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Classification of wetland habitat and vegetation communities using multi-temporal Ikonos imagery in southern Saskatchewan

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Abstract. The Prairie Habitat Monitoring Program, led by Environment Canada, is tasked with assessing and monitoring landscapes for waterfowl and other migratory birds in Manitoba, Saskatchewan, and Alberta. Prairie habitat assessments have been conducted using transects to sample land cover and land use changes and have shown that wildlife habitat, both wetland and upland, is declining in areal extent. An investigation into the use of high-resolution imagery to assist in these assessments was performed in the summer of 2000. Spring and summer Ikonos-2 images, including both panchromatic and multi-spectral bands, were classified according to a Stewart and Kantrud (S&K) wetland habitat class system used for monitoring Canadian prairie wetlands. Two significant issues were noted in the classification process: the S&K wetland habitat classes contained similar vegetation assemblages or communities, and field crews identified areas as homogeneous on the ground that contained mixtures of vegetation communities due to the nature of the S&K classes. Following a traditional training data collection exercise based on the discrimination results in the available field sites, S&K wetland habitat classes could be classified with approximately 47% overall accuracy using multi-temporal imagery, a normalized difference vegetation index (NDVI), and texture measures. Based on these results, individual vegetation communities within these habitat classes were segregated based on sketch maps prepared for each field plot, and an assessment of these communities showed they could be distinguished much more readily, resulting in greater than 84% overall accuracy.

Résumé. Le Programme de suivi des habitats des Prairies, sous la responsabilité d'Environnement Canada, a pour tâche l'évaluation et le suivi des paysages pour la sauvagine et les autres oiseaux migrateurs au Manitoba, en Saskatchewan et en Alberta. Les évaluations d'habitats des Prairies ont été menées en utilisant des transects pour échantillonner les changements du couvert et de l'utilisation du sol et ont montré que les habitats fauniques, en milieux humides et en zone montagneuse, sont en décroissance en terme d'extension spatiale. Une analyse basée sur l'utilisation d'images à haute résolution comme outil dans le cadre de ces évaluations a été réalisée au cours de l'été 2000. Des images Ikonos-2 acquises au printemps et en été, dans les bandes panchromatique et multispectrale, ont été classifiées à l'aide du système de classification des habitats de milieux humides de Stewart et Kantrud (S&K) utilisée pour le suivi des milieux humides dans les Prairies canadiennes. Deux phénomènes significatifs ont été observés dans la procédure de classification: les classes d'habitats de milieux humides S&K contenaient des assemblages ou des communautés semblables, et les équipes de terrain ont identifié sur le terrain des zones considérées comme homogènes alors qu'elles contenaient des mélanges de communautés végétales et ce en raison de la nature même des classes S&K. Suite à un exercice conventionnel de collecte de données d'entraînement basé sur les résultats d'une analyse discriminatoire pour les sites disponibles, les classes d'habitats de milieux humides S&K ont pu être classifiées avec une précision globale d'environ 47% en utilisant des images multidates, le NDVI et des mesures de texture. À partir de ces résultats, des communautés végétales individuelles ont pu être différenciées à l'intérieur de ces classes d'habitats basé sur des cartes schématiques préparées pour chacune des parcelles de terrain et une évaluation de ces communautés a montré qu'elles pouvaient être identifiées plus efficacement résultant ainsi en une précision globale supérieure à 84%.
[Traduit par la Rédaction]

Introduction

In the past decade, several studies have addressed the critical question of wetland inventory from a broad-scale remote sensing perspective (i.e., large areas with minimal detail) (Sader et al., 1995; Kuhl, 1996; Munyati, 2000). For most of these studies, the outstanding issues revolved around the enormous cost of aerial photography balanced with the lack of proven reliability in satellite remote sensing because of coarse spatial resolution (e.g., Satellite pour l'Observation de la Terre (SPOT), Landsat) (Tiner, 1990). The recent availability of high spatial resolution satellite data (Green, 2000), such as those

