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Evaluating the relationship between biomass, percent groundcover and remote sensing indices across six winter cover crop fields in Maryland, United States

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ABSTRACT

Winter cover crops are an essential part of managing nutrient and sediment losses from agricultural lands. Cover crops lessen sedimentation by reducing erosion, and the accumulation of nitrogen in aboveground biomass results in reduced nutrient runoff. Winter cover crops are planted in the fall and are usually terminated in early spring, making them susceptible to senescence, frost burn, and leaf yellowing due to wintertime conditions. This study sought to determine to what extent remote sensing indices are capable of accurately estimating the percent groundcover and biomass of winter cover crops, and to analyze under what critical ranges these relationships are strong and under which conditions they break down. Cover crop growth on six fields planted to barley, rye, ryegrass, triticale or wheat was measured over the 2012–2013 winter growing season. Data collection included spectral reflectance measurements, aboveground biomass, and percent groundcover. Ten vegetation indices were evaluated using surface reflectance data from a 16-band CROPSCAN sensor. Restricting analysis to sampling dates before the onset of prolonged freezing temperatures and leaf yellowing resulted in increased estimation accuracy. There was a strong relationship between the normalized difference vegetation index (NDVI) and percent groundcover ($r^2 = 0.93$) suggesting that date restrictions effectively eliminate yellowing vegetation from analysis. The triangular vegetation index (TVI) was most accurate in estimating high ranges of biomass ($r^2 = 0.86$), while NDVI did not experience a clustering of values in the low and medium biomass ranges but saturated in the higher range (>1500 kg/ha). The results of this study show that accounting for index saturation, senescence, and frost burn on leaves can greatly increase the accuracy of estimates of percent groundcover and biomass for winter cover crops.

1. Introduction

The Chesapeake Bay watershed is located in the mid-Atlantic on the East Coast of the United States. The Chesapeake Bay is the largest estuary in the United States, with the watershed comprising portions of six states and the District of Columbia (Goetz et al., 2004). Nutrient runoff from farmland has negative effects on water quality in the Chesapeake Bay. Residual nitrate in the soil profile after crop harvest is subject to leaching from agricultural areas into groundwater and adjacent tributaries. Pollution from nutrients and sediment has negative consequences for waterways, including eutrophication, reduced stocks of fish, and declining habitats through destruction of submerged aquatic vegetation (Dauer et al., 2000). These conditions have worsened in the Chesapeake Bay over time, in part due to fertilizer and manure application on agricultural lands (Jordan et al., 1997).

1.1. Cover crops

Planting cover crops is an effective method to reduce both nitrogen leaching and sedimentation from agricultural lands (Meisinger et al., 1991). Winter cover crops are planted post-harvest on corn and soybean fields to scavenge residual nitrogen that remains in the soil, and to meet soil groundcover conservation guidelines, providing substantial water quality benefits (Dabney, 1998; Delgado et al., 2007). Cover crops accumulate biomass during the fall, with

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Table 1
Extent of winter cover crops enrolled in the Maryland agricultural cost share program during the winter of 2012–2013. Data were provided by the Maryland agricultural cost share program.

Species	Hectares (% of total)	Hectares	Fields (% of total)	Number of fields
Wheat	67	112061	62	7981
Barley	15	24491	14	1795
Rye	12	20182	17	2246
Forage radish	3	5369	2	320
Triticale	2	3201	2	288
Spring oats	1	2117	2	228
Ryegrass	<1	468	<1	29
Canola/rapeseed	<1	196	<1	14
Clover/wheat	<1	152	<1	5

growth slowing through the winter, and typically green up again in the spring. Earlier planted cover crops are able to accumulate more biomass prior to the onset of cold weather (Hively et al., 2009), leading to increased water quality benefits. In addition to planting date, a variety of factors, including species, planting method, and the amount of residual nitrogen available in soils, can lead to a large range of biomass and groundcover outcomes on cover cropped fields. Because increased biomass is related to increased groundcover and nutrient uptake, it is important to be able to accurately estimate cover crop biomass.

A majority of the Chesapeake Bay estuary is located in Maryland. The Maryland Department of Agriculture (MDA) offers cover crop subsidies to farmers with the Maryland agricultural water quality cost-share (MACS) program, through which farmers can either plant traditional non-harvested cover crops or commodity cover crops for harvest. Table 1 shows the breakdown of Maryland subsidized cover crops that were planted during the 2012–2013 cover cropping season.

During 2012–2013, wheat was the most common cover crop in terms of both acreage and percent of enrolled fields. Together, barley, rye and wheat contributed 96% of the cover crop acreage in Maryland. Triticale and ryegrass covered over 3500 ha combined.

Following winter dormancy, cover crops typically experience a spring green-up when warm temperatures return, allowing for additional nitrogen uptake before kill-down, if residual nitrogen is left in the soil (Dabney et al., 2001). Availability of soil nitrogen also plays a role in the accumulation of biomass, with some cover crops growing poorly due to nitrogen limitation. The amount of fall residual soil nitrogen found in different fields can vary based on the previous crop's performance relative to fertilization, temperature, and rainfall.

In addition to reducing nutrient runoff, cover crop groundcover provides protection from raindrop impact and increases soil aggregate stability, decreasing erosion by wind and water (Dabney et al., 2001). If plants can reach their tiller stage (formation of side shoots) before winter dormancy, they are able to cover a greater amount of soil, resulting in better erosion control and environmental outcomes (De Baets et al., 2011; Fisher et al., 2011). Along with high residue tillage practices, cover crops are often used to meet groundcover requirements on highly erodible lands (Mirsky et al., 2009).

1.2. Phenology and spectral indices

Remote sensing indices that measure plant greenness based on reflectance in the near-infrared and visible wavelengths are often used to estimate aboveground biomass (Gitelson, 2004), and can also be used for measuring percent vegetative groundcover (Purevdorj et al., 1998 Wiegand et al., 1991). Such data can be gathered through remote sensing instruments such as Earth-orbiting satellites, aerial photos, proximal sensors, or other means. The atmosphere can create differences in the relationship between surface reflectance and radiance detected at the sensor, and ground-based proximal sensors can be utilized to minimize atmospheric effects. A majority of solar radiation in the visible spectrum is absorbed by pigments in the leaves, resulting in low transmittance and reflectance, and the chlorophyll adsorption feature maximally reduces reflectance in the red portion of the spectrum (around 660 nm) with slightly less adsorption in the green wavelengths (around 550 nm). Low reflectance in the red is coupled with increased brightness in the near-infrared region of the spectrum, where there is low absorption and high transmittance and reflectance (Tucker and Sellers, 1986). Ratios of low-reflecting red and high-reflecting infrared measurements allow for unit-less measures of the chlorophyll absorption peak in green vegetation. A myriad of vegetation indices have been developed and researched over the years, 10 of which are shown in Table 2.

Testing multiple indices is useful, because at low fractional vegetated groundcover factors such as soil reflectance may interfere with the vegetation signal, and different indices are more sensitive in different ranges of biomass and groundcover. In cover crop fields there may be little growth by the beginning of the winter season due to low temperatures and late planting dates, leading to limited horizontal layering of plants and a reduced impact on reflectance from canopy structure. On one hand, this limited horizontal layering

Table 2
Definition of spectral indices. Bands are designated in the formulas as R (red), B (blue), G (green), RE (red-edge), NIR (near-infrared), and L (soil line).

Index	Name	Citation	Formula
NDVI	Normalized difference vegetation index	Tucker (1979)	(NIR − R)/(NIR + R)
GNDVI	Green normalized difference vegetation index	Moges et al. (2004)	(NIR − G)/(NIR + G)
SR	Simple ratio	Tucker and Sellers (1986)	NIR/R
SAVI	Soil-adjusted vegetation index (L = 0.5)	Huete (1988)	[(NIR − R)/(NIR + R + L)](1 + L)
G − R	Green minus red		G − R
EVI	Enhanced vegetation index	Huete et al. (2002)	2.5(NIR − R)/(NIR + 6 × R − 7.5 × B + 1)
TVI	Triangular vegetation index	Broge and Leblanc (2000)	0.5[120(NIR − G) − 200(R − G)]
NGRDI	Normalized green red difference index	Tucker (1979)	(G − R)/(G + R)
VARI	Visible atmospherically resistant index	Gitelson et al. (2002)	(G − R)(G + R − B)
NDREI	Normalized difference red edge index	Gitelson and Merzlyak (1994)	(RE − R)/(RE + R)

can reduce complexity in the relationship between remote sensing observations and surface conditions. However, low levels of canopy cover may cause inaccuracies due to background reflectance of soils and crop residues interfering with the vegetation signal (Huete, 1988). At higher biomass, plants can have a complicated relationship with biomass due to their canopy structures. At higher biomass, especially in plants with planophile leaf structure, the sensitivity of the normalized difference vegetation index (NDVI) and other indices saturates as the canopy closes, and additional increases in biomass do not result in increased reflectance (Myneni and Williams, 1994).

Winter cover crops are unique because they experience a variety of wintertime conditions that can lead to reduced leaf greenness. Very cold temperatures can cause leaf burn and frost damage that is not recoverable, unlike spring-planted crops that would not experience such low temperatures. Certain species, such as barley, are more susceptible to damage caused by low temperatures (Andrews, 1987). Cover crops are also susceptible to nutrient deficiency over wintertime, in soils with low soil nitrogen and low nitrogen mineralization potential. Once plants have used the residual nitrogen remaining in the soil, chlorosis or yellowing of leaves may occur (Broge and Mortensen, 2002). Lastly, cold temperatures and reduced day length during wintertime can also initiate senescence and dormancy (Gregersen et al., 2008). During this process, the plant partitions resources away from the leaves toward other tissues and chloroplasts begin to degrade (Gan and Amasino, 1997). Unlike frost burn, yellowing leaves can recover during springtime green-up, with the onset of warmer temperatures and increased springtime nitrogen availability. Index saturation, chlorosis, and frost damage may lead to inaccurate estimates of aboveground biomass when using vegetation indices to measure greenness of crops, regardless of species.

