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Wheat yield estimates using multi-temporal NDVI satellite imagery

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Abstract. We examined seasonal growth profiles developed from AVHRR-NDVI for estimating wheat yield at regional and farm scales in Montana for the years 1989–1997. Both regions and farms showed strong relationships between wheat yields and integrated NDVI over the entire growing season, and with late-season NDVI parameters. The use of AVHRR-NDVI growth profiles at the regional level provided the strongest yield estimates. At the farm scale, the spatial resolution (1 km^2) limited the certainty for accurate portrayal of field locations. However, our models provide a basis for further examination of time-series satellite data.

1. Introduction

Agriculture is the largest industry in Montana and the neighbouring Northern Great Plains region. In Montana alone, agricultural production accounts for over 30% of the state's basic industry employment, labour income and gross sales. Wheat is the region's number one cash crop (Montana Agricultural Statistics 1997). Agricultural production is characterized by risks due to weather, international markets and consumer preference. While risk can never be eliminated, it can be minimized with access to timely information that would allow farm managers to monitor crop condition, estimate crop yields prior to harvest and make better, more informed management decisions.

Traditional methods of predicting crop yields throughout the growing season include models that assimilate climate, soils and other environmental data as response functions to describe development, photosynthesis, evapotranspiration and yield for a specific crop (Wiegand and Richardson 1990). Though based on strong physiological and physical concepts, these models are poor predictors when spatial variability in soils, stresses or management practices are present (Wiegand 1984, Wiegand and Richardson 1990). However, remote sensing of crop canopies has been promoted as a potentially valuable tool for agricultural monitoring because of its synoptic coverage and ability to 'see' in many spectral wavelengths (Hinzman *et al.* 1986, Quarmby *et al.* 1993). Numerous studies have recognized that plant development, stress and yield capabilities are expressed in the spectral reflectance from crop canopies and could be quantified using spectral vegetation indices (Jackson *et al.* 1986, Malingreau

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1989, Weigand and Richardson 1990). Vegetation indices (VI), such as the Normalized Difference Vegetation Index (NDVI), are typically a sum, difference or ratio of two or more spectral wavelengths. They are highly correlated with photosynthetic activity in non-wilted plant foliage and are good predictors of plant canopy biomass, vigor or stress (Tucker 1979). When sequential VI observations are taken frequently over a season, seasonal profiles are developed that show the progression of crop canopy emergence, maturation and senescence, which reflect crop performance and are related to crop yields (Idso *et al.* 1980, Pinter *et al.* 1981, Malingreau 1989, Rasmussen 1992, Benedetti and Rossini 1993, Boissard *et al.* 1993, Doraiswamy and Cook 1995). However, most of these studies derived pre-harvest yield estimates with a single VI observation or time-integrated VI over a specific time period for a few growing seasons. Examination of seasonal growth profiles 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).

We examined whether multi-temporal NDVI growth profiles, developed from the Advanced Very High Resolution Radiometer (AVHRR) sensor, could estimate wheat yield at the regional and farm level in Montana. We examined the correlation between regional and farm wheat yields with (1) integrated and summed seasonal growth profiles, (2) early season summation of NDVI, and (3) summation of NDVI during critical periods of crop growth.

2. Methods

2.1. *Study areas*

2.1.1. *Montana regions*

Montana is a region of extreme diversity. Dissected plains characterize the eastern regions, while high mountains and inter-mountain valleys dominate the western regions. The growing season's duration ranges from less than 32 days to more than 135 days depending on elevation, aspect and moisture conditions. Precipitation increases towards the west and with increasing elevation. Mountains and western valleys experience 300–1000 mm of seasonal precipitation, while the semiarid plains east of the Continental Divide average 300–400 mm (Caprio *et al.* 1990).

Since most wheat in Montana is grown under dryland conditions (90+%), dryland acres within regional production districts were selected for this study. Dryland wheat yield data were collected from the Montana Statistics Service for the years 1989–1997 and included spring, winter and durum wheat types. Regional analyses were based on six of seven production districts defined by the Montana Agricultural Statistics Service (Northwest region excluded) (figure 1).