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from Ikonos-2, provides high spatial resolution data in the visible and near-infrared portion of the electromagnetic spectrum. With higher spatial detail, the link between wetland habitat characteristics and remotely sensed data should be more readily determined (Phinn et al., 1999). In addition, higher radiometric resolution may positively influence this relationship. A challenging problem, however, is the analysis approach. Although data similar to the Ikonos-2 imagery have been available for several decades from airborne multi-spectral scanners and spectrographic imagers (e.g., Irons et al., 1987; 1991; Neville and Till, 1991; Babey et al., 1999), the traditional remote sensing methods of extracting information from these high spatial resolution data remain in many ways primitive and untested (e.g., Desachy et al., 1996; Foody, 1999). Few examples exist of relatively simple data products, such as a large-area map of wetland habitat, generated from high spatial resolution digital data.

The Prairie Habitat Monitoring Program, led by Environment Canada, is tasked with assessing and monitoring priority landscapes for waterfowl and other migratory birds in Manitoba, Saskatchewan, and Alberta. Over the past 2 years, prairie habitat assessments have been conducted using transects to sample land cover and land use changes within Prairie Habitat Joint Venture (PHJV) target areas. These transects have shown that wildlife habitat, both wetland and upland, is declining in areal extent within priority landscapes of the PHJV. The PHJV Board has indicated an urgent need to develop landscape habitat monitoring tools that will enable timely and strategic decision making for managing waterfowl and other migratory bird populations and to reduce the amount of time required for major field programs. One possible information resource, not yet fully exploited in this project, is high spatial resolution satellite imagery and digital image processing methods.

In this study, an attempt is made to gain insight and understanding into the spectral characteristics of wetland and upland classes that can be consistently spectrally separated using Ikonos-2 data and both supervised and unsupervised classification methods. These results will be important in the development of an appropriate remote sensing habitat mapping and monitoring methodology that can be applied across the prairie ecozone.

Study area and data collection

The Missouri Coteau region covers over 2 million hectares of southern Saskatchewan and is the focal point of the PHJV (**Figure 1**). It is characterized by a variety of upland cover, wetlands, and land use activities and is considered a priority area for both multi-species bird and native range conservation. The landscape in this region is comprised of moraine deposits and is often referred to as knob and kettle terrain (Millar, 1992). A trial area of one township (Tp 10, R24, W2), identified by the

