

POPULAR SUMMARY:

North American vegetation dynamics observed with multi-resolution satellite data

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North American vegetation has been discovered to be a net carbon sink, with atypical behavior of drawing down more carbon from the atmosphere during the past century. It has been suggested that the Northern Hemisphere will respond favorably to climate warming by enhancing productivity and reducing the impact of fossil fuel emissions into the atmosphere. Many investigations are currently underway to understand and identify mechanisms of storage so they might be actively managed to offset carbon emissions which have detrimental consequences to the functioning of ecosystems and human well being.

This paper used a time series of satellite data from multiple sensors at multiple resolutions over the past thirty years to identify and understand mechanisms of change to vegetation productivity throughout North America. We found that humans had a marked impact to vegetation growth in half of the six selected study regions which cover greater than two million km². We found climatic influences of increasing temperatures, and longer growing seasons with reduced snow cover in the northern regions of North America with forest fire recovery in the Northern coniferous forests of Canada. The Mid-latitudes had more direct land cover changes induced by humans coupled with climatic influences such as severe drought and altered production strategies of rain-fed agriculture in the upper Midwest, expansion of irrigated agriculture in the lower Midwest, and insect outbreaks followed by subsequent logging in the upper Northeast. Vegetation growth over long time periods (20+ years) in North America appears to be associated with long term climate change but most of the marked changes appear to be associated with climate variability on decadal and shorter time scales along with direct human land cover conversions. Our results document regional land cover land use change and climatic influences that have altered continental scale vegetation dynamics in North America.

1 **North American vegetation dynamics**
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19 **Abstract**

20
21 We investigated normalized difference vegetation index data from the NOAA series of
22 Advanced Very High Resolution Radiometers and found regions in North America that experienced
23 marked increases in annual photosynthetic capacity at various times from 1982 to 2005. Inspection of
24 these anomalous areas with multi-resolution data from Landsat, Ikonos, aerial photography, and
25 ancillary data revealed a range of causes for the NDVI increases: climatic influences; severe drought and
26 subsequent recovery; irrigated agriculture expansion; insect outbreaks followed by logging and
27 subsequent regeneration; and forest fires with subsequent regeneration. Vegetation in areas in the high
28 Northern Latitudes appear to be solely impacted by climatic influences. In other areas examined, the
29 impact of anthropogenic effects is more direct. The pattern of NDVI anomalies over longer time periods
30 appear to be driven by long term climate change but most appear to be associated with climate
31 variability on decadal and shorter time scales along with direct anthropogenic land cover conversions.
32 The local variability of drivers of change demonstrates the difficulty in interpreting changes in NDVI
33 and indicates the complex nature of changes in the carbon cycle within North America. Coarse scale
34 analysis of changes could well fail to identify the important local scale drivers controlling the carbon
35 cycle and to identify the relative roles of disturbance and climate change. Our results document regional
36 land cover land use change and climatic influences that have altered continental scale vegetation
37 dynamics in North America.

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40 **Keywords:** AVHRR, NDVI, Vegetation Dynamics, Land Cover, Climate, Landsat

41 **1. Introduction**

42 Land cover and land use change strongly influence terrestrial biogeophysical and
43 biogeochemical process (Brovokin et al., 2004; DeFries et al., 1999; Houghton, 1999). Humans and
44 changing climate, separately or in concert, have affected global vegetation, biogeochemical cycles,
45 biophysical processes, and primary production. To infer North America vegetation changes we used a
46 1982 to 2005 record of normalized difference vegetation index (NDVI) data. This approach, using 8-km
47 NDVI data from the (NOAA) National Ocean and Atmospheric Administration Advanced Very High
48 Resolution Radiometer (AVHRR) instruments, has previously identified large-scale spatial and temporal
49 patterns of vegetation response to climate (Lotsch et al., 2005; Myneni et al., 1997; Nemani et al., 2003;
50 Zhou, 2003). Previous work by others, (Goetz et al., 2005; Gong & Shi, 2003; Ichii et al., 2002; Myneni
51 et al., 1997; Nemani et al., 2003; Slayback et al., 2003; Tucker et al., 2001; Zhou et al., 2001), has
52 addressed continental scale phenomena of changes in photosynthetic capacity since 1981-1982 from
53 NDVI data. Investigations with coarse resolution data are limited in the ability to identify specific
54 regional or local land use and land cover change mechanisms that could be responsible for NDVI
55 anomalies.