Cover crops impact water quality by decreasing erosion and leaching of residual soil nitrogen into waterways. Therefore, it is important to understand what factors influence remote sensing measurements of percent groundcover and biomass when considering cover crops on a landscape scale. Problems persist in methodologies to accurately correlate biomass to greenness, including relating biomass to vegetation indices through various growth stages, accounting for differences in phenology among species, and accounting for wintertime conditions that can cause reduced leaf greenness. As winter cover crops become more popular as a best management practice to prevent nutrient and sediment pollution in waterways, knowledge of factors that influence the relationship between remote sensing measurements and plant groundcover and biomass is necessary.

1.3. Study objectives

The primary objective of this study was to determine to what extent remote sensing indices are capable of accurately estimating the percent groundcover and biomass of winter cover crops. A second objective involved analyzing under what critical ranges these relationships are strong and under which conditions they break down.

2. Materials and methods

2.1. Study site and experimental design

Six field locations at the U. S. Department of Agriculture (USDA), Agricultural Research Service (ARS), Beltsville Agricultural Research Center (BARC) were selected for this study. Fig. 1 shows the study location, the six fields and the sampling points.

The study sites were planted to cover crops in the fall of 2012 at various planting dates, following the harvest of summer row crops, and were not fertilized prior to March 1, 2013. The fields were planted to cover crops as a part of good field management practices but did not follow a specific experimental design, and therefore represented conditions found within the local farm landscape. The species of cover crop included barley (*Hordeum vulgare* L.), ryegrass (*Lolium multiflorum* Lam.), triticale (*Triticale hexaploide* Lart.), 'Aroostook' rye (*Secale cereale*), and wheat (*Triticum aestivum* L.). Information regarding management practices on these fields can be found in Table 3.

ArcGIS 10.2 was used for geospatial processing of field locations and sampling points (Esri, 2013). Field boundaries were digitized by hand, using a "leaf-on" aerial photograph downloaded through the USDA's Farm Services Agency's (FSA) National Agricultural Imagery Program (NAIP) as a base layer.

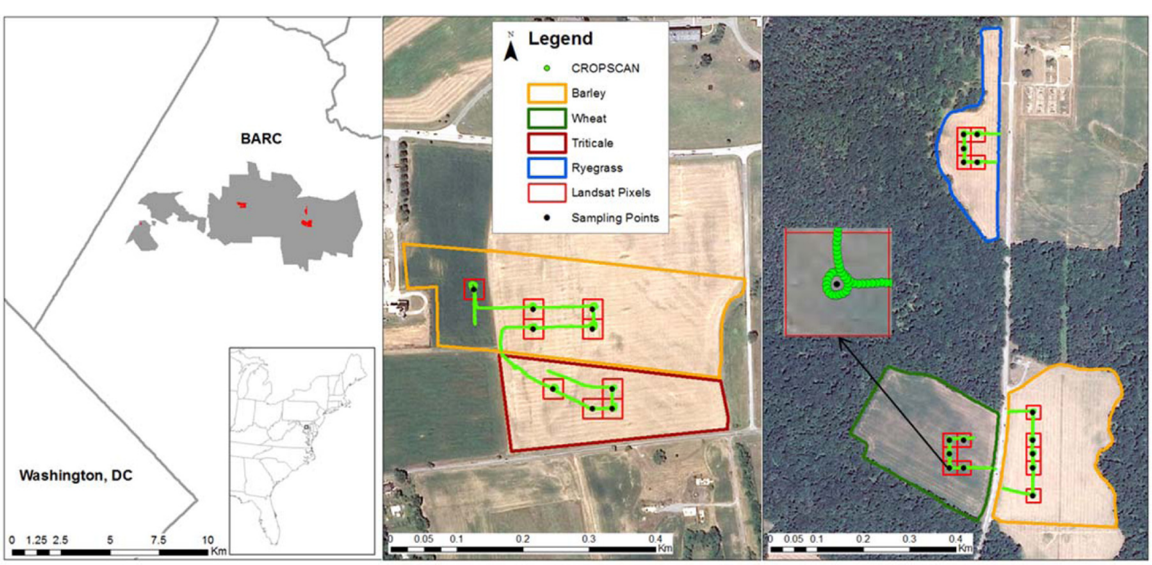

Fig. 1. Red areas in the large area map (left panel) represent the six sampled fields. Field sampling occurred near flagged locations at the centroids (black points) of Landsat pixels (red boxes) falling within the center of each sampled field. Green points indicate the walking track of GPS-enabled CROPSCAN instrument (rye not shown). All fields were located on the USDA Beltsville Agricultural Research Center (BARC) near Beltsville, Maryland. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 3
Agronomic data for the six sampled fields, including fertilization schedules, previous crop, weed treatment, planting, and spring harvest/kill dates.

	Triticale	Wheat	Ryegrass
Planting date	10/11/2012	10/25/2012	9/26/2012
Size (hectares)	3.6	6.6	3.5
Previous crop	Corn silage	Double crop soybean	Corn
Fall fertilizer (%N)	16.5	16.5	16.5
Fall fertilizer UAN (gal)	5	5	5
Weed treatment	na	Harmony Xtra	na
First spring fertilizer date	3/1/2013	3/1/2013	3/1/2013
Second spring fertilizer date	4/1/2013	4/1/2013	4/1/2013
Spring fertilzer type	Nitrogen/sulfur	Nitrogen	Nitrogen/sulfur
Spring fertilizer amount (lb)	60/5	80	60/5
Spring harvest date	5/13/2013	6/30/2013	5/4/2013
Spring harvest type	Silage	Straw and grain	Silage
Spring harvest yield (kg/ha)	10,088	3699	8967
	Rye	Barley1	Barley2
Planting date	9/25/2012	9/24/2012	9/20/2012
Size (hectares)	na	7.0	7.6
Previous crop	Soybean	Soybean	Soybean
Fall fertilizer (%N)	0	16.5	16.5
Fall fertilizer UAN (gal)	na	5	5
Weed treatment	na	Harmony Xtra	Harmony Xtra
First spring fertilizer date	na	3/1/2013	3/1/2013
Second spring fertilizer date	na	4/1/2013	4/1/2013
Spring fertilzer type	na	Nitrogen	Nitrogen
Spring fertilizer amount (lb)	na	65	65
Spring harvest date	na	6/18/2013	6/10/2013
Spring harvest type	na	Grain	Straw and grain
Spring harvest yield (kg/ha)	na	na	3497

For all species except rye, sampling locations were established at the centroid points of Landsat satellite imagery pixels. Landsat pixels were used as a basis for selection of sampling points to allow for future comparisons between ground-based proximal sensor readings and satellite images, but satellite imagery analysis is not reported in this manuscript. Up to five pixels were chosen near the middle of fields to eliminate field border effects, and selected pixels were buffered by 5 m to eliminate edge effects between pixels. A centroid was calculated for each selected pixel, the coordinates of these pixels were loaded into a Trimble GeoXH GPS receiver with sub-meter horizontal accuracy, and flags were placed in the fields at each centroid location.

Unlike other fields, rye measurements were obtained from a plot-scale replicated trial maintained by Beltsville scientists, and rye sampling locations were therefore not based on Landsat pixels. Field sampling in all locations took place at multiple dates between October 12, 2013, and April 26, 2013 (Fig. 2).

2.2. Proximal sensor field measurements and analysis

2.2.1. CROPSCAN

Reflectance spectra at each sampling location were measured using the CROPSCAN MSR16R hand-held multispectral radiometer (CROPSCAN Inc., 2013). The CROPSCAN gathers data across 16 distinct wavebands between 460 and 1640 nm, based on specific filter characteristics. It utilizes a two-way sensor to measure incident irradiation upon the top of the instrument, as well as reflected irradiation from the ground, and uses these two measurements to calculate percent reflectance for each waveband. The unit was linked to a Trimble GPS unit that recorded geographic coordinates of each data point. The handheld sensor recorded a reflectance reading approximately every 3 s as the sensor was walked in a circle within a 3 m radius of each sampling point (Fig. 1). The CROPSCAN was held at a height of approximately 1.8 m directly above the canopy, and the diameter of the field of view was 0.9 m. CROPSCAN relies on skylight illumination, and sun angles far from nadir can contribute to insufficient radiation reaching the sensor. Data were only collected during mid-day times with adequate sun angle and minimal cloud cover. Additionally, all data values that were collected with irradiance measurements below 300 w/m^2 were deleted from the analysis. Readings below this level may be inaccurate due to cloud cover and insufficient signal to noise ratio. Transects of collected data were converted into point shapefiles and were loaded into ArcGIS. To find the average for each sampling location, CROPSCAN points falling within each buffered Landsat pixel were averaged for each band. These averages were later used in calculation of vegetation indices. Multiple vegetation indices (Table 2) were calculated using the following CROPSCAN filter bands: blue (435–521 nm), green (556–566 nm), red (629–687 nm), red-edge (727–737 nm), and NIR (844–856 nm).

2.2.2. RGB photographs

Vertical, downward-looking (nadir) RGB photographs were taken from shoulder height (approximately 1.5 m) using a Nikon D5100 digital single-lens reflex (DSLR) camera in the red, green and blue channels of the visible spectrum. Three photos were taken within 3 m of every flag location on each sampling date. Photos were processed to determine percent vegetative groundcover using SamplePoint software (Booth et al., 2006). This software was used to generate 200 random points over the photo and the user determined the type of groundcover under each crosshair point based on specified categories, including: green vegetation, bare soil, crop residue, frost damaged/yellowed vegetation, dark vegetation, dark bare soil, dark crop residue, dark frost damaged/yellowed vegetation, bright vegetation, bright bare soil, bright crop residue and bright frost damaged/yellowed vegetation. Categories were combined to quantify all vegetation, green vegetation, yellowed vegetation, crop residue, and exposed soil.