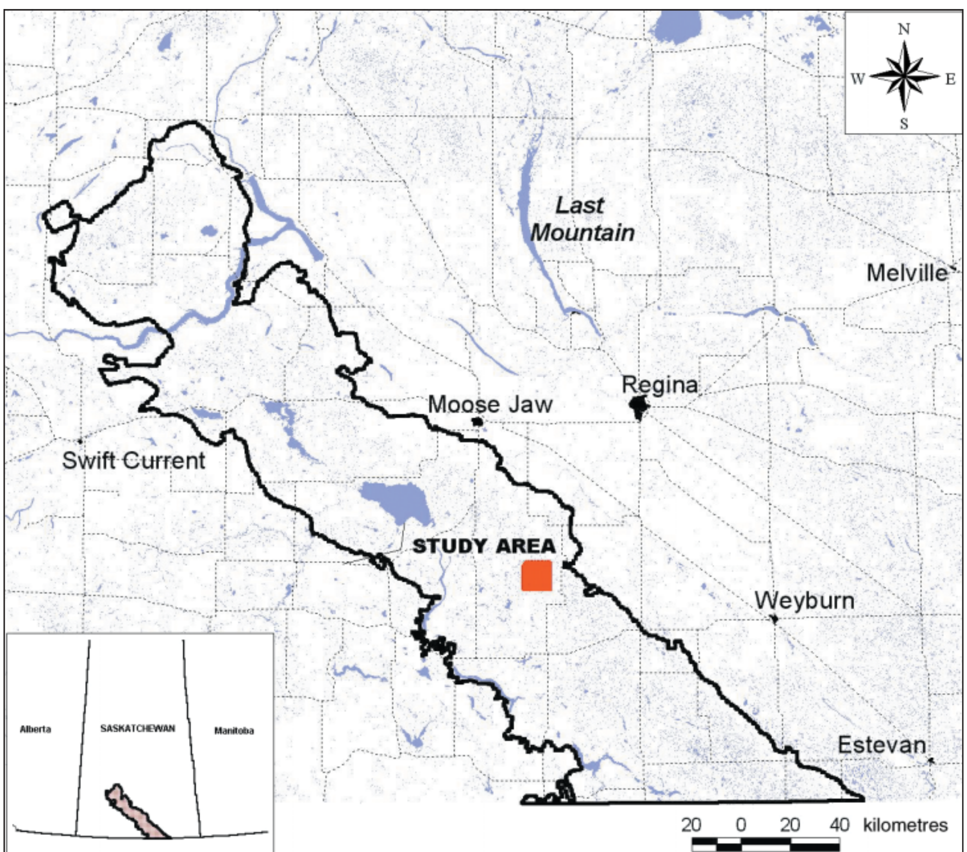

Figure 1. Location of the Missouri Coteau landscape and the study area.

Canadian Wildlife Service (CWS) within the Missouri Coteau region covering an area of 10 × 10 km, has been selected for this assessment because it is being monitored as part of the Prairie Habitat Monitoring Program.

Two Ikonos-2 satellite images were acquired on 24 May 2000 and 29 July 2000 with approximately 1 m and 4 m spatial resolution in the visible (panchromatic) and relatively broad bands in the blue, green, red, and near-infrared portions of the spectrum, respectively. These images were selected because the seasonal variation in dates provided a contrast in vegetation growth from early growth late-spring conditions to the full mid-summer growth. Two image dates also provided information related to permanent or semi-permanent wetlands.

Training sites for field sampling in a wide range of wetlands were identified using a combination of random and stratified random sampling procedures within the confines of the selected study area and known accessible lands. In some cases, lands thought to be accessible were not. Therefore, a purposive sampling strategy (Justice and Townshend, 1981) was used in cases where landowners would not provide permission to access their land or were unavailable to obtain permission.

Coordinates were obtained for each training site using a hand-held global positioning system (GPS); positional accuracy averaged less than 10 m and was calibrated each day based on a comparison with known survey control monuments. In most cases, the training site locations were obtained in the centre of the site, but in certain circumstances, such as deep water, coordinates were obtained at the edge of the selected site area. Each training site was defined as a 16 × 16 m area (or 256 pixels) and was intended to provide the necessary input data to drive a supervised classification algorithm. A total of 271 field sites were sampled.

A field program was conducted 8–16 July 2000 and field sites were classified according to the wetland habitat classification scheme developed by Stewart and Kantrud (1971) (S&K) (**Table 1**). The S&K system has been based on vegetative classification structure, which can include a wide range of individual vegetation cover types and unique "vegetation assemblages" or "communities". Commonly used for typing Canadian wetlands using aerial photography and field sampling, each of the available training sites was sampled and interpreted as one of the S&K habitat classes. It was also refined to a second level of classes that represent more distinctive vegetation communities or unique vegetation assemblages (see list included in **Table 1**). Thus, each training site included a breakdown of all vegetation cover occurrences (in percent estimates as viewed from above and 10% increments) and land use activities within each site on the ground (e.g., agriculture). From this field sample, training sites were identified in the imagery within the field sample site to

Table 1. Wetland habitat and upland classes of Stewart and Kantrud (1971).