56 A number of natural factors influence North American vegetation and primary production, and
57 hence the NDVI: warming and possible reduced arctic snow cover (Chapin et al., 2000; Dye & Tucker,
58 2003); altered plant communities structure (Epstein et al., 2004; Sturm et al., 2005; Sturm et al., 2001;
59 Tape et al., 2006); reduced permafrost extent and effects upon vegetative growth (Hobbie et al., 2002;
60 Stokstad, 2004); insect and pathogen outbreaks (Ayres & Lombardero, 2000); severe drought (Angert et
61 al., 2005; Barber et al., 2000; Ciais et al., 2005; Dai et al., 2004; Lotsch et al., 2005); and forest fire
62 regimes (Flannigan et al., 2000). Anthropogenic influences on vegetation productivity include: more
63 intensive agriculture practices (Malhi et al., 2001; Sainju et al., 2002); expansion of irrigated agriculture

64 (Lemly et al., 2000; Tilman, 1999); decreasing productivity by removing biomass through urban
65 expansion (Imhoff et al., 2000; Masek et al., 2000); and logging and subsequent regeneration (Howard
66 et al., 2004). This analysis was undertaken to understand vegetation dynamics at a regional scale in
67 North America, to explore possible mechanisms that can affect continental-scale primary production.
68 We were specifically interested in investigating NDVI anomalies and determining what caused them,
69 through the combined use of AVHRR NDVI, Landsat, Ikonos, aerial photography, and ancillary data.

70 NDVI data from the NOAA series of AVHRR instruments over the past 24 years have shown
71 variations in photosynthetic capacity across large areas of North America (Slayback et al., 2003). These
72 observed NDVI trends have occurred in a variety of regions, implying possibly a variety of cause(s)
73 (Goetz et al., 2005; Picket & White, 1985; Tucker et al., 2001). Although a number of recent studies
74 have found marked variations in NDVI throughout the Northern Hemisphere, they have not attributed
75 these changes to regional factors that may include natural disturbances and/or human alterations to
76 ecosystem functioning (Gong & Shi, 2003; Lotsch et al., 2005; Lucht et al., 2002; Myneni et al., 2001;
77 Myneni et al., 1997; Nemani et al., 2003; Slayback et al., 2003; Tucker et al., 2001; Zhou et al., 2001).
78 It is important to identify and quantify land cover type, because changes in land cover can alter
79 ecosystem functioning and carbon storage (Baldocchi & Amthor, 2001; Olson, 1975).

80 NDVI (Tucker, 1979) is calculated from channel 1 (0.58-0.68 μm) and channel 2 (0.72-1.10 μm)
81 from the NOAA AVHRR series of polar orbiting satellites as:

$$\text{NDVI} = \frac{\text{Channel 2} - \text{Channel 1}}{\text{Channel 2} + \text{Channel 1}} \quad (1)$$

82
83
84
85 NDVI has been found to have a strong linear relationship to the fraction of photosynthetically active
86 radiation (FPAR), the radiation that drives photosynthesis (0.4 -0.7 μm) (Myneni et al., 1995; Sellers,
87 1985). FPAR is the main determinant of net primary productivity (NPP) of the ecosystem (Monteith,

88 1981). NDVI changes across North America are thus important because they represent variability in
89 vegetation photosynthetic capacity. Few investigations have explored regional vegetation changes in
90 North America responsible for the observed increases in Northern Hemisphere NDVI; (Jia et al., 2003;
91 Stow et al., 2003; Walker et al., 2003) our investigation seeks to understand regional vegetation
92 dynamics across the North American Continent observed by AVHRR NDVI.

93

94 **2. Methods and Data**

95 *2.1. AVHRR NDVI*

96 We used the Global Inventory Modeling and Mapping Studies (GIMMS) version “g”, 1982 to
97 2005 bimonthly AVHRR NDVI record (Tucker et al., 2005) because a consistent inter-calibrated data
98 set is critical for long-term vegetation studies. These data, at 8-km (64 km²) resolution and bimonthly
99 intervals, have been processed to account for orbital drift, minimize cloud cover, compensate for sensor
100 degradation, and effects of stratospheric volcanic aerosols (Brown et al., 2004; Tucker et al., 2005). The
101 GIMMS NDVI data records are accessible from the University of Maryland’s Global Land Cover
102 Facility (www.landcover.org).

