Landscape-scale characterization of cropland in China using Vegetation and Landsat TM images

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Abstract. In this landscape-scale study we explored the potential for multi-temporal 10-day composite data from the Vegetation sensor to characterize land cover types, in combination with Landsat TM image and agricultural census data. The study area (175 km by 165 km) is located in eastern Jiangsu Province, China. The Normalized Difference Vegetation Index (NDVI) and the Normalized Difference Water Index (NDWI) were calculated for seven 10-day composite (VGT-S10) data from 11 March to 20 May 1999. Multi-temporal NDVI and NDWI were visually examined and used for unsupervised classification. The resultant VGT classification map at 1 km resolution was compared to the TM classification map derived from unsupervised classification of a Landsat 5 TM image acquired on 26 April 1996 at 30 m resolution to quantify percent fraction of cropland within a 1 km VGT pixel; resulting in a mean of 60% for pixels classified as cropland, and 47% for pixels classified as cropland/natural vegetation mosaic. The estimates of cropland area from VGT data and TM image were also aggregated to county-level, using an administrative county map, and then compared to the 1995 county-level agricultural census data. This landscape-scale analysis incorporated image classification (e.g. coarse-resolution VGT data, fine-resolution TM data), statistical census data (e.g. county-level agricultural census data) and a geographical information system (e.g. an administrative county map), and demonstrated the potential of multi-temporal VGT data for mapping of croplands across various spatial scales from landscape to region. This analysis also illustrated some of the limitations of per-pixel classification at the 1 km resolution for a heterogeneous landscape.

1. Introduction

Remote sensing technology has been widely used in agriculture for estimating cropland areas and crop production. Over the last few decades, regional to global

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scale mapping and monitoring of croplands have been largely dependent upon the National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) data (Quarmby *et al.* 1992, Bachelet 1995, Zhao *et al.* 1996, Wang and Xia 1996, Fang 1998, Loveland *et al.* 2000). The AVHRR sensor was originally designed for meteorological observation and has only two spectral bands that are useful for vegetation observations (red and near infrared bands, see table 1). Applications of AVHRR data to characterize cropland and other land cover types have been constrained by its limited number of spectral bands for vegetation observations. In an earlier study that compared AVHRR-derived cropland estimates with the agricultural census of cropland in China (Frolking *et al.* 1999), large discrepancies (in the range of 50% to 100%) between remote sensing estimates and agricultural census data were observed across the scales of county, province and region. These were attributed to inaccuracies in both remote sensing and census data.

In comparison with the NOAA AVHRR sensors, the Vegetation (VGT) sensor (aboard the SPOT-4 satellite) was designed with a number of improvements for studying the vegetation and land surface. For instance, the VGT instrument has four spectral bands that are equivalent to the spectral bands of Landsat TM (table 1). The blue band is primarily used for atmospheric correction. The mid-infrared band is highly sensitive to soil moisture content, vegetation cover and leaf moisture content. The VGT instrument provides daily images of the global land surface at 1 km spatial resolution. Therefore, VGT data may have the potential for improved characterization of land cover types across large spatial scales (landscape, regional, continental, global).

In this study we used multi-temporal VGT data to conduct a landscape-scale land cover classification for a study area (175 km by 165 km) in eastern Jiangsu Province, China (figure 1), where agricultural land cover (a winter wheat and paddy rice double cropping system) dominates. The VGT-derived classification results were compared to Landsat TM-derived classification results, and to agricultural census data. The objective of this landscape-scale study was twofold: (1) to develop a better understanding of the characteristics of multi-temporal VGT data in relation to various land cover types; and (2) to assess the potential of VGT data for cropland characterization at large spatial scales.

2. Vegetation sensor data and image classification

SPOT Image Inc. provides three standard VGT products to users: VGT-P (Physical product), VGT-S1 (daily synthesis product) and VGT-S10 (10-day synthesis product). For each month there are three 10-day composites: days 1–10, days 11–20, and day 21 to the last day of the month. VGT-S10 data are generated using the

Table 1. A comparison of Vegetation (VGT) in SPOT 4, Landsat TM and AVHRR sensors.