Category	Definition
Closed deciduous	Greater than 60% crown closure; deciduous trees are 75% or more of total basal area
Low prairie	Class I: ephemeral ponds; central zone represented by low-prairie vegetation (*Poa pratensis*, *Solidago altissima*, etc.)
Wet meadow	Class II: temporary ponds; central zone represented by wet-meadow vegetation (generally fine-stemmed grasses and sedges with associated forbs); subclasses include (a) fresh (*Poa palustris*, *Boltonia latisquama*, etc.) and (b) slightly brackish (*Hordeum jubatum*, *Calamagrostis inexpansa*, etc.)
Shallow marsh	Class III: seasonal ponds and lakes; central zone represented by shallow-marsh vegetation (moderately coarse grasses and sedges with associated forbs); subclasses include (a) fresh (*Carex atherodes*, *Glyceria grandis*, etc.), (b) slightly brackish (*Scolochloa festucacea*, *Eleocharis palustris*, etc.), and (c) moderately brackish (*Alisma gramineum*, *Beckmannia syzigachne*, etc.)
Deep marsh	Class IV: semi-permanent ponds and lakes; central zone represented by deep-marsh vegetation (relatively coarse marsh emergents or associated submerged aquatics); subclasses include (a) fresh (*Scirpus heterochaetus*, etc.), (b) slightly brackish (*Typha* spp., *Scirpus acutus*, etc.), (c) moderately brackish (*Scirpus acutus*, etc.), (d) brackish (*Scirpus paludosus*, *Scirpus acutus*, etc.), and (e) subsaline (*Scirpus paludosus*, etc.)
Open water	Class V: permanent ponds and lakes; central area represented by permanent open-water zone (devoid of emergent vegetation, but submerged vegetation, particularly *Ruppia occidentalis*, often present); subclasses (based on species composition of peripheral zones) include (a) slightly brackish (*Typha* spp., *Scolochloa festucacea*, etc.), (b) moderately brackish (*Scirpus acutus*, *Hordeum jubatum*, etc.), (c) brackish (*Scirpus paludosus*, *Scirpus americanus*, etc.), and (d) subsaline (*Puccinellia nuttalliana*, *Salicornia rubra*, etc.)
Native prairie	Composition of area to contain greater then 75% native grass species; species native to the Canadian Prairies include *Stipa* sp., *Bouteloua gracilis*, *Festuca* spp.
Shrub	At least 20% ground cover with at least one third shrub; shrubs can be native and introduced
Cropland	Consists of lands dedicated to the production of crops; normally croplands would be cultivated on an annual basis
Tame grass	Human-introduced plantings of grass that is homogeneous in species composition; common members include crested wheatgrass, timothy, brome, and tall wheat grass

ensure homogeneous training areas for supervised classification. This involved the manual interpretation of the image data to identify representative areas for each of the desired classes based on the standard principles of object recognition (Avery, 1977) and was aided by ground photographs and sketch maps of vegetation types with each site. Once these data had been reviewed, one third of the total samples were removed for the purposes of testing classification accuracy. This process involved ordering the sites by class and selecting every third sample to be test data.

Data processing

The images were examined for atmospheric effects by histogram and scatterplots to determine the minimum radiance observed over dark objects (such as lakes). The contribution by the atmosphere was considered negligible for the purposes of statistical tests and classification. Initial interpretation suggested that the differences in the two image dates were primarily driven by vegetation phenological and physiological differences.

A geometric correction of the July imagery was performed based on vector data purchase from the Information Services Corporation of the Saskatchewan Government. The quarter-section fabric and road intersection points provide a positional accuracy of less than 5 m. An average root mean square (RMS) of 0.17 pixels was reported. The remaining images were rectified based on an image to image approach and were resampled using a nearest neighbor approach.

Derived image data for inclusion in the assessment of the classification results using linear discriminant analysis (LDA) included fused imagery, a normalized difference vegetation index (NDVI), and texture measures. Several fused-image combinations were generated for the LDA. Each multi-spectral band combination of 3, 2, and 1 and 4, 3, and 2 was fused with the panchromatic imagery using an intensity, hue, and saturation (IHS) transformation (PCI Inc., 1996). It has been demonstrated that the addition of higher resolution imagery can improve classification accuracies in land cover classifications (Price, 1987; Franklin et al., 1994). An NDVI transformation was then performed on bands 4 and 3 to produce an estimate of biomass (Tucker, 1979). It was felt that this transformation would assist in the identification of emergent vegetation and permit the separation of some higher biomass plant types (such as *Scolochloa festucacea* (white top) versus *Eleocharis acicularis* (spike rush)).