103 The first step in our analysis was to identify regions for further investigation. Next we used
104 Landsat data to understand NDVI anomalies in terms of land cover at the 30 m scale. Anomaly images
105 were generated by year relative to the 1982 to 2005 average May to September NDVI for North
106 America. Areas were selected for further study if they met 2 criteria: 1) a contiguous region > 2,000
107 km² with a > 0.1 NDVI anomaly at a 98% confidence interval; and 2) high resolution remote sensing
108 data and corresponding validation were also available for analysis for the 1982 to 2005 time period.
109 Specific time periods were selected to investigate the occurrence of the respective NDVI anomalies.

110 A lengthening of the growing season may increase plant growth, increase biomass formation,
111 and increase carbon sequestration (Menzel & Fabian, 1999). Nemani, et al. (2003), suggested multiple
112 mechanisms affecting net primary productivity (NPP): nitrogen deposition, CO₂ fertilization, forest
113 regrowth, temperature, precipitation and solar radiation. Recovery from disturbance in forest
114 ecosystems has been noted to produce a net terrestrial carbon sink by which net primary production
115 (NPP) exceeds heterotrophic respiration (Rh) due to enhanced resource availability, and reduced detritus
116 input into the soil (Odum, 1969). We selected regions with increasing NDVI to explore possible
117 changes in ecosystem functioning due to conversion and/or recovery of vegetation.

118

119 2.2. *Landsat*

120 Landsat data were acquired for the same areas that had > 0.1 NDVI anomaly values. We first
121 used data from NASA's orthorectified global Landsat data set (also called the "Geocover" data set)
122 because these data have a < 50 m root mean square location error among the 1970s, 1990, and 2000 data
123 layers (Tucker et al., 2004) and are available free of charge from the Global Land Cover Facility at the
124 University of Maryland. We acquired additional Landsat data for other time periods as needed and
125 coregistered these data to the corresponding Geocover data.

126 We developed a methodology to determine land cover for three time periods (> 150 scenes), to
127 quantify land cover changes that could be responsible for trends in NDVI. We used the International
128 Geosphere Biosphere (IGBP) classification because of its simplicity in defining North American
129 vegetation types. These vegetation types include: evergreen needleleaf forest; mixed evergreen
130 needleleaf and broadleaf deciduous forest; broadleaf deciduous forest; dwarf trees and shrubs; short
131 vegetation C4 grasslands; agriculture C3 grasslands; water; barren lands; clouds and snow and ice
132 (Table 1).

133 An additional coregistration between images was carried out between images to avoid
134 misregistration errors that could be confused with land cover change (Townshend et al., 1992). A
135 minimum of 25 ground control points distributed over the image were selected between the
136 orthorectified base image and the added image. A root mean square error of less than 0.25 pixels was
137 used as the maximum threshold for error before the image was used in our analysis. All Landsat images
138 were processed in a similar manner with the same accuracy.

139 When using multispectral data, changes in surface reflectance have been associated with changes
140 in vegetation cover and extent. Generally, a higher reflectance is associated with sparse vegetation
141 cover, and a lower reflectance is associated with dense vegetation or water in visible wavelengths.
142 When investigating pixel response to changes in land cover, deforestation will typically increase pixel
143 brightness (darker vegetation to lighter soil) whereas afforestation and succession would decrease pixel
144 brightness (bare soil to vegetation) (Jensen, 2006). We use this simple observation to quantify variance
145 in land cover. Radiance values are used in our analysis because the selected study sites have marked
146 changes in land surface reflectance observed by AVHRR. The spectral changes observed between
147 vegetated and non-vegetated pixels far outweigh the influences of sun angle, variability in atmospheric
148 attenuation, and sensor degradation.

149 A number of change detection transforms have been applied to Landsat data: Principal
150 Component Analysis (PCA), tassell cap (TC), and change vector analysis (CVA) (Crist & Cicone, 1984;
151 Kauth et al., 1978; Richards, 1984). These methods all identify change in multi-temporal data and have
152 been enhanced with hybrid methods (Guild et al., 2004; Jin & Sader, 2005; Lanjeri et al., 2004; Lunetta
153 et al., 2002; Nackerts et al., 2005; Rigina, 2003; Warner, 2005). Our analysis developed two methods to
154 stratify multispectral observations into thematic maps of land cover and land cover change. The first
155 method was developed for the boreal zone where variance in spectral reflectance is observed from forest

156 to non-forest changes. Method two required adaptation to identify interannual land use changes that
157 may be difficult to distinguish in regions of intense agriculture. Deriving an assessment of annual active
158 productivity within a region of crops that are rotated seasonally requires an approach to capture all of the
159 active croplands from native short and tall grass prairies. Both methods are based on change detection
160 algorithms currently in use (Guild et al., 2004; Lanjeri et al., 2004).