	VGT (nm)	TM (nm)	AVHRR – 11 (nm)
Blue band	B0 (430–470)	TM1 (450–520)	–
Red band	B2 (610–680)	TM3 (630–690)	CH1 (580–680)
Near-infrared band	B3 (780–890)	TM4 (760–900)	CH2 (725–1100)
Mid-infrared band	MIR (1580–1750)	TM5 (1550–1750)	–
Spatial resolution	1 km	30 m	1 km
Revisit time	daily	16 days	daily

Figure 1. Approximate location of the landscape-scale study area near Nanjing, Jiangsu Province, China (filled black circle). The background of the figure is a digital elevation model at 1 km resolution, (from the Global Land One Kilometer Base Elevation dataset at the NOAA National Geophysical Data Center (NDGC), see web site <http://www.ngdc.noaa.gov/>). The polygons in the figure are the provincial boundaries of China.

composite approach that is based on the maximum Normalized Difference Vegetation Index (NDVI) values within a 10-day period for a pixel, which helps minimize the effect of cloud cover and variability in atmospheric optical depth. The four spectral bands (B0, B2, B3, MIR, see table 1) in the VGT-S10 products are the estimates of ground surface reflectance, as atmospheric corrections for ozone, aerosols and water vapour have already been applied to the VGT images using the SMAC algorithm (Rahman and Dedieu, 1994). The ground surface reflectance values of the four spectral bands were used in data analysis. Seven VGT-S10 products from the period 11–20 March up to the end of the period 11–20 May 1999 for the study area were used in this study.

VGT's mid-infrared band (MIR), which is comparable to TM band 5 (table 1), is very sensitive to soil moisture and plant canopy water content. Tucker (1980) suggested that the mid-infrared band (TM5) of TM was best suited for space-borne remote sensing of plant canopy water content. Gao (1996) proposed the Normalized Difference Water Index (NDWI) for remote sensing of vegetation liquid water from

space, using reflectance values of two near-infrared bands (one band centred approximately at 860 nm, and the other at 1240 nm). NDWI was considered to be a complementary vegetation index to the NDVI (Gao 1996, Jürgens 1997). For each of the seven 10-day composites of VGT data, NDWI and NDVI were calculated using the ground surface reflectance values of the spectral bands:

$$\text{NDWI}_{\text{VGT}} = (\text{B3} - \text{MIR}) / (\text{B3} + \text{MIR}) \quad (1)$$

$$\text{NDVI}_{\text{VGT}} = (\text{B3} - \text{B2}) / (\text{B3} + \text{B2}) \quad (2)$$

Instead of using the original four spectral bands of the seven VGT-S10 products from 11–20 March to 11–20 May 1999 (a total of 28 bands), the seven 10-day NDVI and NDWI data (a total of 14 bands) were used for image classification. An iterative unsupervised classification approach (ISODATA, ENVI 3.2 version) was applied, with 45 spectral clusters generated. A convergence level of 95% was assigned, this being the percentage of pixels that do not change clusters between iterations even with a small shift in cluster means. The main advantage of unsupervised classification procedures is that one need not specify *a priori* the classes and their spectral expression - the aim is to identify all important spectral groupings without initially knowing which are thematically significant (Cihlar *et al.* 1998). Because the spectral signatures of the same land cover type can differ over large areas (e.g. 175×165 km) unsupervised classifications are recommended at this scale (Cihlar *et al.* 1998).

In this study we used the land cover classification scheme for the International Geosphere and Biosphere Program (IGBP; Loveland *et al.* 2000, Belward 1996), as it is a well-documented global land cover classification system and our long-term goal is to use VGT data for mapping and monitoring of land cover and vegetation at continental to global scales. The IGBP DIScover Land Cover Classification System (Belward 1996) has 17 land cover classes: evergreen needleleaf forest, evergreen broadleaf forest, deciduous needleleaf forest, deciduous broadleaf forest, mixed forest, closed shrubland, open shrubland, woody savannas, grasslands, persistent wetland, cropland, urban and built-up, cropland/other vegetation mosaic, snow and ice, barren or sparsely vegetated, and water. Various ancillary data were used for interpretation of the 45 spectral clusters in relation to land cover, including the 1:1 000 000 Land Use Map of China (Wu 1990), the 1:1 000 000 Grassland Resource Map of China (Su 1993), and the Atlas of Forestry in China (Shi 1990). The 45 spectral clusters from the unsupervised classification of multi-temporal VGT data were interpreted, labelled and aggregated into 9 land cover types as defined by the IGBP DIScover Land Cover Classification Scheme.