The spatial texture measures of entropy (or the amount of randomness in an image area) and homogeneity from spatial co-occurrence matrices were assembled with window sizes of 15 × 15 m in the panchromatic band (Earth Resources Mapping Pty Ltd., 1998). This area was approximately equal to the same area as that sampled on the ground during the collection of field data for training sites. Texture has also been shown to improve classification accuracy in forests (Franklin, 1994), and it was felt that it would improve the accuracy in wetlands.

Classification method

Two classification algorithms were used to classify Ikonos-2 imagery according to the S&K habitat classes and the individual vegetation communities represented within each class: (*i*) linear discriminant analysis (LDA) based on pixels that make up the individual calibration sites sampled in the field; and (*ii*) unsupervised ISODATA classification of image data and LDA analysis of validation pixels supplemented with additional field observations. In essence, the LDA method provides an initial analysis of the separability of the classes and vegetation communities in the field data set (Tom and Miller, 1984). Augmented with the larger numbers of pixels from an additional field visit, an ISODATA classifier extends this separability to create a classification map. The accuracy of each classification algorithm was determined by examining pixels in the sites that were not used in the formation of the decision rules. Overall accuracies were computed from contingency tables.

Results and discussion

Stewart and Kantrud (S&K) wetland habitat classes

Overall classification accuracies were based on the categories using all bands of the May and July imagery plus the addition of a normalized difference vegetation index (NDVI) and texture measures. Sites to be used as training areas were evaluated based on an LDA assessment to provide an indicator of how well the S&K categories were represented by the field data (Franklin et al., 2001). **Table 2** contains the results of spectral discrimination of the training and test sites according to the logic in the S&K wetland habitat classification system. Based on the LDA, a low representation of training sites to field data is evident by a 48.6% agreement (sample size (n) = 14 375), and as expected, extensive overlap in the spectral signatures was obtained as expressed by a low classification accuracy of 46.9% (n = 4792). The low prairie and shallow marsh classes were very poorly separated as represented by low

Table 2. Classification accuracy based on LDA analysis of field samples for nine S&K wetland habitat classes.

Class	Calibration (%)	Validation (%)
Closed deciduous	86	79
Deep marsh	70	68
Low prairie	24	25
Native prairie	64	62
Shallow marsh	25	23
Shrub	61	63
Wet meadow	51	50
Cropland	82	79
Tame grass	39	38
Overall accuracy	48.6	46.9

Note: LDA results are based on all bands for the two image dates, NDVI, and texture.

class accuracies. Based on the calculated accuracies, some of the general classes, such as cropland and closed deciduous, appeared highly separable (**Table 2**).

These low classification accuracies for the S&K wetland habitat classes are indicative of two significant problems: (*i*) the lack of correspondence between wetland habitat classes identified within the S&K system and the available Ikonos spectral classes, which are principally driven by vegetation or land cover spectral response; and (*ii*) the fact that the 16 × 16 m training areas represent an "assemblage" of vegetation found in other classes, such as *Scirpus* spp., which is found in S&K classes of open water and deep marsh.

In other words, because the S&K wetland habitat classes were not comprised of unique, unvarying signatures, but instead were the result of the particular assemblages of features, the "agglomerated" classes (i.e., everything put together) to generate signatures were not optimal for wetland habitat mapping. S&K habitat classes were designed for field or airphoto assessment and rely on human skill to separate out the different components and are not well suited to automated analysis of imagery, given the availability of the current classification tools.

Mapping specific vegetation communities

An unsupervised classification based on an ISODATA decision rule of an IHS-fused image (bands 4, 3, and 2 and pan) was used to create a map which is illustrated with the small wetland area shown in **Figure 2**. Individual class accuracies for the 25 vegetation communities were generated from contingency tables and are shown in **Table 3**. These communities included several different agricultural cropland classes; for example, crop stubble varied from fallow fields. The accompanying ground photograph shows that the vegetation patterns in the wetland correspond to the classification. *Carex*, *Calamagrostis*, and *Scolochloa festucacea* (white top) are distinguishable in the image data and also were classified as separate vegetation communities within this wetland. Two densities of *Calamagrostis* are identified as shown by the two shades of pink. Some mixing with other vegetation classes, such as native prairie and tame grasses, occurred near the open-water areas of this wetland.