161 A base map was first generated from the 2000 image from the red (Channel 3), near infrared
162 (Channel 4), and mid infrared (Channel 5) from the Landsat Enhanced Thematic Mapper plus (ETM+).
163 An unsupervised ISODATA classification was performed with all three channels. ISODATA is a
164 standard clustering algorithm available in most image processing software packages and is based on
165 procedures in which cluster centers are iteratively determined sampled means (Tou & Gonzales, 1974).
166 If a scene contains atmospheric constituents, multiple iterations of the classification were performed to
167 mask and eliminate cloud, cloud shadow, and haze cover. This was necessary to minimize atmospheric
168 contamination that alters the class distribution structure. That was the basis for selecting and
169 distinguishing the classification cover types.

170 Once a base map of recent land cover was derived, we reverted in time to define locations of
171 change in land cover and mask the current thematic map for prior land cover types (Fig. 1). A similar
172 method has been performed by (Lanjeri et al., 2004). This method was applied to reduce
173 misclassifications between dates with no land cover changes.

174 Change detection was subsequently performed once a base thematic map had been developed for
175 each anomaly area. A linear tassle cap transformation was first applied to the temporal images reducing
176 multispectral redundancy to indices of brightness, greenness, and wetness (Crist & Cicone, 1984; Huang
177 et al., 2002). The linear tassle cap also enhanced differences in brightness, greenness, and wetness that
178 may occur between multi-date images. The weights of the linear tassle cap transformation were fixed,

179 were sensor specific, and were not scene dependent (Guild et al., 2004). The sensor specific weights of
180 the linear tassell cap transformation aid in normalizing between sensors for change detection analysis.
181 Finally, an unsupervised ISODATA clustering algorithm was performed to all transformed images to
182 group similar spectral vectors into 'change' and 'no change' clusters from the bi-temporal images
183 (Richards, 1993).

184 The same procedure was also performed in agriculture regions with the modification of adding
185 an additional pair of images from the same year as the base period of investigation (Fig. 2). This was
186 done to capture crop rotation during a growing season while distinguishing irrigated agriculture from
187 fallow croplands and natural grasslands. Irrigated agriculture generally has an enhanced signature of
188 wetness and greenness compared to non-irrigated vegetation in the semi-arid high plains environment.
189 The additional image required image processing to produce a meaningful bi-temporal tassell cap image.

190

191 2.3. *Validation*

192 Accuracy assessment of land cover maps incorporated two levels of stratification. This was
193 performed to capture two separate indicators of accuracy: map accuracy; and an assessment of change.
194 The sample design contains three components similar to Stehman & Wickham, (2006), that were used
195 for the National Land Cover Assessment: (1) the sample design, that determines the spatial locations at
196 which the reference data were obtained; (2) the response design, that details how the reference data were
197 obtained; and (3) the analysis plan for producing the accuracy assessments. Error matrices are then
198 created between the thematic map and reference data. Matrices are constructed with the rows
199 representing the map land cover and columns representing the reference land cover.

200 The sample design employed nested hierarchical partitions to stratify the sampling distribution.
201 Each study region was subdivided into two by two degree cells. The spatial extent of the maps

202 developed for analysis in this investigation were large with study areas ranging from ~8 to ~18 million
203 hectares (62,136 km² to 111,846 km²). Multiplied times six study regions, and three temporal periods
204 produced maps containing ~324 million hectares (2,013,202 km²). An adequate sampling of validation
205 data from in situ field surveys was impractical and cost prohibitive due to the spatial extent of the maps.
206 A cost effective large sampling method was employed to develop an adequate validation reference
207 dataset for cross comparison.

208 The validation dataset was derived from very high-resolution (~0.5 – 2 m) archived digital aerial
209 photography, Ikonos high resolution remote sensing imagery (1-4 m), and in situ field plot surveys with
210 aerial over flights of Global Position System (GPS) referenced photography. The 2000 Landsat analyses
211 were validated the most, because they were the most current satellite information (Fig. 3). The 1990 and
212 1975 Landsat data was investigated with digital aerial photography from a similar time period to verify
213 observed changes in cover types. Unfortunately a very limited amount of high-resolution aerial
214 photography data existed for our selected study regions in 1975. This limitation was reported in
215 accuracy assessments as the number of samples used in the confusion matrix as comparisons of dates
216 between air photos and Landsat scenes. Accuracy assessment of historical maps is vital due to the
217 implications of land cover land use change within disturbance-modified ecosystems. Biogeochemical-
218 modeled results rely on remote sensing input datasets to derive quantitative estimates of carbon (Potter
219 et al., 1993; Powell et al., 2004).