3. Landsat TM image and classification method

One Landsat 5 TM image (Path 120 and Row 38; 30 m spatial resolution and 7 spectral bands) acquired on 22 April 1996 was used in this study, as it is the only TM image for this region with minimal cloud coverage (<20% cloud coverage criterion) during the period of early 1995 to late 1999. The image preprocessing at the ground receiving station includes systematic geometric correction and the image is in the Universal Transverse Mercator (UTM) map coordinates. During field visits to the study area in summer 2000, we collected ground control points (GCPs) for the TM image, which were later used for precision geometric correction of the image. Four TM spectral bands (TM3, 4, 5, 7) were selected for image classification, as the

three visible bands (TM1, TM2 and TM3) are highly correlated to each other. For visual interpretation of land cover types, NDVI and NDWI of the TM image (see table 1) were calculated using the at-atmosphere reflectance values:

$$\text{NDVI}_{\text{TM}} = (\text{TM4} - \text{TM3}) / (\text{TM4} + \text{TM3}) \quad (3)$$

$$\text{NDWI}_{\text{TM}} = (\text{TM4} - \text{TM5}) / (\text{TM4} + \text{TM5}) \quad (4)$$

The ISODATA unsupervised classification approach was used and 45 spectral clusters were generated. The image was classified with a specified ISODATA convergence threshold of 95%. Two rounds of classification were performed for the image to account for mixed clusters. 'Non-mixed' or 'pure' clusters were assigned a land-cover class value and removed from further classification. Land cover classes were assigned based on the analyst's knowledge of the landscape and spectral patterns, and this was aided by ancillary maps and data. 'Mixed' clusters were subject to a second round of clustering. Some clusters remained mixed after two rounds of clustering. Pixels in these clusters were manually assigned to one of the land-cover classes.

The 45 spectral clusters from the unsupervised classification of the TM image were interpreted, and labelled and aggregated into 10 land cover types, according to the IGBP DIScover Land Cover Classification Scheme (Loveland *et al.* 2000, Belward 1996). The resultant TM land cover classification map was re-projected from UTM projection to Lambert Azimuthal Equal Area projection, to be consistent with the VGT data. The TM classification map (30 m spatial resolution) was then co-registered with the VGT classification map (1 km spatial resolution), and aggregated to a 1 km resolution map using the VGT image as the reference, which facilitates direct comparison with the VGT 1 km classification map. The aggregated 1 km TM classification map contains the percentage of each IGBP land cover class within a 1 km² pixel, and was used to quantify percent fraction of cropland within individual 1 km VGT pixels of the VGT classification map.

4. County-level agricultural census data for cropland area estimates

County-level agricultural census data for China in 1990 were described in an earlier study (Frolking *et al.* 1999). The database (hereafter called AC90) contains county statistics on crop areas for twenty major crops, the total area of cropland and the total sown area, which is typically larger than the total cropland area due to double or multiple cropping. Agriculture in the study area is dominated by double cropping systems that consist of either (1) winter wheat and paddy rice or (2) rapeseed and paddy rice. Winter wheat or rapeseed is usually seeded in late October or early November of the previous year, it commences its leaf-on stage in early March, and is harvested in late May to early June. Recently, Chinese researchers (Dr. Liu Chuang, Institute of Geographical Sciences and Natural Resources, Chinese Academy of Sciences, personal communication, 2000) have assembled a digital version of county-level agricultural statistics of China for 1995 (hereafter called AC95). The AC95 database also includes acreage of total cropland for individual counties. Both the AC90 and AC95 databases are consistent with the official cropland statistics reported by the State Statistical Bureau (State Statistical Bureau 1994). Table 2 summarizes the 1990 and 1995 census cropland statistics for the fourteen counties of the study area. In the period 1990 to 1995, cropland areas were reported to have decreased in all but one county, generally by 1–5% (table 2). The sum of

Table 2. County cropland areas (all as 1000 ha) as determined by ground census (AC90 and AC95), and by Landsat TM and VGT sensors.