2.3. Plant and soil samples

Field samples of aboveground biomass were gathered within 3 m of each flagged sampling location using a destructive quadrat sampling (0.5 m^2) technique where three adjacent 1 m rows of cover crop were cut at ground height. The field study sites for barley1, barley2, wheat, and ryegrass had five flagged sampling

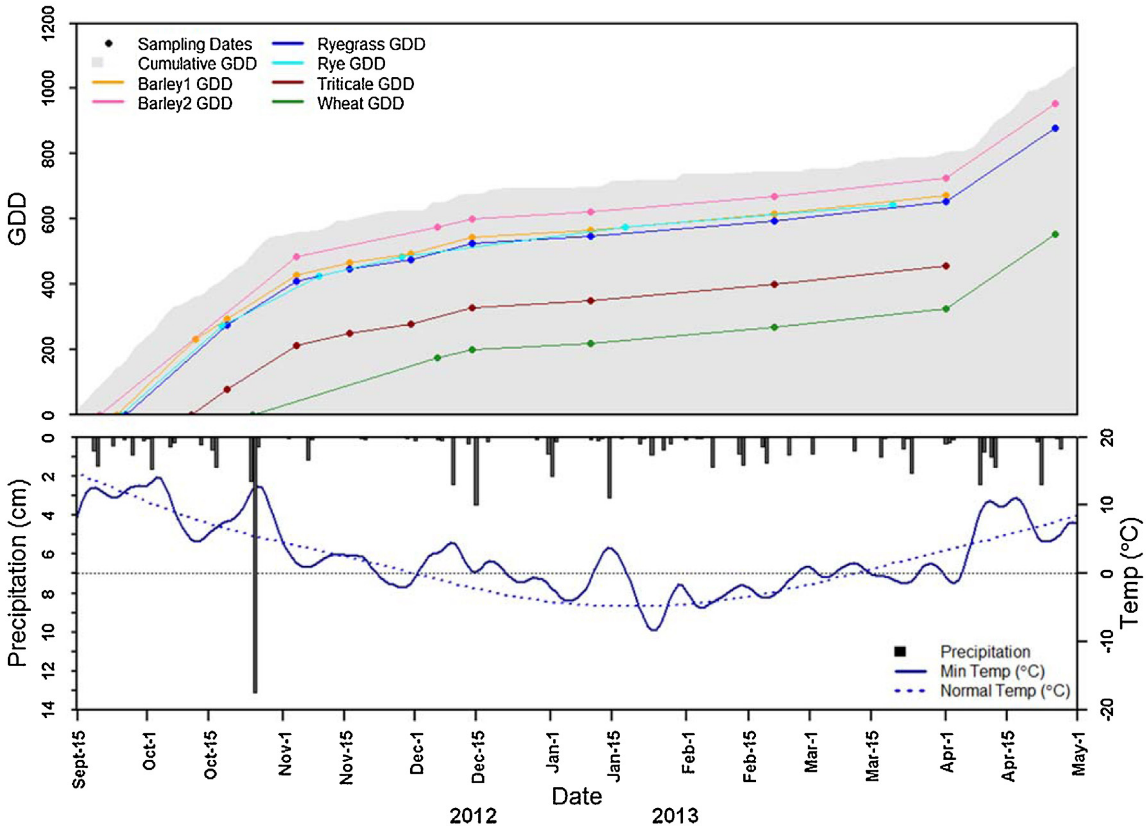

Fig. 2. Accumulated growing degrees (GDD) after planting for each sampled field with sampling dates (points), along with daily precipitation (black bars), 30-year daily normal minimum temperature (dashed blue line), and the observed daily minimum temperature (solid blue line) for 2012–2013 (NOAA–NCDC). The horizontal dotted black line represents 0 °C. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

points per field; triticale had four sampling points; and rye had three sampling points. Plant samples were dried overnight at 60 °C and weighed. Dry weights and sampling area were extrapolated to estimate cover crop biomass at the field scale (kg/ha). Three 30-cm deep, 4-cm diameter soil cores collected near each flag location were combined into one bulk sample, dried at 50 °C, extracted with 2 M KCl, and analyzed for nitrate/nitrite content using colorimetric Lachat flow injection analysis in the laboratory.

2.4. Growing degree days

Calculation of growing degree days (GDD) predicts the timing of phenological milestones and normalizes for planting date by incorporating accumulated temperature, which is often a better predictor of plant growth than calendar date (McMaster and Wilhelm, 1997). The calculation assumes a base temperature below which plants are unable to grow, and although this base temperature can vary based on species, for winter small grains it is often calculated with base temperatures of either 0° or 4 °C. Daily GDD were calculating using the following formula (McMaster and Wilhelm, 1997):

$$GDD = \left[\frac{T_{max} + T_{min}}{2}\right] - T_{base}$$

where T_{max} and T_{min} were daily maximum and minimum temperatures, and T_{base} was set to 4 °C on advice of local agronomists. Mean temperatures below T_{base} were set to T_{base}, and then base temperature was subtracted from this value. The results were then used to calculate a cumulative sum of GDD between the planting date and the sampling date. For cover crops with planting dates in early fall, a larger number of GDD will elapse before spring termination, and the plants tend to produce higher biomass compared to late-planted species. This reaction to planting date and GDD has been widely documented in other research (Dabney et al., 2001; Hively et al., 2009).

2.5. Climate data

Daily weather data for Beltsville were gathered from the National Atmospheric and Ocean Administration (NOAA) National Climatic Data Center (NCDC) for the Beltsville, Maryland, weather station. Long-term (30-year) climate daily normals (averages) were obtained for the same climate station.

3. Results and discussion

Planting dates for each field ranged from September 20, 2012, to October 25, 2012 (Table 3), and field sampling dates ranged from October 12, 2012, to April 26, 2013. Fig. 2 shows sampling dates and cumulative GDD for each field over time.

Precipitation in 2012–2013 was well-distributed (Fig. 2) and sufficient for cover crop growth. Subzero weather, during which plant tissue damage might be expected, occurred in four distinct periods: November 22–December 1; December 23–January 10; January 19–March 5; and March 10–April 4. The two periods from December 23 to January 10, and from January 19 to March 5, were the coldest and most prolonged periods of subzero weather.

3.1. Species-specific crop growth

The USDA Natural Resources Conservation Service has established a minimum threshold for conservation tillage at 30%

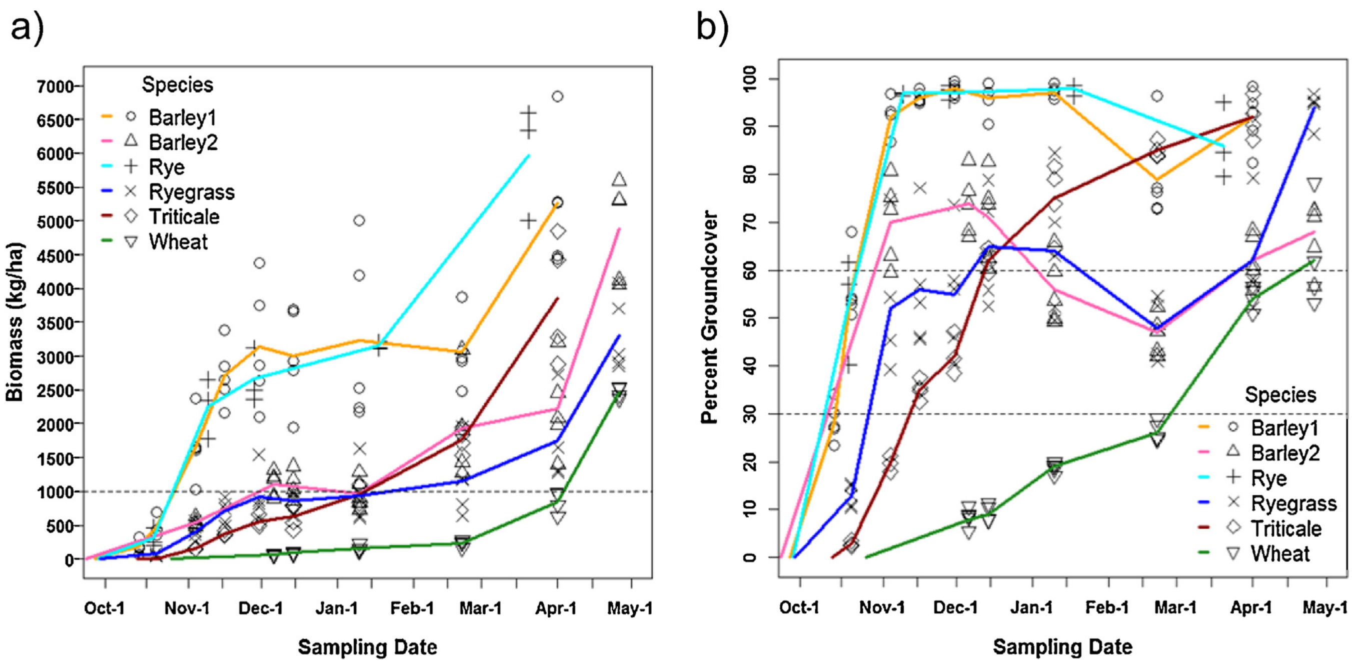

Fig. 3. (a) Biomass accumulation and (b) percent groundcover on sampled fields.

groundcover (ASAE, 2005), which will control approximately 50% of soil erosion resulting from raindrop impact. A threshold of 60% groundcover will reduce erosion by approximately 80%, depending on soil texture (Daniel et al., 1999). The Chesapeake Bay Program currently defines residue management classes as: high intensity tillage (0–30% groundcover); low intensity tillage (30–60% groundcover); and high residue management practices (>60% groundcover) (Chesapeake Bay Program, 2013). Groundcover thresholds can be achieved using either crop residue or vegetative materials such as winter cover crops. For nitrogen conservation, achieving a wintertime cover crop biomass threshold of at least 1000 kg/ha has been shown to substantially reduce soil nitrate concentrations (Hively et al., 2009), accounting for approximately 20 kg/ha N if a 2-% tissue N content is assumed. Reaching these conservation goals can lead to increased water quality benefits by cover crops.