220

221 *2.3. Ancillary Data*

222 Once the primary cause of land cover change was identified with Landsat regional analysis, we
223 used fire, logging, agriculture production, temperature, and precipitation data to investigate these factors
224 as possibly contributing to NDVI trends within the areas studied. Fire and logging extent datasets were

225 derived from the Canadian forest service (Canada, 2006; NRC, 2006) and were reported annually by
226 province in hectares. A fire database from the boreal ecosystem-atmosphere study (BOREAS) that
227 spans from 1945 to 1996 was also used (Sellers et al., 1997). Agriculture production data were derived
228 from the United States Department of Agriculture (USDA) National Agriculture Statistics Service
229 (NASS) (USDA, 2006) for areas selected for study in the U.S. Data were reported by county, crop
230 type, and production method.

231 Influences of temperature and precipitation were investigated with daily meteorological station data
232 (where available) from the Meteorological Service of Canada (MSC) in regions with NDVI trends with
233 no land cover change (MSC, 2007). Analyses were performed to investigate whether drought, or a
234 change in growing season length had occurred. The beginning of the growing season was calculated as
235 the first appearance of five consecutive days with the daily average surface temperature,
236 $T=(T_{\max}+T_{\min})/2$, above 5° C and the end of the growing season as the last occurrence of five consecutive
237 days of temperature with $T>5^{\circ}$ C (Feng & Hu, 2004; Frich et al., 2002).

238

239 3. Results

240 NDVI anomalies in the AVHRR data revealed six areas for investigation with high-resolution
241 data to evaluate land cover land use change. We selected six contiguous regions based on two
242 assumptions: (I) A contiguous region > 2,000 km² has an NDVI trend greater than >0.1 from selected
243 observational periods and; (II) High resolution remote sensing data and corresponding validation data
244 were available for intensive analysis for the entire AVHRR record. Six regions met these criteria: (1)
245 the Mackenzie River delta; (2) Northern Saskatchewan; (3) Southern Saskatchewan; (4) Oklahoma
246 Panhandle; (5) Southern Quebec; and (6) Newfoundland (Fig. 4). Two areas that experienced large-

247 scale NDVI trends were not investigated due to a lack of high-resolution remotely sensed data (Northern
248 Quebec and Labrador).

249

250 *3.1. The Arctic slope of Alaska, Yukon, and Northwest Territory*

251 A large area of North America bordering the Arctic Ocean in Alaska and Canada, roughly from 60°
252 to 70° N exhibited a zone of NDVI increases from 1982 to 2005. We selected the Mackenzie River
253 Delta area of Canada for investigation, because numerous high-resolution aerial photographs are
254 available for the entire AVHRR record.

255 The Mackenzie River delta study region is located in the Arctic Circle where extreme variations
256 in solar insolation and temperature are the norm. Winter extends nine months in this region, and the
257 surrounding landscape is underlain with continuous permafrost while the land cover consists primarily
258 of alpine tundra to open lichen woodland (Archibold, 1995). The river delta has a unique ecosystem to
259 neighboring lands due to the northward flow of warm waters to the Arctic Circle. The depth of the
260 permafrost controls nutrient availability and vegetative cover while temperature exerts considerable
261 control over permafrost depth and the active organic soil layer in surrounding ecosystems (Pavelsky &
262 Smith, 2004). Chen et al., (2003), noted a decline of 22% in the permafrost zone from 1940 to 1995 in
263 northwestern Canada. Higher temperatures have increased the active soil layer depth and extent while
264 extending growing season length.

265 This area is located just above the Northern limit of the North American boreal forest and has
266 little anthropogenic disturbance. The largest concentration of human settlement in the region is Inuvik
267 (68°18'N, 133°30'W), which has 3,600 residents (Fig. 5, A). The lack of human occupation implies the
268 observed anomaly was not associated with human alterations of land cover but the change in vegetation
269 was related to climate.

270

271 *3.1.1. Land Cover*

272 Land cover results for this region indicated minor changes in vegetation cover from 1976 to
273 2000. ~80,000 km² were mapped and dwarf trees and shrubs increased by ~720 km² (+ < 1% change in
274 area), short vegetation grassland declined ~950 km² (-1% change in area), and water extent changed by
275 ~400 km² (+ < 1% change in area). The largest event was a fire that burned ~710 km², reducing
276 vegetation to barren lands (+ < 1% in area).