County	ID ¹	Total county area ²	AC90 crop area	AC95 crop area	TM _{pure} crop area	TM _{mix} crop area	TM _{total} crop area ³	% diff. TM/ AC95 ⁴	VGT _{pure} #pixels	VGT _{mix} #pixels	VGT _{pure} %crop ⁵	VGT _{mix} %crop ⁵	VGT _{total} crop area	% diff. VGT/ AC95 ⁶
Nanjing	1	92.10	25.47	25.47	28.89	7.21	32.49	32.2	247	182	49.8	48.7	23.3	-5.0
Jiangning	2	151.79	55.47	53.43	65.88	16.02	73.89	38.3	489	588	62.4	50.0	56.9	6.4
Jiangpu	3	82.12	22.40	21.92	33.41	8.80	37.81	72.5	166	479	54.7	49.0	32.4	47.7
Lishui	5	103.39	31.27	30.92	41.74	10.84	47.16	52.5	414	386	57.0	45.3	42.9	38.8
Gaochun	6	76.20	31.07	30.54	44.35	6.13	47.42	55.3	645	30	66.9	49.0	40.1	31.4
Jintan	7	90.25	43.20	42.64	44.15	6.12	47.21	10.7	565	122	64.1	47.0	39.6	-7.0
Liyang	8	150.94	64.33	63.44	62.45	13.39	69.15	9.0	738	314	58.8	44.3	59.0	-7.0
Dantu	9	96.01	36.13	34.12	43.21	8.83	47.62	39.6	501	203	65.1	44.3	39.6	16.0
Jurong	10	129.11	48.33	48.41	54.22	16.63	62.54	29.2	647	416	57.9	47.7	58.3	20.5
Danyang	11	107.63	61.07	60.02	69.93	9.13	74.50	24.1	1013	67	69.2	46.7	64.0	6.6
Ma'anshan	12	27.82	6.00	5.45	8.43	1.97	9.41	72.8	48	89	45.7	41.0	7.0	29.3
Dangtu	13	143.92	43.67	43.15	70.27	9.09	74.82	73.4	893	183	62.7	44.9	62.2	44.1
Hanshan	14	99.61	22.60	22.33	38.67	8.50	42.92	92.2	213	417	60.7	45.5	32.3	44.6
Hexian	15	145.83	52.20	51.30	77.96	13.71	84.82	65.3	861	357	66.0	51.6	68.4	33.3
TOTAL		1496.74	543.20	532.23	683.57	136.38	751.76		7440	3833	60.1	46.8	626.1	
MEAN								41.2						21.4

¹ See figure 2.

² Area based on CIESIN (1998) county boundary map for China (Arc/Info coverage).

³ $TM_{total} = TM_{pure} + 0.5 * TM_{mix}$.

⁴ Percent by which TM_{total} exceeds AC95 cropland area estimates.

⁵ Mean across each county of percent cropland area of each VGT_{pure} pixel, based on TM-derived cropland area for that pixel.

⁶ Percent by which VGT exceeds AC95 cropland area estimates.

the cropland areas for the fourteen counties in the study area was reported to have decreased by 2% from 1990 to 1995.

In this study, a county-level administrative boundary map (1:1 000 000 scale) representing county borders as of 31 December 1990 (CIESIN 1998) was overlaid on both the VGT-derived and the TM-derived classification maps. Numbers of pixels for individual land cover classes within each county were counted. The derived county-level estimates of cropland area from VGT and TM classification maps were then compared with the AC90/AC95 estimates of total cropland area at county scale.