All sampled cover crops except for the late-planted wheat field eventually reached 60% groundcover (Fig. 3b, Fig. 4). Barley1 and rye accumulated groundcover quickly and had 60% groundcover by November 4 and 9, 2012, respectively. Barley2 reached 60% groundcover by November 4, fell below the threshold during mid-winter, and recovered by April 1, 2013. Triticale, although planted late, achieved 60% groundcover by December 14, 2012. Ryegrass, although planted in early fall on September 26, did not uniformly reach 60% groundcover until very late in the spring, on April 26, 2013.

For biomass, barley1 and rye exceeded 1000 kg/ha by early November (Fig. 3a). Ryegrass and barley2 reached 1000 kg/ha by early December, and triticale slightly later, in early January. Wheat did not reach the 1000-kg/ha threshold until early April, much later than the other fields.

The growth differences between the two barley fields, which had similar planting dates, could be explained by initial soil nitrogen. On November 4, 2012, barley1 had high residual soil nitrogen content (50 N kg/ha) due to long-term historical manure application on that field, whereas barley2 was more nitrogen limited with a residual soil nitrogen content of 6 N kg/ha. Although barley2 was planted slightly earlier, barley1 exhibited faster growth and earlier achievement of environmental thresholds. Despite these differences, both fields reached the critical thresholds before the onset of winter temperatures.

3.1.1. Greenness over time

The amount of leaf yellowing varied considerably among species over the sampling period. Triticale and wheat, which had later planting dates (October 11 and 25, 2012, respectively) exhibited negligible yellowing of leaves (Fig. 4) with a continuous rise in NDVI values from 0.3 in the fall to greater than 0.8 in the spring (Fig. 5a and b). Ryegrass and rye had earlier planting dates (September 26 and 25, 2012, respectively), and exhibited yellowing of up to 20% of leaves during winter (Fig. 4) with a corresponding slight dip in NDVI (Fig. 5c and d), and by the spring had greened up to less than 10% yellowed leaves, The two barley fields, planted on September 23 and 24, experienced more yellowing than all other fields during the sampling period, with over 40% of leaves affected by February (Fig. 4). Although the barley fields also greened up in springtime, there was still a large amount of yellowing in spring. Mid-winter NDVI values decreased significantly on both barley fields due to frost damage and leaf yellowing (Fig. 5e–f). These results indicate that early planted cover crops experienced more frost damage, perhaps because they achieve a later growth stage by the onset of cold weather, with particular susceptibility of barley. Leaf yellowing and frost damage reduced reflectance in the NIR and increased reflectance in the red wavelengths, resulting in reduced NDVI values.

3.1.2. Biomass over time

Biomass increased on all fields over time, although some fields experienced a slight decrease in biomass over the mid-winter months. Triticale, wheat, and rye rose steadily with no decrease in biomass or NDVI. Although rye did not experience a reduction in NDVI, it reached NDVI saturation earlier than triticale or wheat. Due to some yellowing on ryegrass, NDVI dipped during the wintertime, though not as severely as barley1 and barley2, both of which reached NDVI saturation and experienced yellowing that resulted in a drop in NDVI during the winter months (Fig 5c and e–f). Barley2 followed a similar pattern as barley1, accumulating biomass before it experienced a drop by January 10, 2013. Barley2 experienced greening up by the last sampling date.

3.1.3. Percent groundcover over time

All fields except for wheat and barley2 reached near 100% groundcover by the end of the sampling period. Triticale and wheat had steady rises in both percent groundcover and NDVI (Fig. 6a and b). Ryegrass generally followed the same trend but did experience some yellowing and had a drop in NDVI corresponding to percent groundcover (Fig. 6c). Rye also rose steadily but reached 100% cover earlier than all fields except for barley1 (Fig. 6d). Both barley fields experienced a drop in percent groundcover from significant mid-winter yellowing, with a corresponding drop in NDVI, although barley1 achieved higher overall groundcover (Fig. 6e–f).

3.2. Spectral indices and percent groundcover

Preventing erosion by achieving high percent groundcover on agricultural fields is a goal of planting winter cover crops. Vegetative groundcover prevents erosion from both wind and water, regardless of whether it is green or yellowing, and accurately estimating percent groundcover is important for assessing cover crop success.

There was considerable yellowing and damage to leaves after January 1, 2013, on all fields except for triticale and wheat. Groundcover assessment of shoulder-height photos showed that frost damage occurred during three periods of sub-zero temperatures between January 1, 2013, and mid-March (Fig. 2), particularly in barley and ryegrass fields (Fig. 6). Spectral vegetation indices are most sensitive to healthy green vegetation and do not detect yellowed and browned leaves, although this plant material continues to reduce erosion and nutrient loss. A higher percentage of leaves with yellowing or damage will reduce the correlation between remote sensing indices and percent groundcover. Such winter effects varied widely across the fields (Fig. 6). The percent groundcover measurements that were determined from RGB shoulder-height photos were split into two categories: green plus yellowed and frost damaged groundcover, and green groundcover only. Regressing the spectral indices with groundcover data collected prior to January 1, 2013, before the onset of reduced leaf greenness, resulted in higher correlations than using the entire date

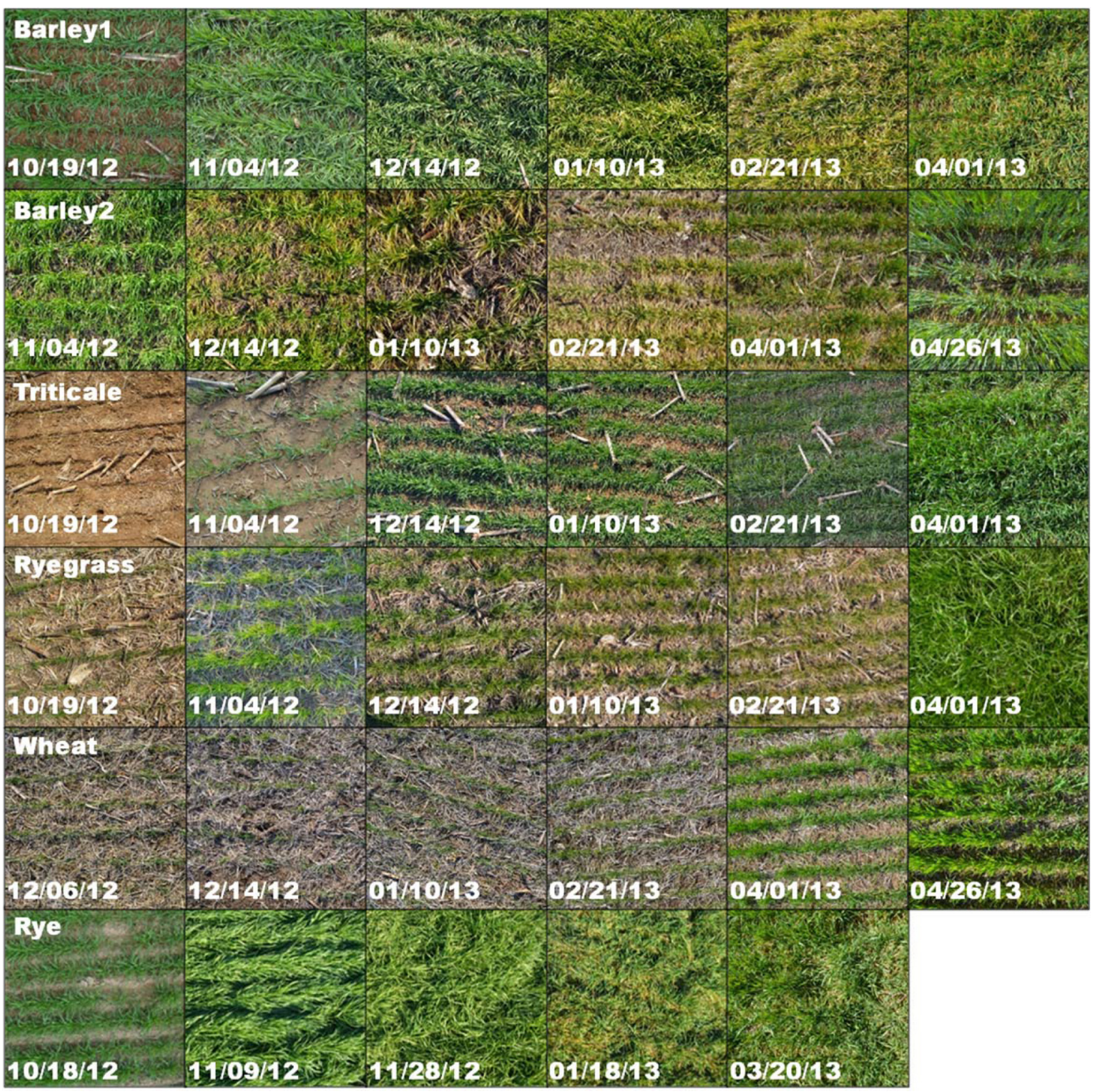

Fig. 4. Shoulder-height photos of the measured cover crop species at various sampling dates throughout the winter of 2012–2013. Leaf yellowing can be noted in the January and February images.