A second set of LDA tests was conducted on 25 vegetation communities extracted from S&K field samples based on several band combinations and multi-temporal imagery. Overall accuracies of validation sites for these classifications

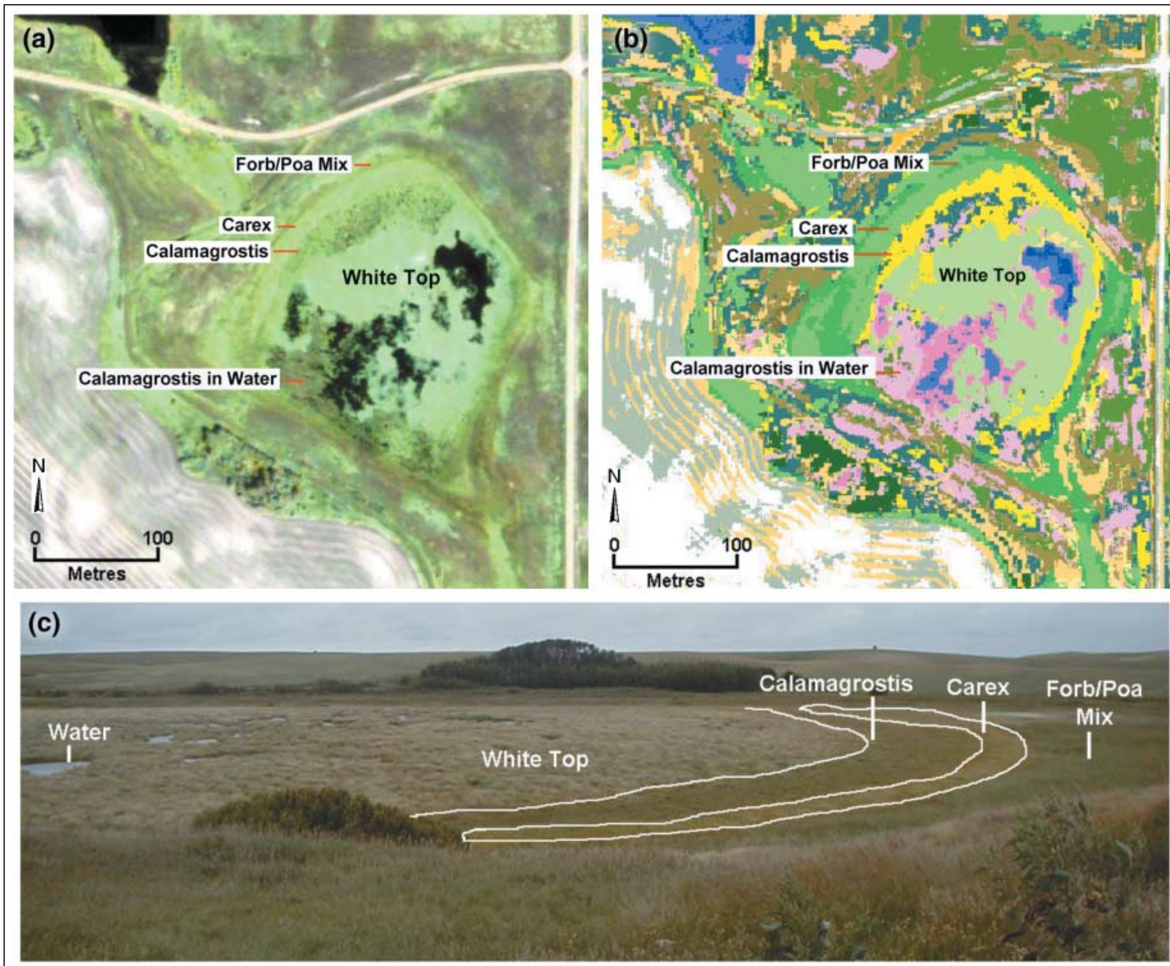

Figure 2. Typical prairie wetland: (a) panchromatic and multi-spectral fused Ikonos image (© Space Imaging 2000); (b) classified Ikonos image; and (c) ground view looking to the southwest.