2.1.2. *Farm study sites.*

Five study sites across Montana were evaluated (figure 1) over a nine-year period (1987–1997). Production at site 1 consisted of spring wheat planted in alternate years from 1989–1997. Production at site 2 varied from year to year, from alternate crop–fallow to annual crop production and from winter to spring wheat, complicating year-to-year comparisons. To compensate, yield estimates equivalent to spring wheat yields were derived using the conversion ratio 1.12:1 for winter wheat yields to spring wheat yields (Brown and Carlson 1990). Sites 3 and 4 were alternate crop–fallow systems from 1989–1997, varying between winter wheat, spring wheat and barley. Yields were converted to spring wheat yield equivalents for consistency with other

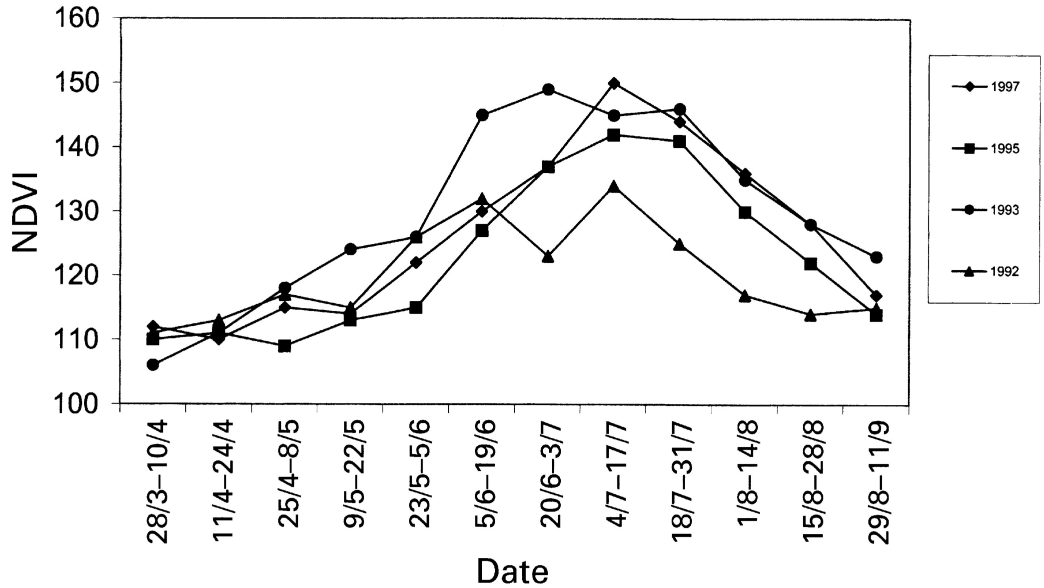

Figure 3. NDVI seasonal growth profiles for a Montana farm.

procedure, the growing season begins following two consecutive biweekly periods with positive NDVI increments. The defined minimum increase was an increment of $\geqslant 1$ digital value followed with an increment of $\geqslant 3$ digital values. This could be seen as the 'steepening' of the growth curve when photosynthetic activity is first increasing. Conversely, end of season was estimated as a decrease of $\leqslant 2$ followed by a decrease of $\leqslant 1$ digital value. This could often be seen as the 'flattening of the curve' when photosynthetic activity has decreased substantially. Integration of the growth profiles was accomplished using the trapezoidal approximation:

$$\textit{Integrated Area} \cong I_h = \frac{h}{2}(y_0 + 2y_1 + 2y_2 .... + 2y_{n-2} + 2y_{n-1} + y_n) \quad (1)$$

where h is the distance between intervals (biweekly periods), y is the height of the rectangle (NDVI value for that biweekly period), and n is the number of intervals (total number of biweekly periods included in the integration) (Dorn and McCracken 1972).