5. Results

5.1. TM-derived cropland classification

The false colour composite image (figure 2) clearly shows the spatial patterns of land cover types in the study area. The Yangtze River flows through the study area from southwest to northeast. Other surface water bodies include four large lakes and numerous fish and aquaculture ponds. In late April, winter wheat and rapeseed crops were at the peak of green biomass, and thus had high NDVI and NDWI values (Xiao *et al.* 2001), resulting in a bluish colour in the false-colour image (figure 2). Cropland was concentrated in the north eastern and south western parts, and accounted for a large portion of the study area. Forests (green colour in figure 2) were mostly distributed in areas of low mountains and hills. According to the global digital elevation model (DEM) data at 1 km spatial resolution, elevation in the study area varies from 1 m to 500 m. Of a total area of 28,875 km², approximately 95.3% of the land is at an elevation of less than 100 m, and 86.5% of the land is at an elevation of less than 50 m. Croplands are primarily distributed in low elevation and flat plain areas.

According to the TM classification map (figure 3), cropland accounts for 43% of the total area of the TM image. Although individual farm families in the study area have 3–5 mu of cropland (Chinese measurement unit of land area, 1 mu equals 1/15 ha or 667 m²), dependent upon their family size, the majority of these small holdings lie adjacent to each other in flat areas and thus form large parcels of cropland landscape. However, even using Landsat TM at 30 m spatial resolution, there was still a significant number of cropland/other natural vegetation mosaic pixels (table 2), mostly attributed to small-scale variations and constraints of topography and soil, resulting in very small parcels of cropland. The cropland/other vegetation mosaic category accounts for 8% of the total area of the TM image. In the summer of 2000, field surveys were conducted in the study area using a hand-held GPS receiver and a GPS camera. Because of budget/time constraints and the agricultural focus of the analysis, the field data collection was biased towards cropland sites (table 3). The field data collected during visits to the study area in the summer of 2000 were used to assess the accuracy of the TM classification for cropland. Of the 44 cropland sites visited during the field surveys, 35 (80%) were classified as 'cropland' or 'cropland/natural vegetation mosaic' in the TM classification (table 3).

Agricultural census data and TM-derived cropland area estimates at the county level are compared in table 2. The total TM-derived cropland area in a county was estimated by summing both TM_{pure} and TM_{mix} areas for that county (table 2):

$$\text{Total TM-derived cropland area} = b_{\text{pure}} \times \text{TM}_{\text{pure}} + b_{\text{mix}} \times \text{TM}_{\text{mix}} \quad (5)$$

To derive estimates of b_{pure} and b_{mix} statistically would require a large sample of aerial photos or space-borne remote sensing data at very fine spatial resolution (e.g.

Figure 2. Land cover characteristics in the study area as illustrated by a false colour composite of Landsat TM image acquired on 26 April 1996. The figure was generated using band TM 7 (red), NDVI (green) and NDWI (blue). For TM data, NDVI is calculated using TM4 and TM3, and NDWI is calculated using TM4 and TM5 (see equations (3) and (4), and table 1). In the figure, water bodies are black; forests are green; urban and built-up areas are bright red; croplands are bluish. The borders and numbers identify the counties in the study area (see list in table 2).

1 m and 4 m resolution IKONOS images provided by Space Imaging, Inc.), but these were not available for this study. Therefore, a simple assumption was made for TM data at 30 m spatial resolution: a 100% proportion (b_{pure}) of cropland within a cropland pixel (TM_{pure}), and a 50% proportion (b_{mix}) of cropland within a cropland/other vegetation mosaic pixel (TM_{mix}). The TM-derived estimates of cropland area exceed the 1995 agricultural census data (AC95) for all 14 counties, in a range of 9% in Liyang County to 92% in Hanshan County (table 2). The sum of TM-derived cropland area for the 14-county region was 751 760 ha, approximately 41% larger than the AC95 census total.