Table 3. Percent accuracy of vegetation communities based on image interpretation and field assessment.

Community	Class accuracy (%)
Foxtail (*Hordeum jubatum*)	67.8
White top (*Scolochloa festucacea*)	100.0
Deciduous	68.6
Shrubs	65.2
Shallow water	97.7
Carex	52.1
Tame grass	86.5
Native grass	100.0
Cropland	
Stubble 40%, bare soil 60%	95.6
Bare soil 100%	100.0
Stubble 20%, bare soil 80%	51.6
Cereal crop 60%, bare soil 40%	100.0
Pasture: tame grass 95%, bare soil 5%	53.5
Slender wheatgrass	6.8
Calamagrostis	78.3
Forb, *Poa*	100.0
Symphoricarpos	100.0
Alkali water	100.0
Bare soil, alkali	100.0
Alfalfa	4.5
Gravel	92.7
Road	85.2
Typha	96.7
Carex, dead *Typha*	36.4
Deep water	100.0

Note: Overall accuracy = (5068 correctly classified samples)/(6002 validation samples) = 84.4%.

are presented in **Table 4**. The May imagery clearly had the lowest accuracy (50.5%), and a multi-temporal combination of the May and July dates had the highest accuracy (95.9%). From a practical perspective, however, the improvement in accuracy over the infrared summer image (84.4%) alone may not be enough to justify the cost increase for multi-temporal image acquisitions.

Conclusions

Using traditional supervised and unsupervised classification techniques, May and July Ikonos images were classified into a number of wetland habitat classes and vegetation communities in southern Saskatchewan. IHS-fused images, an NDVI, and texture measures were employed in a linear discriminant analysis. Accuracies were approximately 47% in the broad wetland habitat classes defined in a common structural classification system used in the Prairies, the Stewart and Kantrud (1971) or S&K wetland habitat classes. High variability in vegetation communities was apparent within these classes, however, and training-area homogeneity as shown in a satellite image was different from that identified by field personnel. Subsequently, the classes were defined according to the dominant vegetation communities, and additional training areas were identified. Overall accuracy of the final map improved to greater than 84% overall.

Table 4. Summary results of accuracy assessment in vegetation communities.

Data	Overall accuracy (%)
May IHS fusion of bands 3, 2, and 1 and pan	50.5
May IHS fusion of bands 4, 3, and 2 and pan	55.8
July IHS fusion of bands 3, 2, and 1 and pan	82.0
July IHS fusion of bands 4, 3, and 2 and pan	84.4
May and July together	94.7
May and July together and texture	95.9

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References

Avery, T.E. 1977. *Interpretation of aerial photographs*. Burgess Publishing Company, Minneapolis, Minn. 392 pp.

Babey, S.K., Anger, C.D., Achal, S.B., Ivanco, T., Moise, A., Costella, P.R., and DeBliek, J. 1999. Development of a next generation compact airborne spectrographic imager. In *Proceedings of the 4th International Symposium on Airborne Remote Sensing and the 21st Canadian Symposium on Remote Sensing*, 21–24 June 1999, Ottawa, Ont. Canadian Aeronautics and Space Institute, Ottawa, Ont., pp. 229–239.

Desachy, J., Toux, L., and Zahzah, E.H. 1996. Numeric and symbolic data fusion: a soft computing approach to remote sensing image analysis. *Pattern Recognition Letters*, Vol. 17, pp. 1361–1378.

Earth Resources Mapping Pty Ltd. 1998. *ER Mapper 6.0 users guide*. Earth Resources Mapping Pty Ltd., West Perth, Australia.

Foody, G.M. 1999. The continuum of classification fuzziness in thematic mapping. *Photogrammetric Engineering and Remote Sensing*, Vol. 65, pp. 443–451.

Franklin, S.E. 1994. Discrimination of subalpine forest species and canopy density using digital CASI, SPOT PLA, and Landsat TM data. *Photogrammetric Engineering and Remote Sensing*, Vol. 60, pp. 1233–1241.