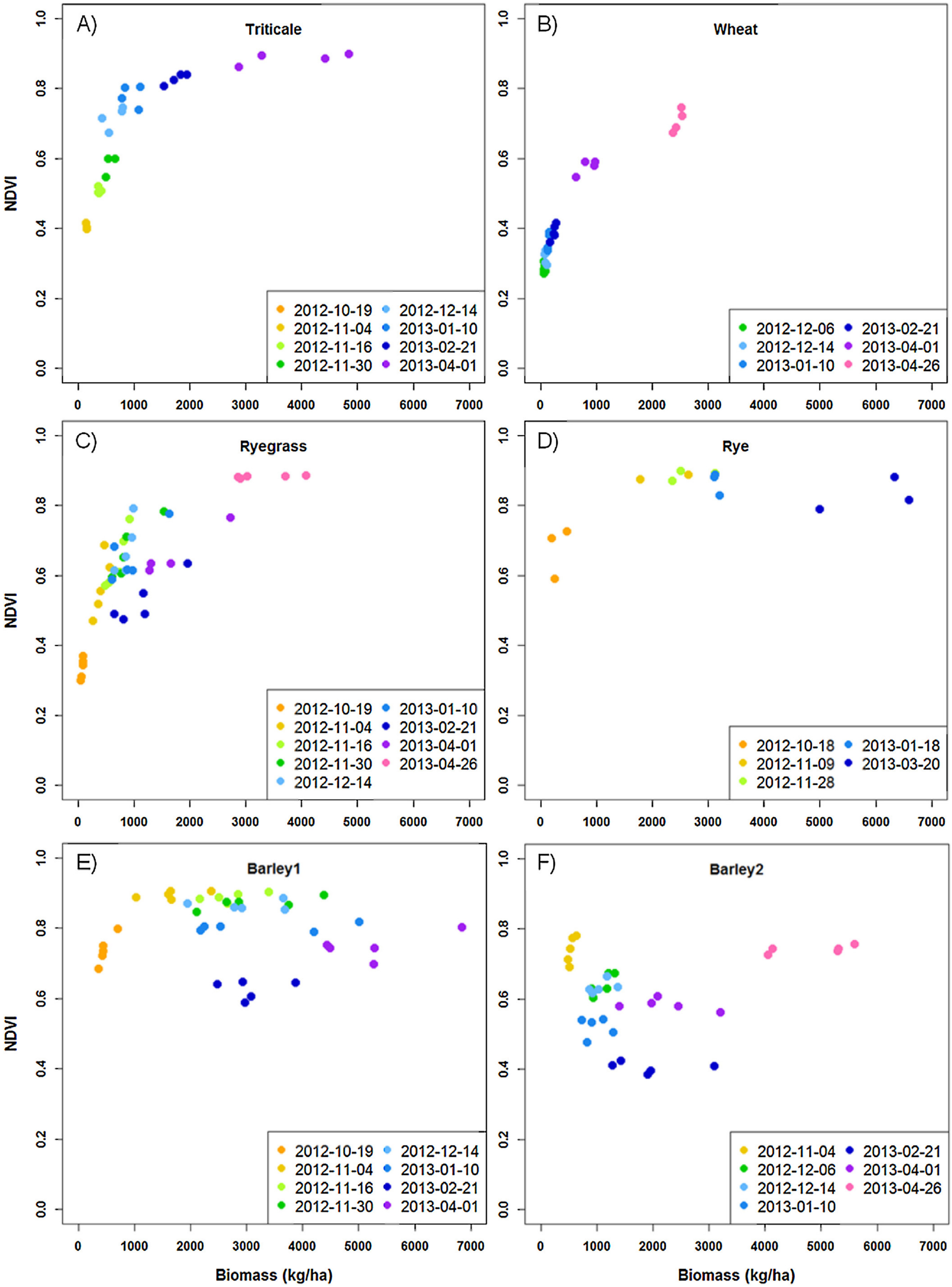

Fig. 5. Aboveground biomass for the six sampled fields versus the normalized difference vegetation index (NDVI) associated with each sampling date.

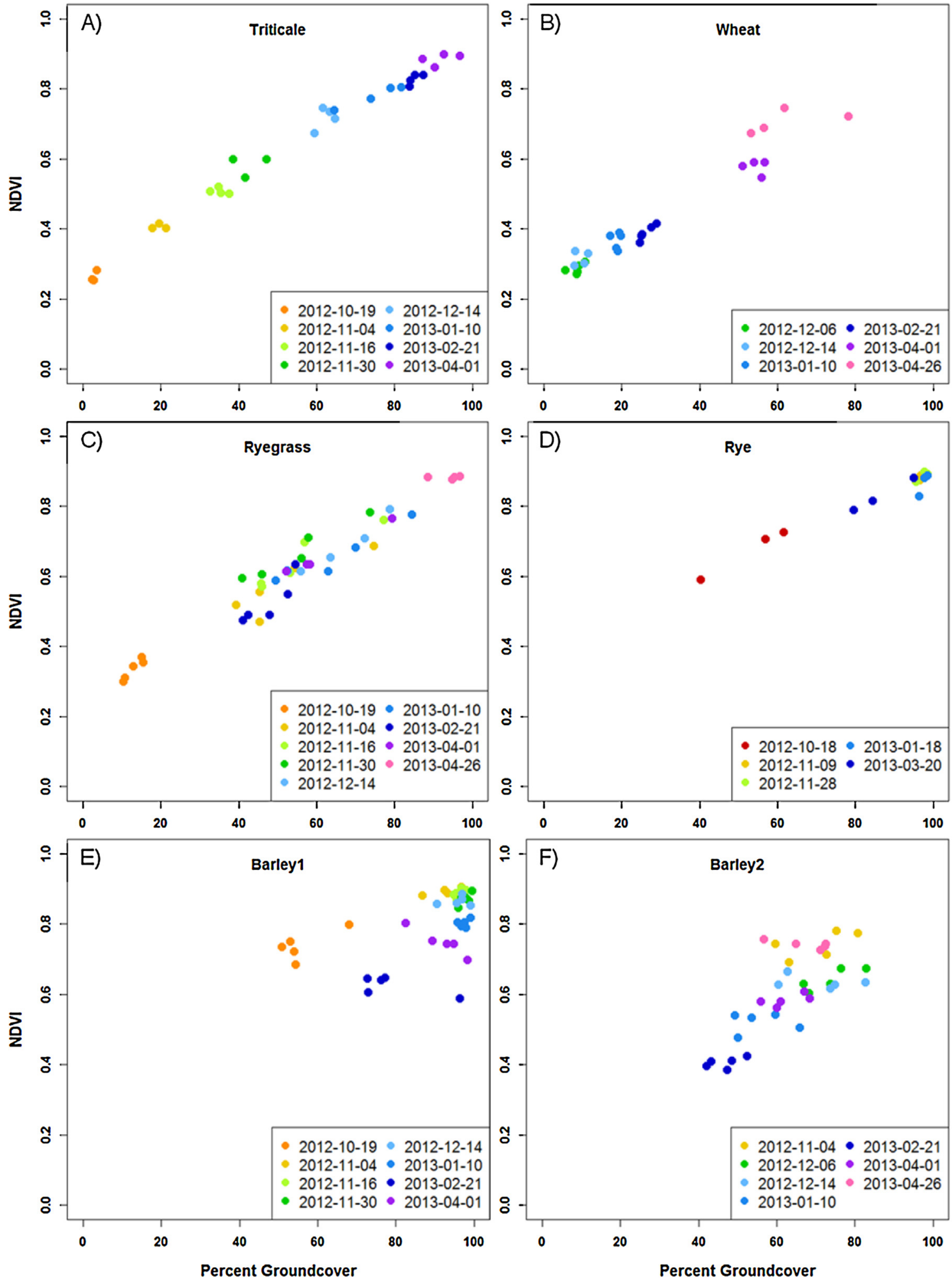

Fig. 6. Percent groundcover for the six sampled fields versus the normalized difference vegetation index (NDVI) associated with each sampling date.

range, and were comparable to those made using green vegetation only (Table 4).

Although vegetation indices performed relatively well (r^2 = 0.64–0.88) in predicting the groundcover of all vegetation (green, yellowed, and frost damaged) for all sampling dates, goodness of fit increased across all indices (r^2 = 0.74–0.94) when groundcover was restricted to green-only vegetation (Table 4). Regression using restricted dates, prior to January 1, yielded similar values to green-only (r^2 = 0.75–0.95) and can be used as a proxy for green vegetation. This is evidenced by small differences of less than 0.08 in r^2 values between all vegetation and restricted dates versus green-only and unrestricted dates. The highest correlations were

Table 4
Linear model goodness of fit (r^2) values between spectral indices and percent groundcover for all vegetation (green plus yellowed and frost damaged) versus green-only vegetation, for all sampling dates and for early sampling dates (October 18, 2012, through December 14, 2012). For definitions of indices see Table 2.

All sampling dates	NDVI	GNDVI	SR	SAVI (L = 0.5)	G – R	EVI	TVI	NGRD	VARI	NDREI
All vegetation	0.87	0.84	0.64	0.88	0.78	0.79	0.85	0.73	0.73	0.83
Green vegetation	0.94	0.90	0.74	0.94	0.86	0.90	0.87	0.83	0.83	0.90
Early sampling dates										
All vegetation	0.93	0.88	0.72	0.93	0.94	0.88	0.89	0.88	0.88	0.89
Green vegetation	0.95	0.91	0.75	0.95	0.93	0.91	0.89	0.89	0.89	0.92

for green-only and restricted dates, as this eliminated yellowing and frost damaged vegetation.

For prediction of green groundcover, NDVI, SAVI, and G – R performed better than other indices. SAVI was calculated setting L = 0.5, a typical value for medium amounts of vegetative cover, creating an upper limit of 1.5 (Huete, 1988). However, setting the optimal value for L requires some existing knowledge on amount of groundcover, whereas NDVI does not require such knowledge. G – R yielded good results for percent groundcover. As green reflectance is high in healthy vegetation and red reflectance is low, while the opposite is generally true with soils, positive values can be associated with vegetative groundcover while negative values are associated with soil. Further discussion regarding measurement of groundcover using spectral indices is limited to NDVI, as this index always outperformed or performed equally to the other indices when assessing percent groundcover.