5.2. VGT-derived cropland classification

The false colour composite VGT image on 21–30 April 1999 (figure 4(a)) shows that the spatial pattern of croplands is consistent with the TM false colour image

Figure 3. Land cover classification map at 30m spatial resolution for the study area in Nanjing, Jiangsu Province, China, generated using the TM image acquired on 26 April 1996 (see figure 2). Out of the total area in the TM image, cropland accounts for 43%, cropland/other vegetation mosaic 8%, water 12%, open shrubland 15%, closed shrubland 8%, mixed forest 6%, evergreen forest 2%, grassland 1%, urban/built-up 5% and bareland 0.006%.

Table 3. Accuracy assessment of TM classification and VGT classification with a focus on cropland, using the field data collected in the summer of 2000.

Field data in 2000	Classification of TM image acquired on April 26, 1996						Classification of VGT in 3/11–5/20, 1999			
	Cropland	COVM	OS	CS	Forest	Total	Cropland	COVM	CS	Total
Cropland	31	4	4	2	3	44	36	7	1	44
Open shrub	1	2				3	1	2		3
Abandoned field ¹	1					1		1		1
Total	33	6	4	2	3	48	37	10	1	48

COVM—cropland/other vegetation mosaic, OS—open shrubland, CS—closed shrubland.
¹In 2000, this field had recently been cleared for development, and was likely to have been cropland in 1996 and 1999.

Figure 4. Land cover characteristics in the study area as illustrated by 10-day synthetic product of VGT images for the study area near Nanjing, Jiangsu Province, China. (a) A false colour composite on 21–30 April 1999, using VGT spectral band B3 (red), MIR (green) and B2 (blue) VGT image in 4/21–30, 1999. (b) A scatter plot of NDVI versus NDWI for VGT pixels on 21–30 April 1999 NDVI vs NDWI in 4/21–30, 1999. (c) VGT-derived land cover classification map at 1 km spatial resolution VGT classification. (d) Percent cropland within a 1 km pixel, aggregated from a TM-derived land cover classification map at 30 m spatial resolution (see figure 3) % cropland within 1-km pixel. Out of the total area of VGT classification map, cropland accounts for 43%, cropland/other vegetation mosaic 29%, water 8%, open shrubland 2%, closed shrubland 7%, mixed forest 4%, evergreen forest 5%, grassland 3%, and urban/built-up 1%.

(figure 2) and the TM-derived land cover classification (figure 3). Winter wheat and rapeseed had high biomass and high reflectance values in the near-infrared band. The scatter plot of NDVI and NDWI for all the pixels in the study area shows that croplands have high NDVI and NDWI values (figure 4(b)). NDWI values for croplands in the northeast (blue colour in figure 4(b)) were lower than NDWI values for croplands in the southwest (green colour in figure 4(b)). Forests (red colour in figure 4(b)) had lower NDWI values than croplands, although NDVI values were in a similar range for both forests and croplands.

Using field data collected during visits to the study area in the summer of 2000 (table 3), the accuracy of the VGT classification was assessed. Of the 44 cropland sites visited during the field survey, 43 (98%) were classified as 'cropland' or 'cropland/natural vegetation mosaic' in the VGT classification (table 3). During the field surveys in 2000, relatively homogenous areas of cropland (some several square kilometres in area) were chosen as field points. Because the VGT pixels are 1 km², these pixels would be classified as 'cropland' even though portions of non-cropland land cover exist in these areas. The spatial patterns of VGT-derived croplands (figure 4(c)) match well with the fractional map of croplands from aggregation of TM-derived land cover types (figure 4(d)). Most VGT-derived cropland pixels (figure 4(c)) are distributed in those areas that have more than 50% cropland within a 1 km pixel as illustrated by the TM 1 km aggregated classification (figure 4(d)). At 1 km spatial resolution, the number of VGT pixels that were classified as 'cropland' (VGT_{pure}) varied from 48 in Ma'anshan City to 1013 in Danyang County (table 2). There were also many pixels classified as 'cropland/other vegetation mosaic' (VGT_{mix}) in each county, ranging from 30 in Gaochun County to 588 in Jiangning County (table 2).