Franklin, S.E., Connery, D.R., and Williams, J.A. 1994. Classification of alpine vegetation using Landsat thematic mapper, SPOT HRV, and DEM data. *Canadian Journal of Remote Sensing*, Vol. 20, No. 1, pp. 49–56.

Franklin, S.E., Stenhouse, G.B., Hansen, M.J., Popplewell, C.C., Dechka, J.A., and Peddle, D.R. 2001. An integrated decision tree approach (IDTA) to mapping landcover using satellite remote sensing in support of grizzly bear habitat analysis in the Alberta Yellowhead ecosystem. *Canadian Journal of Remote Sensing*, Vol. 27, No. 6, pp. 579–592.

Green, K. 2000. Selecting and interpreting high-resolution images. *Journal of Forestry*, Vol. 98, pp. 37–39.

Irons, J.R., Johnson, B., and Linebaugh, G. 1987. Multiple-angle observations of reflectance anisotropy from an airborne linear array sensor. *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 25, pp. 372–383.

Irons, J.R., Ranson, K.J., Williams, D., Irish, R., and Huegel, F. 1991. An off-nadir pointing imaging spectroradiometer for terrestrial ecosystem studies. *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 29, pp. 66–74.

Justice, C.O., and Townshend, J.R.G. 1981. Integrating ground data with remote sensing. In *Terrain analysis and remote sensing*. Edited by J.R.G. Townshend. George Allen & Unwin, Boston, Mass., pp. 38–58.

Kuhl, D. 1996. Fusing remote sensing technology to enhance habitat monitoring. In *Eco-Informa,* Vol. 2, 4–7 Nov. 1996, Lake Buena Vista, Fla. ERIM, Ann Arbor, Mich. pp. 843–848.

Millar, J.B. 1992. *Baseline (1985) habitat estimates for the settled portions of the Prairie Provinces*. Report 8, Saskatchewan Mixedgrass Prairie, Prairie Habitat Monitoring Project, Canadian Wildlife Service, Edmonton, Alta. 58 pp.

Munyati, C. 2000. Wetland change detection on the Kafue Flats, Zambia, by classification of a multitemporal remote sensing image dataset. *International Journal of Remote Sensing*, Vol. 21, pp. 1787–1806.

Neville, R., and Till, S. 1991. MEIS-FM, a multispectral imager for forestry and mapping. *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 29, pp. 184–186.

PCI Inc. 1996. *Using PCI software*. PCI Inc., Richmond Hill, Ont. 530 pp.

Phinn, S.R., Stow, D.A., and Van Mouwerik, D. 1999. Remotely sensed estimates of vegetation structural characteristics in restored wetlands, southern California. *Photogrammetric Engineering and Remote Sensing*, Vol. 65, pp. 485–493.

Price, J.C. 1987. Combining panchromatic and multispectral imagery from dual resolution instruments. *Remote Sensing of Environment*, Vol. 21, pp. 119–128.

Sader, S.A., Ahl, D., and Liou, W.S. 1995. Accuracy of Landsat thematic mapper and GIS rule-based methods for forest wetland classification in Maine. *Remote Sensing of Environment*, Vol. 53, pp. 133–144.

Stewart, R.E., and Kantrud, H.A. 1971. *Classification of natural ponds and lakes in the glaciated prairie region*. Resource Publication 92, Bureau of Sport Fisheries and Wildlife, U.S. Fish and Wildlife Service, Washington, D.C.

Tiner, R.W. 1990. Use of high-altitude aerial photography for inventorying forested wetlands in the United States. *Forest Ecology and Management*, Vol. 33, pp. 593–604.

Tom, C.D, and Miller, L.D. 1984. An automated mapping comparison of the Bayesian maximum likelihood and linear discriminant analysis algorithms. *Photogrammetric Engineering and Remote Sensing*, Vol. 50, pp. 193–207.

Tucker, C.J. 1979. Red and photographic infrared linear combinations for monitoring vegetation. *Remote Sensing of Environment*, Vol. 8, pp. 127–150.