where dryland agriculture dominates in Montana.

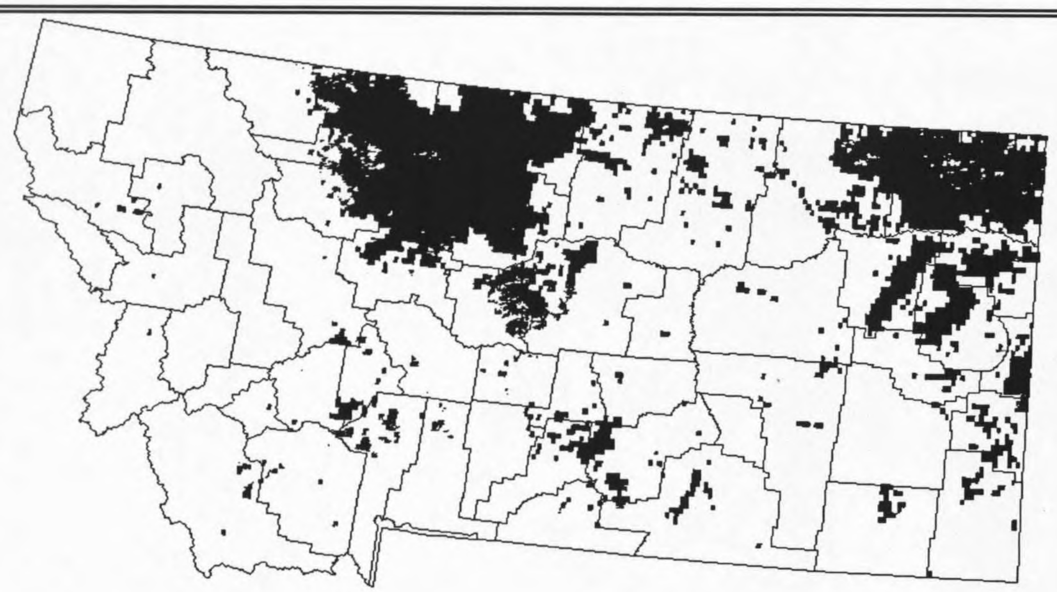

Figure 2. Regions and associated counties included in study, as defined by the Montana Agricultural Statistics Service.