277 Landsat imagery was limited in applicability to define the spectral differences between short
278 vegetation grasslands and dwarf trees and shrubs. This excludes the ability to define subtle vegetative
279 growth on a decadal basis. Extensive multi-temporal high-resolution data are needed to evaluate if
280 expansion of shrub lands is occurring. This remote area has incurred limited human disturbance
281 implying that alterations to this ecosystem have been induced by abiotic factors. Plant growth is
282 increasing as warmer temperatures extend the growing season length (Fig. 5, E, F, and G).

283 Higher surface temperatures during late winter and early spring have been reported in the high
284 arctic of North America (Hansen et al., 1999). We found an increase in warmer temperatures was
285 associated with a corresponding increase in NDVI in this region. Warming resulted in an earlier start of
286 the growing season. We found temperatures increased $\sim 2^\circ \pm 1^\circ$ from March to August while the
287 beginning of growing season was ~15 days earlier (from mid May to early May) over the same 1982-
288 1999 time period. Warming in this region enhanced May to August NDVI by permitting a longer
289 growing season (Fig. 5, G). Our results capture an increase in photosynthetic capacity (duration and
290 amplitude) of vegetation due to longer available periods of productive growth due to earlier onset of
291 spring. An in depth quantitative analysis of climate influence to vegetation productivity is beyond the
292 scope of this work; these phenomena will be investigated with simulation modeling in the future. As

293 suggested by Sturm et al., (2005), abiotic and/or sun-target-sensor influences have altered vegetation
294 dynamics in this region.

295

296 3.2. Northern Saskatchewan

297 The northern Saskatchewan study region lies on the boundaries of two ecoregions, the closed
298 boreal forest and the open lichen woodland. The division between closed spruce-feather moss boreal
299 forests and open lichen woodland is abrupt in the northern boundaries of the provinces of Manitoba and
300 Saskatchewan. This boreal ecoregion is a small portion of the North American boreal forest that covers
301 ~10° of latitude, but it is a floristically poor biome (Jarvis et al., 2001). Two species are nearly
302 ubiquitous in this region, white spruce (*P. glauca*) and black spruce (*P. marianiana*) with other species of
303 larch or tamarack (*L. laricina*), balsam fir (*A. balsamea*), balsam poplar (*P. banksiana*), trembling aspen
304 (*P. tremuloides*) and white or paper birch (*B. papyrifera*) are intermixed depending on the age of the
305 current successional state. Extensive peat bogs and muskegs sporadically dot the landscape among
306 dense stands of conifers as remnants of glacial times of the past.

307 There is little human interference with the land cover in this region because access is limited.
308 However, fire is one of the most important disturbances in this region (Wein & MacLean, 1983; Wright
309 & Heinselman, 1973). Boreal forests are very productive following fire events. Amiro et al., (2000),
310 found that aboveground NPP increased linearly for the first 15 years following forest fires in Canada and
311 steady states of aboveground NPP were not present until 20+ years after fires. Carbon storage in this
312 ecosystem is closely related to fire history, as fire is a major disturbance that alters community structure
313 and vegetative productivity.

314 The average fire frequency is ~60 years depending on forest type in North American boreal
315 forests (Archibold, 1995). Fire frequency in the boreal zone has increased due to increased warming and
316 associated drying over the past 20 years (Amiro et al., 2001). Typically 9,000-10,000 fires burn in

317 coniferous forest across Canada, which annually consume more than 20,000 km² or 0.6% of the forested
318 area (Higgins & Ramsey, 1992). This variation in stand age with fire revisit times can be seen in conifer
319 energetics, as peak photosynthesis has been observed in NDVI to vary throughout the life cycle of
320 boreal stands (Kasischke, 1997).

321

322 3.2.1. *Land Cover*

323 Land cover analyses for this region indicate marked changes in vegetation cover. ~160,000 km²
324 were mapped with the largest changes occurring between short vegetation grasslands and needle leaf
325 evergreen forests. During our study, needleleaf evergreen forests declined by ~13,000 km² (-8% change
326 in area), dwarf trees and shrubs declined by ~8,000 km² (-5% change in area), while short vegetation
327 grasslands increased by ~2,000 km² (+13% change in area) (Fig. 6, C). Extensive wildfire burn scars
328 were observed in Landsat TC data as decreases in brightness, greenness, and wetness. All anniversary
329 scene pairs over the thirty-year period revealed extensive burn scars from boreal fires. No other
330 apparent changes in land cover or land use were observed, as this region is located in a remote region
331 outside the impact zone of anthropogenic land use change. Ancillary data from the Canadian Forest
332 Service indicated extensive burn scars in this region. We found recently burned forest with recovering
333 young forest stands to be the cause for the observed NDVI anomaly.