There was a strong linear relationship between percent groundcover (green, yellowed, and frost damaged) and NDVI, regardless of species, and across all levels of groundcover, with an r^2 value of 0.87. Restricting the analysis to dates before reductions in leaf greenness occurred increased this correlation and resulted in an r^2 value of 0.93, making it nearly as effective as the correlation with green-only vegetation (0.94). This demonstrates that improvements can be made in the relationship between NDVI and percent groundcover by using climate data to assess when freezing may have occurred and modeling data separately before and after freezing temperatures. This method is especially useful where information about amounts of green versus yellowed or frost-burned vegetation is not readily available.

As previously noted, vegetative cover, whether green, yellowed or frost damaged, is useful in preventing sediment erosion into waterways. NDVI performed well when assessing percent groundcover but, like other indices designed to measure vegetation vigor, it underestimated total vegetative cover because NDVI is not sensitive to senesced vegetation. Early-planted cover crops, including barley and ryegrass, had more leaves at the onset of prolonged freezing temperature and suffered increased frost damage to leaves. Wheat had the latest planting date and while it did not yellow or experience frost burn, it also did not achieve maximum groundcover or biomass (Fig. 4, Fig. 5b and Fig. 6b). Although late planted crops may experience less leaf damage and may have a better correlation to vegetation indices, they are not more successful than cover crops that suffered extensive leaf damage but exhibited high biomass and percent groundcover due to robust growth in the early winter period. Because of the effects of leaf yellowing and frost burn on vegetation indices, remote sensing tends to underestimate the groundcover of winter cover crops.

As seen in Fig. 7, saturation in both NDVI and percent groundcover measurements results in a clustering of points near 100% groundcover and 0.9 NDVI. Removing these points from analysis yields an r^2 of 0.89 for all vegetation across restricted dates. This demonstrates that NDVI and other indices can successfully measure percent groundcover resulting from cover crop establishment through critical thresholds, from 0 to 80% groundcover, with considerable accuracy.

3.3. Spectral indices and biomass

Wintertime assessments of cover crop biomass are unique in that the plant tissues are subject to freezing temperatures that can result in significant leaf yellowing and frost burn. As a result, the utility of vegetation indices to estimate total plant biomass may become limited. Results for the 10 vegetation indices that were correlated with biomass using linear regression and log-linear regression (ln Biomass) are shown in Table 5.

Spectral indices are most sensitive to green living vegetation, whereas field sampled biomass included both living and dead plant material. Therefore, index performance for all sampling dates was poor with r^2 ranging from 0.26 to 0.40 (Table 5). When evaluation was limited to early sampling dates prior to January 1, 2013, to avoid the effects of leaf yellowing and frost damage, correlations improved substantially with r^2 ranging from 0.59 to 0.84.

When linear regression was limited to early sampling dates, SR, EVI, NGRD, VARI and NDREI all demonstrated a limited ability to detect meaningful differences at low biomass and also saturated at high biomass (figures not shown) leading to low overall goodness of fit (Table 5, early sampling dates with log transformation). While NDVI, GNDVI, SAVI and G – R where more accurate at lower biomass, they also saturated at high biomass. The problem of index saturation has been widely documented in the literature, especially for agricultural landscapes (Mutanga and Skidmore, 2004; Thenkabail et al., 2000). As an example, Fig. 8 shows the relationship between measured biomass and NDVI for all species. In Fig. 8b, the NDVI index saturates above approximately 0.8, associated with a biomass of approximately 1500 kg/ha, beyond which further increases in biomass do not result in corresponding increases in NDVI.

Once data were limited to early dates, the linear regression fit between indices and biomass was further improved by calculating

Table 5
Goodness of fit (r^2) values between vegetation indices and biomass for both date unrestricted and date restricted (prior to January 1, 2013) values. Values are also included for date restricted regressions.

No transformation	NDVI	GNDVI	SR	SAVI (L = 0.5)	G – R	EVI	TVI	NGRD	VARI	NDREI
All sampling dates	0.37	0.39	0.32	0.37	0.26	0.33	0.37	0.28	0.28	0.40
Early sampling dates	0.59	0.60	0.74	0.60	0.64	0.65	0.84	0.70	0.69	0.65
Log transformation	NDVI	GNDVI	SR	SAVI (L = 0.5)	G – R	EVI	TVI	NGRD	VARI	NDREI
All sampling dates	0.61	0.63	0.38	0.61	0.44	0.50	0.57	0.40	0.40	0.58
Early sampling dates	0.86	0.84	0.63	0.86	0.84	0.78	0.86	0.74	0.74	0.80

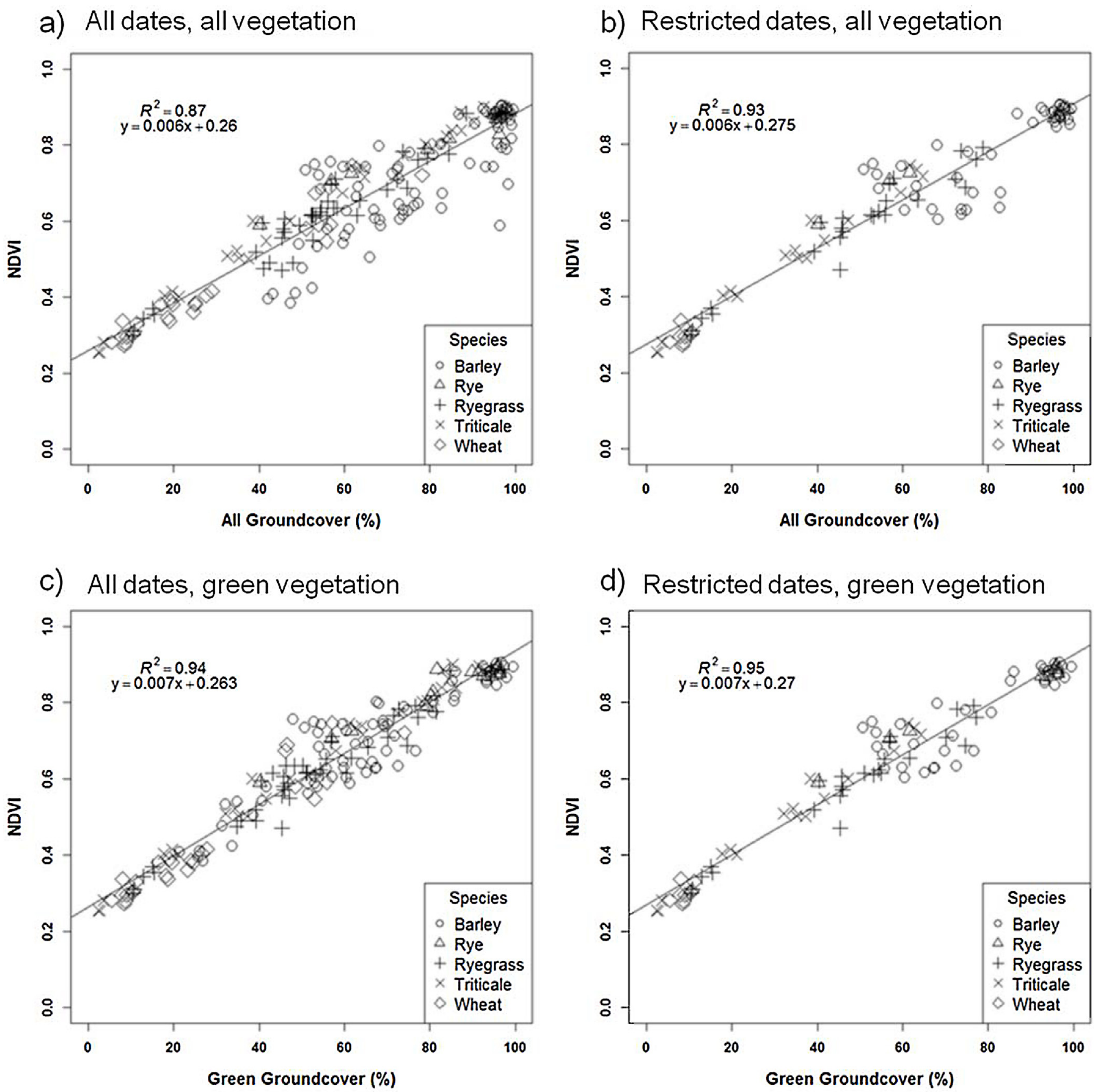

Fig. 7. Linear model goodness of fit (r^2) values from a linear regression between NDVI and vegetative cover, for all dates on the left (a and c) and early dates on the right (b and d). The two top graphs represent all groundcover (a and b), while the two bottom graphs represent green groundcover only (c and d).

the natural log of biomass data. For NDVI, doing so resulted in an r^2 value of 0.86.

While restricting sampling dates before January 1, 2013, eliminates all high biomass points with yellowing leaves, eliminating saturation from the data also was necessary to achieve high correlation. The barley and rye fields in this study all reached 1000 kg/ha earlier than other fields and before the onset of cold temperatures, and comprise the saturated values shown in Fig. 8. Although fast accumulation of biomass is desirable from an environmental perspective, it causes index saturation and complicates estimation of biomass.

While it seems that a natural log transformation can be used to account for saturation, in reality it is not possible to derive a proportional relationship between indices and biomass as biomass increases in the saturated range. Transforming data prior to removing saturated values can therefore mask real issues within the data. A superior method is to eliminate saturated values and then apply a natural log transformation to the remaining data. Overall, saturation, yellowing, and frost damage will result in underestimation of cover crop biomass by remote sensing indices.