Within a 1 km pixel, the land surface in this part of China is mostly a mix of vegetation (e.g. crops, forests, grass), soil (including bare land, urban and built-up) and water bodies. It is critical to quantify the fraction of cropland within a VGT-derived 'cropland' pixel (VGT_{pure}) and a VGT-derived 'cropland/other vegetation mosaic' pixel (VGT_{mix}), which may vary significantly over space. For each of the 14 counties, we calculated the fractional cropland area in every VGT_{pure} and VGT_{mix} pixel, based on TM-derived cropland areas (TM_{pure} + TM_{mix}, see equation (5)). For most counties, VGT_{pure} pixels had fractional cropland areas ranging from >40% to <80% (figure 5), with mean county values (C_{pure}) ranging from 46% in Ma'anshan City to 69% in Danyang County (table 2). TM-derived fractional cropland areas for VGT_{mix} pixels were generally less than 60% (figure 5), with county mean values (C_{mix}) ranging from 41% in Ma'anshan City to 52% in Hexian County (table 2). To derive an estimate of total cropland area in a county from the VGT classification data, we multiplied the county mean values (C_{pure} and C_{mix}) by the numbers of VGT_{pure} and VGT_{mix} pixels:

$$\text{Total VGT-derived cropland area} = C_{\text{pure}} \times \text{VGT}_{\text{pure}} + C_{\text{mix}} \times \text{VGT}_{\text{mix}} \quad (6)$$

The county-level estimates of total cropland area from the VGT classification (after the sub-pixel correction) range from 7045 ha in Ma'anshan City to 68 408 ha in Hexian County (table 2). The differences between the VGT-derived cropland area and the agricultural census data in 1995 at county-level vary from -7% in Jintan County to +45% in Hanshan County (table 2). The VGT-derived cropland area estimate for the 14-county region, using TM-derived sub-pixel cropland fractions of 60% for pure cropland pixels and 47% for mixed pixels (table 2), was 626 116 ha,

Figure 5. A comparison of VGT-derived cropland estimates (VGT_{pure} and VGT_{mix}) and TM-derived cropland estimates ($TM_{pure} + 0.5 TM_{mix}$) by county at 1 km spatial resolution. (a) Histograms for each county of VGT-derived ‘Cropland’ (VGT_{pure}) pixels with given fractional area of cropland as given by TM classification; (b) Histograms of VGT-derived ‘Cropland/other vegetation mosaic’ (VGT_{mix}).

21% greater than the AC95 census total. For all 14 counties, VGT-derived cropland area estimates are smaller than TM-derived cropland area estimates (table 2). This may be attributed mostly to the fact that many crop fields in the study area are small and are distributed in places dominated by other land cover types (e.g. forests; see figures 2, 3, 4(d)), and thus VGT data at 1 km spatial resolution would not be able to differentiate them.

6. Discussion

In comparison to AVHRR data, the MIR band of the VGT sensor provides additional information on vegetation and land cover. Visual interpretation of VGT images indicates that NDVI and NDWI together provide much better separation of land cover types in the study area of Jiangsu Province, including croplands and forests (figure 4). In an earlier study using Landsat TM data, Jürgens (1997) proposed the term 'modified Normalized Difference Vegetation Index (mNDVI)', which is the same as NDWI, and applied the index to determine frost damage in agriculture, which is not a significant issue in our study area. This landscape-scale study in eastern Jiangsu Province demonstrates the potential of multi-temporal NDVI and NDWI data for image interpretation and characterization of cropland using a per-pixel classification approach (e.g. ISODATA unsupervised classifier). Note that multi-temporal VGT data were used in this study, but analysis of the bidirectional reflectance distribution function (BRDF) of the land surface was not taken into consideration in preprocessing of VGT-S10 data, which may introduce some uncertainty in land cover classification based on VGT-S10 data. The BRDF can be used to compare observations obtained at different angles or standardize observations to a common geometry (Hu *et al.* 1997). Therefore, further studies are needed to incorporate the BRDF correction into preprocessing of VGT-S10 data and to assess the effect of BRDF in VGT data on land cover characterization at large spatial scales.