Summation of NDVI growth profiles was also examined as a third procedure for assessing seasonal growth profiles. Summations of the entire NDVI growth profile (sum 12 periods) and through each consecutive month (sum through April–sum through August) were included to detect how early accurate yield estimates could be made. Summation of NDVI over select dates within a growing season was selected as a fourth procedure for examining NDVI growth profiles. We considered three summation periods around the time of maximum NDVI that encompass a 'critical period' in grain production that approximates flowering through maturity in wheat in the Northern Great Plains (Benedetti and Rossini 1995, Doraiswamy and Cook 1995). The three summation periods included four NDVI biweekly periods (total of 8 weeks) and were as follows: sum 4 June–2 August, sum 22 June–16 August and sum 6 July–30 August. A fifth procedure investigated the relationship of wheat yield and end of the month NDVI values throughout the growing season (end of April–end of August).

2.3.1. *Statistical analyses*

Regions and farms were included as indicator variables in multiple linear regressions (MLR). The model equation for a regional NDVI parameter with indicator variables and interaction was:

$$Yield = \beta_0 + \beta_1\, NDVI\ parameter + \beta_2\, region + \beta_3\, NDVI\ parameter{*}region \qquad (2)$$

where regions (or farms for farm data) were included as indicator variables to reduce the error effects caused by location differences and show only the overall relationship of NDVI variables and yield. Interactions were included to show differences in NDVI response to yield and reveal heterogeneity of slope. The inclusion of a region, farm or interaction term was determined by significance (*p*-value), with a *p*-value = 0.05 level of significance. For models with insignificant *p*-values, a simple regression analysis was performed between wheat yield and the NDVI parameter. Because of the limited sample size, all data were used for model fitting.

3. Results

3.1. *Regional wheat yield–NDVI parameter relationships*

Integration of seasonal NDVI profiles (integrate 12 periods and integrate AGS) and summation of the seasonal NDVI growth profile (sum 12 periods) relationships with yield were all significant estimators of yield, though the adjusted R^2 was slightly lower for the AGS and sum 12 periods parameters (table 1). Monthly parameters (sum through each month and end of the month) show trends of increasing association with final yield as the season progresses with the strongest relationship occurring with summation through August (sum August) and end of August (end August) parameters (table 1). Summations of critical periods (sum 4 June–2 August; sum 22 June–16 August; sum 6 July–30 August), showed increasing correlation as summation periods approached July–August, with strongest correlation for the summation period of 6 July–30 August (table 1). The significance of the NDVI-region interactions for monthly parameters increased as the season progressed, however they did not become significant until August was reached (table 1). For these parameters, interaction terms were included in the final model.

Plots of the wheat yield–integrate 12 periods relationships for each region are presented in figure 4(a–f). These plots represent the fit of the predicted slopes to the reported yield values for each region using the coefficients from the multiple linear regression model. The relationship for this model is the strongest of all NDVI parameters examined at the regional scale (table 1). Regional variation is evident from different predicted intercepts and slopes. For example, southwest Montana reveals a strong variation in reported wheat yields (1815–4035 kg ha^{-1}), while southeast Montana has significantly less variation in reported wheat yields (1412–2152 kg ha^{-1}). Regional differences affected both the intercepts and interaction terms in the prediction equations. Interaction is evident by the differences in slopes among regions, revealing variation in regional wheat yield–integrated NDVI relationships.

3.2. *Farm spring wheat yield–NDVI parameters relationships*

Adjusted R^2 for models ranged from no relationship to moderate relationship, with the strongest correlations occurring between spring wheat yields and NDVI integrated and summed over the growing season (integrate AGS, integrate 12 periods, sum 12 periods) (table 2). Early season NDVI parameters indicated little relationship