Unlike NDVI, which has an upper limit of 1.0, the triangular vegetation index (TVI) does not reach an upper limit, thereby reducing the effects of asymptotic biomass saturation and making it better at estimating high biomass (Fig. 9). However, the TVI is not as sensitive at low biomass, when crop reflectance is minimal relative to background soil reflectance, as was evidenced by the clustering of low

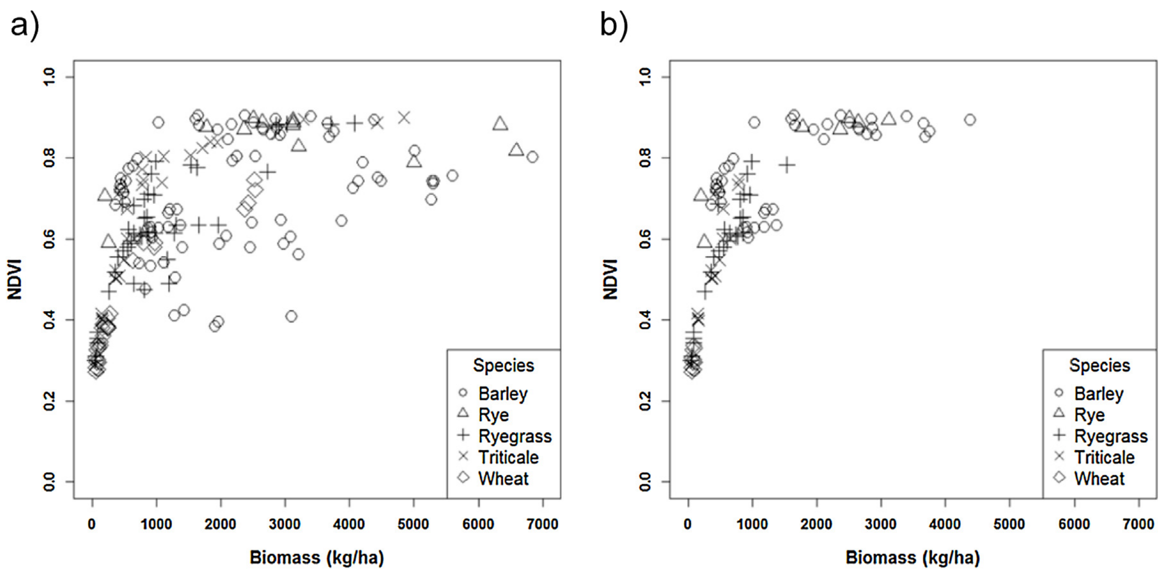

Fig. 8. (a) NDVI versus measured biomass (kg/ha) for all species and sampling dates, and (b) restricted to early sampling dates prior to January 1, 2013. This date falls before the onset of the frost period that occurred between December 14, 2012, and January 10, 2013.

biomass points in Fig. 9b compared to the distinction of the same values in Fig. 8b. TVI calculates the total area of a triangle with the three vertices in different parts of the electromagnetic spectrum. These areas include minimum red reflection due to high absorption by chlorophyll, near-infrared, and variable reflection in the green portion of the spectrum (Haboudane et al., 2004). Increases in chlorophyll increase both absorption in the red portion of the spectrum and reflection approaching the near-infrared, increasing the size of the triangle while also decreasing the height of the triangle determined by reduced reflection in the green portion of the spectrum. TVI is less effective at differentiation at low biomass due to TVI's decreased sensitivity in this range. Removing low biomass points does improve r^2 values slightly, from 0.83 to 0.85 using TVI.

This analysis suggests that data should be restricted to early sampling dates to avoid the effects of frost damage and achieve accurate estimates of biomass using vegetation indices. Once dates are restricted, NDVI is most useful for estimates at low to medium vegetation levels (Broge and LeBlanc, 2000), and TVI is useful for higher canopy biomass (Chen et al., 2009).

3.4. Biomass and percent groundcover

The relationship between accumulated GDD and cover crop biomass can be used to help assess whether fields are reaching critical water quality goals, as more biomass leads to greater nutrient uptake and increased groundcover. Across all dates (Fig. 9a), the relationship between aboveground biomass and percent groundcover was complicated by a number of factors, including saturation of percent groundcover with respect to biomass, and reduction in midwinter biomass resulting from leaf senescence.

Restricting analysis to early sampling dates before January 1, 2013, tightened up the relationship between percent groundcover and biomass. As seen in Fig. 10b, percent groundcover appears to reach 100 percent and saturate with respect to biomass saturation

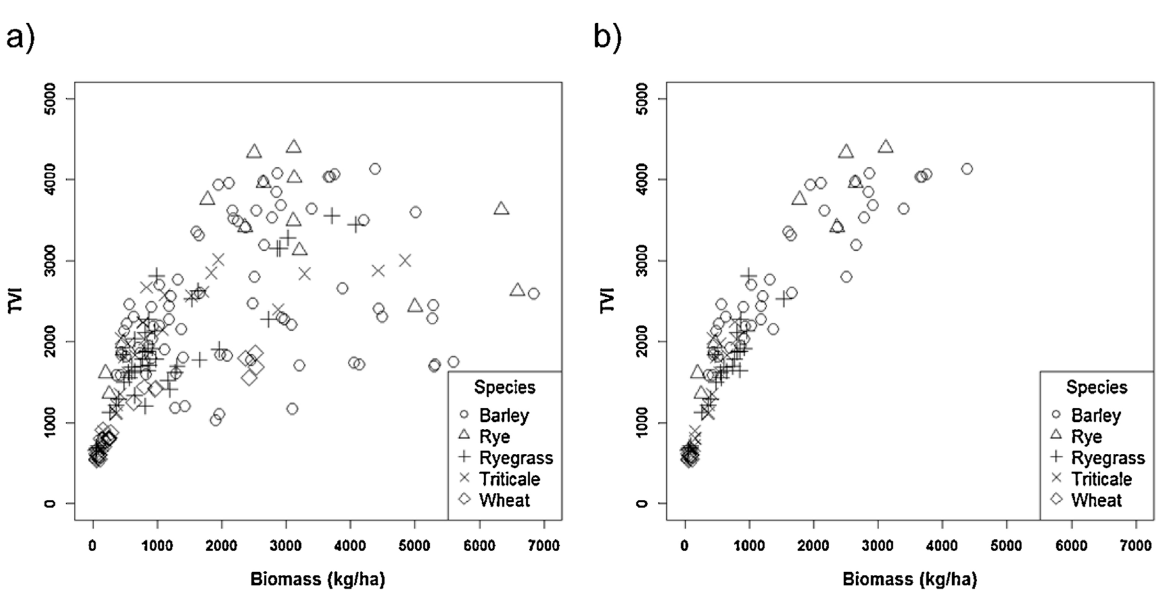

Fig. 9. TVI versus measured biomass (kg/ha) for all species and sampling dates (a). Plot B has been restricted to early sampling dates (before January 1, 2013) prior to the onset of yellowing or frost damage.

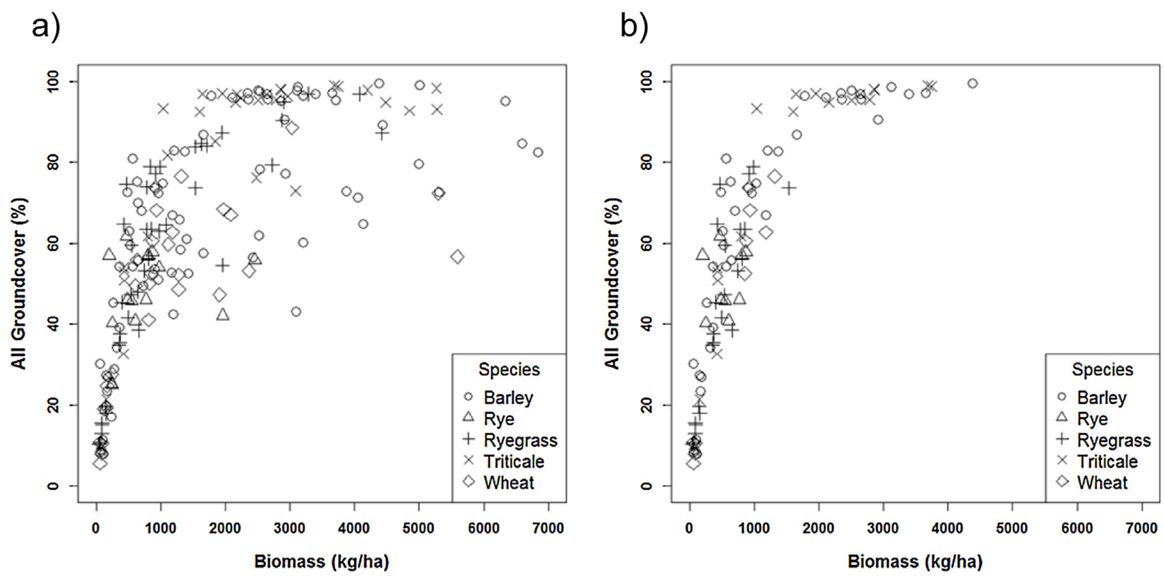

Fig. 10. Percent groundcover for all vegetation across all dates versus biomass (kg/ha) (a); (b) shows early dates, prior to January 1, 2013.

Table 6
Estimates of biomass needed to reach percent groundcover thresholds.

Percent groundcover	Biomass (kg/ha)
30	200
60	825
100	1658

at roughly 1500 kg/ha of biomass. Eliminating the higher biomass measurements from analysis results in an r^2 value of 0.75 across all vegetation and has the same effect as eliminating percent groundcover values above 90%, when changes in percent biomass do not correlate to meaningful changes in groundcover. The biomass levels associated with critical groundcover thresholds are listed in Table 6.

3.5. Percent groundcover and GDD

Establishing a relationship between accumulated GDD and cover crop percent groundcover is helpful to determine when fields are reaching critical water quality goals, as increased groundcover is associated with decreased soil erosion and sedimentation.

Table 7
Estimates of growing degrees (GDD) needed to reach groundcover thresholds.