During the 1990s, coarse-resolution remote sensing imagery (e.g. AVHRR) was a major data source for large-scale and operational mapping and monitoring of agriculture and land cover change (e.g. Loveland *et al.* 2000). Several studies have compared cropland estimates derived from AVHRR data with agricultural census data (Ramankutty and Foley 1998, Frolking *et al.* 1999). Frolking *et al.* (1999) compared AVHRR-derived estimates of croplands with agricultural census data at the county level (AC90) for more than 2000 counties in China. The AVHRR cropland estimates were extracted from the China Land Cover Characteristics Database which was generated at the US Geological Survey EROS Data Center in cooperation with the Chinese Academy of Surveying and Mapping, using monthly AVHRR-derived NDVI from April 1992 to March 1993 (Z. Zhu, USGS, personal communication, 1997). As the AVHRR-derived land cover database was generated using a per-pixel classification approach (e.g. ISODATA unsupervised classifier), there is no explicit information on sub-pixel heterogeneity or fractional cover of cropland within a 1 km pixel. A simple assumption was made for cropland fraction within a 1 km pixel: 100% cropland for pure cropland pixels and 50% cropland for mixed cropland/natural vegetation pixels (Frolking *et al.* 1999); and the resultant estimates of cropland area for the 14 counties in this study area range from 83% (Danyang County) to 229% (Ma'anshan City) larger than the AC95 census values, with a mean of 146%. Applying our TM-derived sub-pixel cropland fractions (see table 2) to the above AVHRR-based China Land Cover Characteristics Database, the sum of the AVHRR-derived cropland area estimates for the 14 counties in the study area was 790,449 ha, 53% higher than the AC95 census total. The official agricultural census datasets for cropland areas are known to underestimate actual cropland area by an estimated 30% at national scale (Crook 1993, Fischer *et al.* 1998, Smil 1999). Smil (1999) reported a range of 25–50% discrepancy between reported cropland area and 'actual' cropland area for Jiangsu Province, with the agricultural census data consistently underestimating the 'actual' cropland area. The TM and VGT analyses in this study also confirm the under-reporting of cropland areas in the AC90 and AC95 census

datasets. Given the large discrepancies among the agriculture census data, land cover datasets derived from coarse-resolution images (e.g. AVHRR, VGT) and derived from fine-resolution images (e.g. TM) observed at this landscape-scale study and the other study at the national scale (Frolking *et al.* 1999), caution should be taken in using land cover datasets derived from coarse-resolution image data and per-pixel classification approach. Quantification of sub-pixel heterogeneity would lead to a significant reduction in uncertainty in the coarse-resolution land cover database that might be used for biogeochemical modelling and agricultural production estimation.

For cropland classification using medium to coarse-resolution images and per-pixel classification algorithms, classification assessment is critical due to sub-pixel heterogeneity and this could be done at three spatial scales: (1) field-based point survey data (micro-scale); (2) fine-resolution space-borne remote sensing data (e.g. Landsat TM, SPOT) and aerial photo data (medium-scale) and (3) agricultural census data at county level (macro-scale). Field-based surveys require collection of a large sample of field sites, which is usually constrained by limited resources of personnel, time and budget. Over the last two decades, numerous Landsat TM images (30 m spatial resolution) have been used in mapping croplands at many places in the world (e.g. Gonzalez-Alonso *et al.* 1997, Ortiz *et al.* 1997), resulting in many fine-resolution maps and databases of cropland and other land cover types. In this landscape-level study we combined fine-resolution TM data, coarse-resolution VGT data, county-level agricultural census data and an administrative county boundary map (GIS). Together with an appropriate statistical sampling design, this would be an efficient and effective approach for obtaining better estimates of cropland areas from county to country scales, using medium-resolution (e.g. MODIS) to coarse-resolution (e.g. VGT) sensor data. As an alternative to this approach of per-pixel analysis of coarse-resolution imagery combined with sub-pixel fractions derived from fine-resolution data, we are evaluating the use of spectral mixture analysis of VGT data, and the results will be summarized in another paper. As more cloud-free image data from Landsat 7 ETM+, MODIS and VGT become available over time, which are comparable both temporally and spectrally, efforts to quantify the sub-pixel heterogeneity of land cover types at large spatial scales will be substantially enhanced.

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