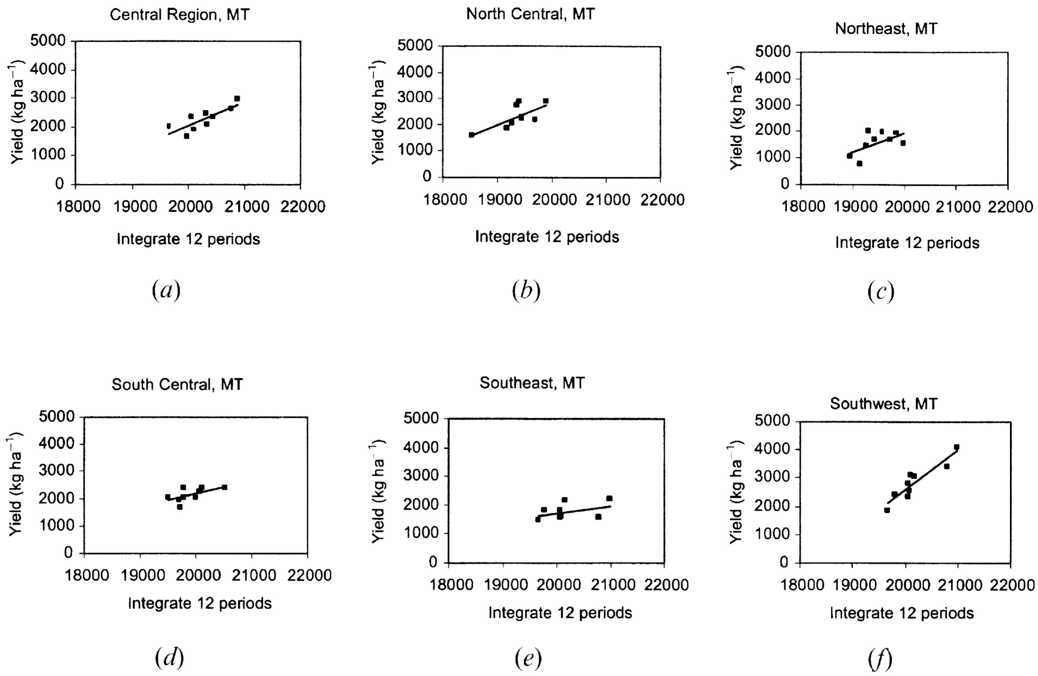

Figure 4. Regional wheat yield–integrate 12 periods relationships. Model includes interaction terms. Adjusted $R^2 = 0.753$, p-value = 0.0001: (*a*) central yield = (−216.32) + (−0.012) (integrate 12 periods); (*b*) north central yield = (−220.01) + (0.013) (integrate 12 periods); (*c*) northeast yield = (−180.6) + (0.010) (integrate 12 periods); (*d*) south central yield = (−118.67) + (0.007) (integrate 12 periods); (*e*) southeast yield = (−49.66) + (0.004) (integrate 12 periods); (*f*) southwest yield = (−388.84) + (0.021) (integrate 12 periods).

Table 1. Wheat yield–NDVI parameter relationships for regional study sites. The table includes the adjusted R^2, and p-value of each wheat yield–NDVI parameter relationship. Regions and interaction p-values are presented to show when they were included in a model.

NDVI parameter	Adjusted R^2	p-value, model	p-value, interaction	p-value, region
Integrate 12 periods	0.753	0.0001	0.034*	0.0001*
Integrate AGS	0.738	0.0001	0.038*	0.0001*
Sum 12 periods	0.745	0.0001	0.042*	0.0001*
Sum through April	0.440	0.620	0.973	0.0001*
Sum through May	0.454	0.234	0.241	0.0001*
Sum through June	0.454	0.234	0.743	0.0001*
Sum through July	0.463	0.135	0.644	0.0001*
Sum through August	0.748	0.0001	0.0001*	0.0001*
Sum 4 June–3 August	0.587	0.0001	0.175	0.0001*
Sum 22 June–16 August	0.644	0.0001	0.160	0.0001*
Sum 6 July–30 August	0.686	0.0001	0.055	0.0001*
End of April	0.444	0.442	0.899	0.0001*
End of May	0.563	0.0006	0.631	0.0001*
End of June	0.471	0.087	0.602	0.0001*
End of July	0.555	0.001	0.452	0.0001*
End of August	0.697	0.0001	0.046*	0.0001*

*Region and/or interaction term included in final model.