334

335 3.2.2. *Fire/Logging*

336 Large fires (>200 hectares) were noted in 1980, 1981, 1993, 1994, and 1995 (Fig. 6, E), while
337 area logged for all of Saskatchewan has remained relatively stable, fluctuating between 160 km² and 250
338 km² per year. The most extensive fire occurred in 1981, burning over 22,455 km² or over three hundred

339 fifty, 8 km² AVHRR pixels across the entire province. The second most extensive fire event occurred in
340 1995 burning over 16,400 km².

341 A fire event spatial database from the BOREAS was used as a surrogate to the Landsat land
342 cover evaluation (Sellers et al., 1997). A similar method to Domenikiotis et al., (Domenikiotis et al.,
343 2002) was used to verify the spatial extent of fire events. Similar results to the Landsat data in annual
344 fire extent support that fire recovery is producing increases in NDVI. A majority of the large fire events
345 occurred in Northern Saskatchewan. Large-scale wildfires are a natural part of this ecosystem
346 reoccurring at intervals that are started from a number of different means and can be observed in NDVI
347 data (Kasischke, 1997). Fire recovery in this study region was the primary factor in the observed
348 increases in NDVI. We also observed higher near infrared reflectance values in Landsat data for
349 recovering vegetation in burned regions than for forests that were not burned (Fig. 6, F and G).

350 Growth is often limited in coniferous forest by mineral poor soils with productivity controlled by
351 nutrient cycling (Cole & Rapp, 1981). Deep beds of feather mosses of Schreber's feather moss (*P.*
352 *schreberi*) and mountain fern moss (*H. splendens*) typically form the understory of forests within this
353 study area. These mosses insulate the ground and reduce decomposition because of low soil
354 temperatures. Fires release nutrients stored in mosses much faster than decomposition and therefore
355 enhance growth at post fire sites (Auclair et al., 1976; vanCleve et al., 1983). Albedo declines in burn
356 scar sites and this can increase the soil temperature by absorbing more solar radiation. AVHRR NDVI
357 anomalies observed from 1982 through 2005 were from these ecosystems that were in recovery from the
358 extensive fires that occurred in 1980 and 1981. The anomalies observed in this case were not due to
359 direct abiotic influences on productivity; they are attributable to ecosystem recovery and nutrient
360 enhancement from large-scale fire disturbance events.

361

362 3.3. *Southern Saskatchewan & the Dakotas*

363 The Southern Saskatchewan and Dakotas study region lies in the northern boundaries of the
364 Great Plains. This area is commonly referred to as the 'Prairie Pothole' region because of ancient
365 glacial depressions. Several hundred thousand small (< 100 ha), shallow (maximum depth < 5 m)
366 pothole lakes lie in depressions that extend over 776,900 km² in the American Midwest and Western
367 Canada (Covich et al., 1997). Stream drainage is primarily absent in this region, and numerous wetlands
368 have formed between mounds of glacial till that dot the landscape. A diverse aquatic ecosystem exists
369 here where playas, pothole lakes, ox-bow lakes, springs, groundwater aquifers, and intermittent and
370 ephemeral streams are responsive to climatic fluctuations (Winter & Rosenberry, 1998). Many of the
371 wetlands are underlain by low-permeability glacial till making groundwater exchange slow. This forces
372 these wetlands to be highly dependent upon precipitation for their water supply. Precipitation and
373 evapotranspiration act as the largest forcing on the extent of surface water (Covich et al., 1997; Winter
374 & Rosenberry, 1998).

375 Most of the prairie that existed before human occupation has been replaced with agro ecosystems
376 where vegetation productivity is controlled with fertilizers and irrigation (Goudrian et al., 2001). Agro
377 ecosystems are managed and improved with new technology to produce crops nearer to their maximum
378 physiological potential. Changes in land use in agro ecosystems to enhance productivity are achieved
379 by: extensification (expanding the area of cultivated land); and/or intensification (increasing the number
380 of cropping cycles sown on a particular area of land or by increasing the yield per unit area), or both
381 (Gregory et al., 1999).