All groundcover (%)	GDD base 4
10	192
20	220
30	248
40	275
50	303
60	330
70	358
80	385

Fig. 11b demonstrates that there is a strong linear relationship ($r^2 = 0.81$) between percent groundcover and growing degree days in the early part of the growing curve, below 400 GDD. Using the linear equation in Fig. 11b, it is possible to estimate the number of

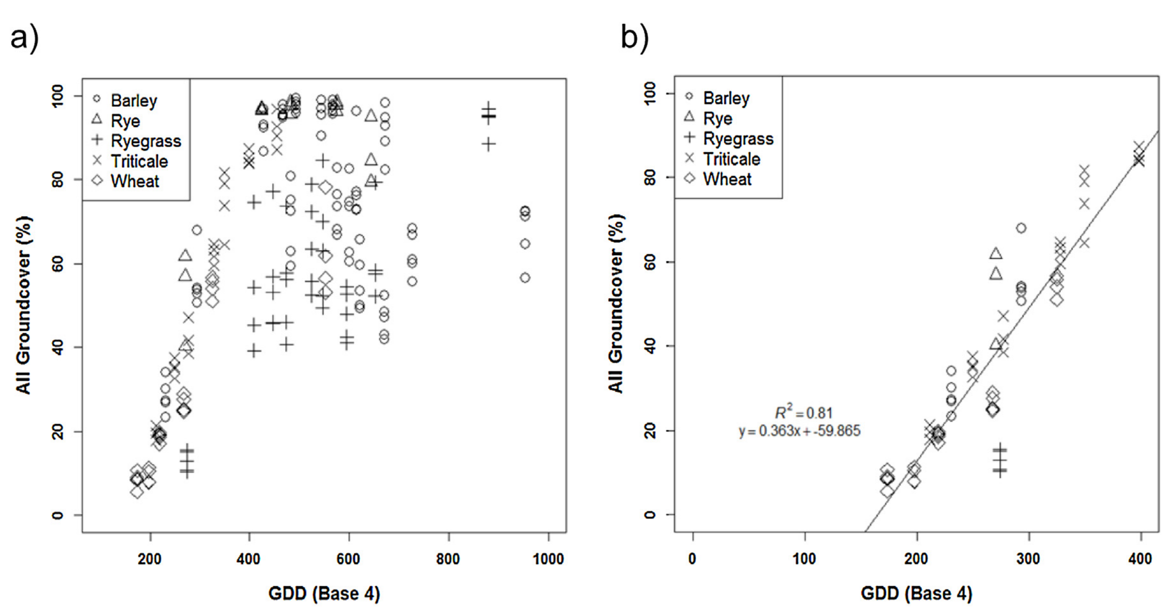

Fig. 11. Trends in groundcover as they relate to accumulated growing degrees (GDD) following cover crop planting, including (a) percent groundcover versus GDD for all dates, and (b) percent groundcover versus GDD with GDD restricted to <400.

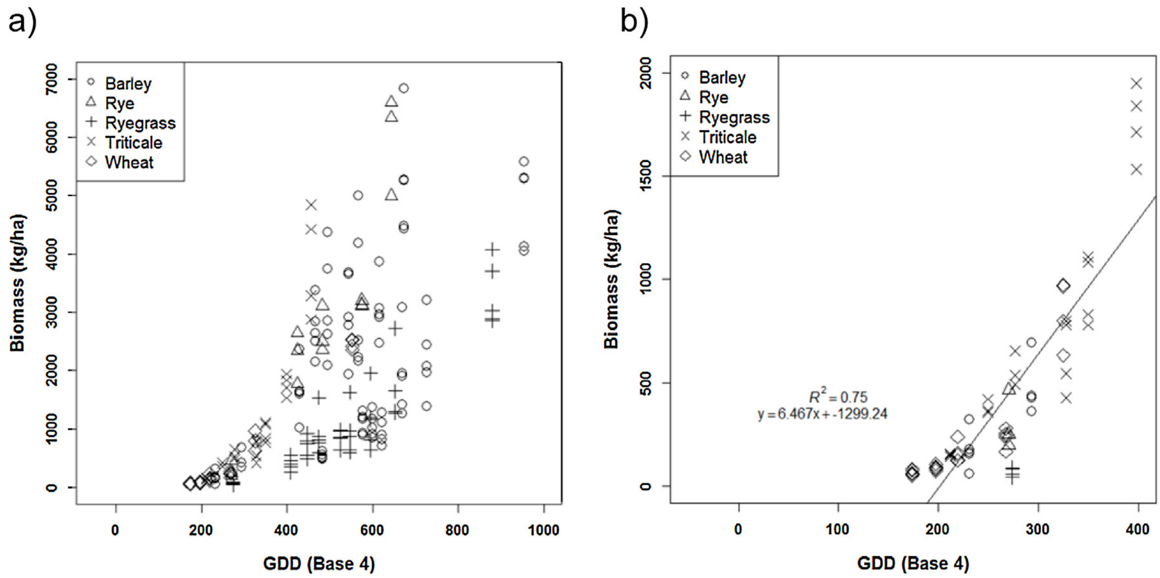

Fig. 12. Trends in biomass as they relate to accumulated growing degrees (GDD) following cover crop planting, including (a) biomass (kg/ha) versus GDD for all dates, and (b) biomass (kg/ha) versus GDD with GDD restricted to <400.

Table 8
Estimates of growing degrees needed to reach biomass thresholds.

Biomass (kg/ha)	GDD base 4
250	240
500	278
750	317
1000	356
1250	394

accumulated growing degree days needed to reach critical groundcover thresholds (Table 7).

Table 7 provides estimates of the number of GDD needed to reach different groundcover thresholds, with analysis restricted to early growth (less than 400 accumulated growing degrees). The low number of days needed to achieve high groundcover shows that cover crops generally accumulate groundcover quickly during the early part of their growth cycle, before the onset of winter dormancy.

3.6. Biomass and GDD

The relationship between GDD and cover crop biomass is a useful indicator of how quickly fields accumulate biomass. Fields with higher accumulated biomass generally have higher nutrient uptake, reducing nutrient runoff into waterways.

Fig. 12b demonstrates that there is a good relationship ($r^2 = 0.75$) between biomass and growing degree days in the early part of the growing curve, below 400 GDD. Estimates of the number of accumulated growing degree days needed to reach critical biomass thresholds are shown in Table 8. Average nitrogen content in cover crops can be estimated at roughly 2% (Hively et al., 2009), resulting in an associated sequestration of between 2 and 23 kg N.

Similarly to percent groundcover, the relationship between aboveground biomass and GDD becomes more complex as GDD increases. Above 400 GDD some fields began to experience frost damage and yellowing of leaves, and over time there is far greater variation between GDD and biomass. Species that were planted early and experienced more yellowing of leaves may have a high number of accumulated GDD but a declining biomass through the winter. Conversely, triticale and wheat fields that were planted later and had fewer accumulated GDD had steadily rising biomass and were less affected by reduced leaf greenness over winter.

4. Conclusion

This study employed a GPS-enabled CROPSCAN proximal sensor to collect surface reflectance data from cover cropped fields, over the winter of 2012–2013. Results compared the utility of 10 vegetation indices for measuring cover crop aboveground biomass, and percent vegetated groundcover. Remote sensing techniques were most successful for measuring both percent groundcover and biomass of winter cover crops prior to the onset of freezing weather. Throughout the winter cover crop season, accurate measurements were made as long as frost damage, leaf yellowing, and index saturation were handled properly.

In areas that experience cold temperatures during the winter season, adjusting remote sensing measurements to account for frost damage and leaf yellowing is critical to ensure accuracy in estimating both percent groundcover and biomass. Fortunately, the effects of leaf yellowing and frost damage result in underestimation, rather than over-estimation, of the water quality benefits (nutrient and sediment capture) associated with cover crops. When dates were restricted, the linear relationship between percent groundcover and NDVI improved from r^2 of 0.87 to r^2 of 0.93. In fact, restricting the date was as effective as separating out green groundcover from yellowed and frost-burned vegetation, which was a time- and data-intensive process.

The effects of index saturation at high biomass and clustering of points at low biomass should be considered when measuring cover crop biomass. Many indices cannot differentiate the amount of biomass when there is too much vegetation, and a clear proportional relationship between the index and biomass is lost. This study showed that choosing different indices for high and low biomass ranges can prevent both low and high index saturation and increase predictive capability when early dates are modeled. Once saturation was removed, using a natural log transformation further increased the correlation between biomass and spectral indices.

Of the 10 indices that were evaluated, G − R, GNDVI and SAVI performed similarly to NDVI, detecting differences at low biomass and saturating at high. SR, EVI, NGRD, VARI and NDREI were not as effective with low biomass and also experienced saturation. TVI was the best at estimating high biomass points. However, TVI was not as good as NDVI at detecting low levels of biomass. NDVI was equal or superior to the other indices in predicting percent groundcover.

There was a good relationship between growing degree days and both percent groundcover and biomass for early in the growing season. When GDD was restricted to <400, or the early part of plant growth curves, there was a strong relationship between percent groundcover and GDD with an r^2 of 0.81; and similarly for biomass and GDD, with an r^2 or 0.75. Biomass and percent groundcover both increased rapidly during the beginning of growth. After 400 GDD, the increase in growing degree days was not well correlated with biomass due to a decreased groundcover and biomass in species that experienced wintertime leaf damage.

Although this study was conducted in Maryland, areas with comparable winter conditions planted with small grain winter cover crops could benefit from the information put forward here. Chosen fields were reflective of realistic winter cover crop scenarios, but future research could include controlled planting dates and field management to further analyze species-specific and treatment-specific differences in plant growth over the winter crop season. Additionally, although it is beyond the scope of this paper, extending these data and scaling up this study to make comparisons between satellite index measurements, especially from readily-available Landsat data, and proximal surface reflectance would allow for greater operational applications of remote sensing to map the water quality benefits associated with winter cover crops.

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