Table 2. Spring what yield–NDVI parameter relationships for farm study sites. The table includes the adjusted R^2, and p-value of each wheat yield–NDVI parameter relationship. Farms and interaction p-values are presented to show when they were included in a model.

NDVI parameter	Adjusted R^2	p-value, model	p-value, interaction	p-value, farm
Integrate 12 periods	0.628	0.0001	0.512	0.0003*
Integrate AGS	0.688	0.0001	0.068	0.0002*
Sum 12 periods	0.613	0.0001	0.401	0.0003*
Sum through April	0.000	0.4263	0.174	0.090
Sum through May	0.360	0.0041	0.033*	0.026*
Sum through June	0.242	0.017	0.461	0.042*
Sum through July	0.089	0.0343	0.432	0.080
Sum through August	0.619	0.0001	0.503	0.0003*
Sum 4 June–3 August	0.092	0.032	0.293	0.098
Sum 22 June–16 August	0.052	0.084	0.129	0.083
Sum 6 July–30 August	0.028	0.053	0.054	0.069
End of April	0.226	0.045	0.106	0.031*
End of May	0.093	0.031	0.919	0.066
End of June	0.324	0.001	0.549	0.031*
End of July	0.510	0.0001	0.148	0.019*
End of August	0.352	0.0006	0.066	0.010*

*Farm and/or interaction term included in final model.

with spring wheat yields. Correlations increased later in the season as dates approached harvest (July and August). Summation through August (sum through August) revealed a stronger relationship than summation through the entire growing season (sum 12 periods), while NDVI at the end of July (end July) had a stronger relationship with spring wheat yields than NDVI at the end of August (adjusted $R^2=0.510$ and 0.352, respectively). No significant relationships were found between critical periods and yields (table 2).

A plot of the spring wheat yield–AGS relationship for each farm is presented in figure 5(a–e). Figure 5 represents the fit of the predicted slopes to the reported yield values based on integrated NDVI for the apparent growing season (integrate AGS) for each farm using the coefficients from the multiple linear regression model. This relationship is the strongest of all NDVI parameters examined at the farm scale (table 2). The plots also reveal that the range in reported yields is quite broad. Site 1 shows the largest range in reported yield values (1143–5716 kg ha^{-1}), while site 5 had the smallest range (740–2757 kg ha^{-1}). Our model predicts site 1 would produce the highest yields for a given AGS value, while site 5 would produce the lowest.

4. Discussion

AVHRR-NDVI seasonal growth profiles were effective at representing wheat grain yields at regional and farm scales in Montana. AVHRR-NDVI growth profiles most likely relate to seasonal biomass production. Those seasons with higher biomass result in higher wheat yields that are represented by larger areas under the seasonal growth profile or larger summations over the season. This effect can be seen in the predicted slopes of the wheat yield–integrated NDVI scatter plots (figures 4 and 5). Reported and predicted yields from most regions and farms showed moderate to strong positive relationships with integrated NDVI. Seasonal biomass–NDVI

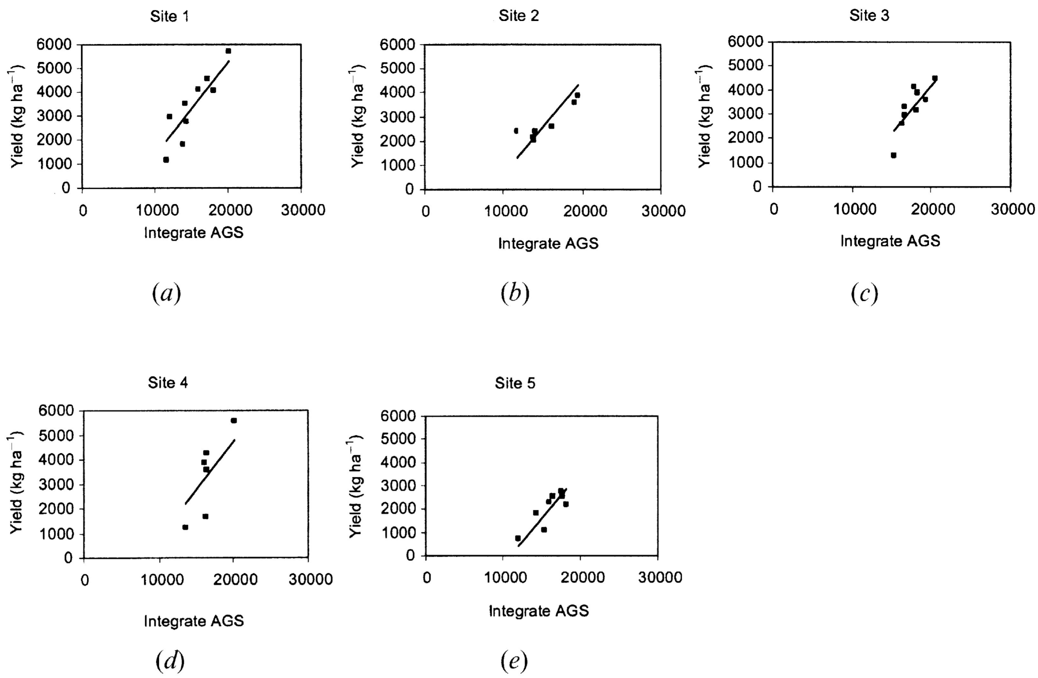

Figure 5. Farm spring wheat yield–NDVI (integrate AGS) relationships. Model includes interaction terms. Adjusted $R^2=0.688$, p-value$=0.0001$: (*a*) site 1 yield$=(-38.48)+(0.006)$ (integrate AGS); (*b*) site 2 yield$=(-49.34)+(0.006)$ (integrate AGS); (*c*) site 3 yield$=(-54.68)+(0.006)$ (integrate AGS); (*d*) site 4 yield$=(-46)+(0.006)$ (integrate AGS); (*e*) site 5 yield$=(-63.14)+(0.006)$ (integrate AGS).

relationships have been observed in many studies (Benedetti and Rossini 1993, Groten 1993, Quarmby *et al.* 1993, Thoma 1998). For this study, 'high biomass years' are typically years of higher grain production, presumably because of favourable growing conditions. For example, precipitation in 1993 and 1995 was abundant throughout the growing season for most of Montana. These were also years of higher than average yield across much of the state (Montana Agricultural Statistics Service 1997). In addition, slopes for the regions with cool summer temperatures, such as those in central and southwest regions, tend to be steeper compared to those of the south central and southeast regions (figures 4(a–f)). Cool temperatures during grain filling promote greater translocation of carbohydrates into the kernels by prolonging the grain-fill duration (Sofield *et al.* 1977, Wiegand and Cuellar 1981). Hence, climates with cool temperatures have larger kernel weights, higher yields and greater harvest index values than regions with hot mid-summer temperatures.

At the farm scale, integration of the apparent growing season (integrate AGS), which takes into account seasonal and location differences between crop emergence and senescence, shows an improved correlation over using fixed dates (integrate 12 periods) (adjusted $R^2=0.628$ and 0.688, respectively). At this scale, adjusting for specific crop emergence dates became useful as we focus on small areas where site-specific characteristics were not averaged over large areas. Site-specificity can also be seen in the figure 5(a–e). Our model predicts that site 1 will produce the highest spring wheat yield for any given integrate AGS value, while site 5 will produce the lowest among our five study sites. Soil background reflectance differences among study sites could cause different intercepts, and thus the different prediction lines

(Huete 1988). However, since reported yields show a trend similar to predicted yields, it is likely that there are differences in the biomass–wheat yield relationships among farm sites due to site-specific factors such as soils, climate, topography, wheat cultivars or farming practices regardless of the integrated NDVI values from the farm and adjacent areas. This indicates significant interaction between NDVI and location that affect the wheat yield–NDVI parameter relationships. Examination of the shape, length and amplitude of individual farm growth profiles might help interpret biomass–wheat yield relationships. Variations in seasonal growth curve shapes among locations, such as high amplitude/short length or low amplitude/long length, can indicate the climatic and site-specific influences that affect crop performance. While these two curves might produce the same integrated NDVI value, the shape and timing of events in the growth profile might reveal more about the wheat yield than integrated NDVI alone.

Early season NDVI parameters were not consistent indicators of wheat yields. NDVI growth profiles show stronger relationship with spring wheat yield later in the season during grain-filling stage, particularly in late July and August, indicating NDVI values are less related to final grain yield than to biomass accumulation on the ground (tables 1 and 2). For grain crops, a large biomass accumulation early in the season is not directly associated with a large final grain yield. Conditions that affect the flag leaf and second leaf, which are the most active photosynthesizing parts of the plant during grain filling, might greatly increase or decrease final grain yield (Benedetti and Rossini 1993). Therefore, while early-season monitoring might be useful for indicating whether crops have higher biomass than in a typical year, which could be a precursor to a high yield year, subsequent events such as drought, heat stress, insect infestation, disease or lodging that occur later in the season when grain is forming are unpredictable. Crops must be monitored and modelled carefully during this time to make accurate pre-harvest yield estimates.

Critical periods examined on or around the time of maximum NDVI show a significant relationship with wheat yields at the regional scale but not at the farm scale (tables 1 and 2). These summations occur towards the later part of the growing season in July and August, where we have already found good relationships between wheat yield and late season NDVI at the regional scale. Results from our regional study are similar to those obtained by Benedetti and Rossini (1993) and Doraiswamy and Cook (1995), who found NDVI summation periods around the time of maximum NDVI (end of vegetation phase) could be used to estimate wheat grain yields ($R^2=0.515$ and $R^2=0.57$, respectively). At the farm scale, the coarse resolution of NDVI or the biweekly compositing of the images might not adequately characterize crop productivity and farm-scale yields if crop critical periods are 'smoothed over' by the compositing algorithm. Fluctuations in the NDVI crop profile might be lost, or might not be associated with the field from which our data came. In addition, the farm fields of interest, as well as the lands surrounding them, are diverse and vary in size, shape, topography and management practices. Riparian, fallow, a neighbour's crop field or an adjacent field in the same farm can and will contaminate pixels with data that are not associated with the field data used in this study. For use of AVHRR imagery at a farm-scale, coarse resolution will always be a limitation when studying small land features (Quarmby *et al.* 1993, Fischer 1994).

5. Conclusions

NDVI seasonal growth profiles can provide good estimates of regional and farm-scale yield at the end of the growing season and during the later part of the growing season, prior to harvest, at the regional scale. Wheat yield estimates made at the end of the growing season might allow state agencies to improve the accuracy of regional yield statistics, but are too late for aiding early to mid-season farm management decisions. Early-season NDVI parameters provided poor estimates of yield, limiting our ability to provide yield estimates early in the growing season when some farm management decisions need to be addressed. However, early-season farm monitoring with weekly updated NDVI imagery could provide crop yield estimation when little other data is available to land managers for yield estimation.

AVHRR biweekly composite imagery currently provides the best source of regular and historical data at low cost, making it ideal for satellite imagery users. However, higher resolution imagery would provide more accuracy with respect to specific wheat producing areas and provide finer spatial resolution for more precision in-field NDVI parameters, as long as the temporal resolution is adequate. Commercial and government satellites launched starting in 1999/2000 will have higher spatial and spectral resolution, better positional accuracy, improved processing and be available at the temporal frequency needed to monitor fields site-specifically. The cost of these products might be the determining factor for many agricultural applications.

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