382 This region is heavily modified by agriculture where upland areas produce primarily sorghum,
383 corn and wheat. During the growing season, precipitation is a limiting factor to growth. Irrigation
384 networks are currently not extensively developed as this region has enough rainfall to support most

385 crops compared to the Southern High Plains. Average annual rainfall ranges from 33-58 cm. A
386 majority of the time, evaporation exceeds precipitation ranging from 0 to 60 cm (Covich et al., 1997).
387 Droughts are common throughout the high plains. Trenberth et al., (1988), noted a drought in 1988 in
388 the northern and eastern high plains; this was the only climatic event in the region concurrent with the
389 AVHRR NDVI observations. This region is well populated around urban centers and agriculture is the
390 primary land cover type. The NDVI anomaly followed the Missouri Coteau, a large topographic feature
391 that was formed by glacial deposition. It separates two major biogeographic zones of the Great Plains
392 and Central Lowlands (Fig. 7, A).

393

394 3.3.1. *Land Cover*

395 Land cover results for this region indicated marked changes in vegetation cover. $\sim 90,000 \text{ km}^2$
396 were mapped, and during observations agriculture fluctuated by $\sim 7,460 \text{ km}^2$ and stabilized near 1970s
397 extent, short vegetation grassland declined $\sim 5,930 \text{ km}^2$, barren lands increased by $\sim 4,190 \text{ km}^2$, and water
398 extent changed by $\sim 860 \text{ km}^2$. The drought in 1988 is apparent in the reduction of agriculture extent in
399 the 1990 map and recovery in the 2000 map (Fig. 7, D, F and G).

400 No extensive changes in land use have been noted in this region and the land cover is primarily
401 composed of agriculture (corn, wheat, sorghum) and rangeland for cattle grazing. Large increases in
402 standing water (prairie potholes or sloughs) were observed in the Landsat record spanning from 1972-
403 2000. Previous fall precipitation has been found to account for 63% to 65% of the variation in the
404 number of wetland basins (Larson, 1995). Apparent dramatic increases in wetland size have been
405 recorded from increases in precipitation and may contribute to observed crop yield. Land cover change
406 does not appear to be the motivator for the observed change in vegetation dynamics in this region.
407 Climate impacting dry land agriculture produced the NDVI anomaly.

408 The drought ended in 1992 and the NDVI AVHRR anomaly appeared during the 1982-2000
409 period because of recovery (Trenberth et al., 1988; Winter & Rosenberry, 1998). Increases in
410 precipitation influenced dry-land crop production in this area by enhancing plant growth. Near infrared
411 reflectance was observed to increase with crop production in Landsat (Fig. 7, F and G). Corn production
412 was noted to be highly variable and was limited by erratic precipitation patterns (USDA, 2006). Winter
413 et al., (1998), have noted current conditions to be the wettest on record over the past 130 years, and
414 potentially the past 500 years. The responses of wetlands and agricultural lands to increased
415 precipitation was consistent with our observed NDVI anomalies.

416

417 3.3.2. *Crop Data*

418 To verify if abiotic changes were enhancing vegetation photosynthetic capacity, we investigated
419 the NASS records. Sequential seasonal vegetation indices profiles revealed crop canopy emergence,
420 maturation, and senescence. These measurements have been related to crop condition and yield
421 (Benedetti & Rossini, 1993; Boissard et al., 1993; Doraiswamy & Cook, 1995; Labus et al., 2002;
422 Rasmussen, 1992). Marked increases in wheat production have been noted, which we found impacted
423 the NDVI.

424 Yields of wheat increased in three selected Northeastern Montana counties within the NDVI
425 anomaly area. Acres of wheat production rose >40% (>400 km²), and a marked increase was noted after
426 the 1988 drought (Fig. 7, E). Increases in yield were associated with the increased precipitation after the
427 drought of 1988, returning crop production in this region to its normal state. Adjacent counties to the
428 anomaly region were also investigated and they did not have a marked increase in production. The
429 primary limiting factor to growth in this area was precipitation which increased substantially and caused
430 the observed NDVI anomaly.

431

432 3.4. *High Plains*

433 The Oklahoma Panhandle study area is dominated by human land use of agriculture and pasture
434 land. A similar agro ecosystem to the Southern Saskatchewan/ Dakotas study region exists here. The
435 landscape consists of flat to irregular plains where sedimentary bedrock is overlain by alluvial deposits.
436 The High Plains have a semi-arid environment where precipitation is the limiting climatic variable to
437 vegetation growth. Precipitation has been found to spatially and temporally modulate NDVI in Kansas
438 (Wang et al., 2001). Over the past 20 years, variations in crop type and production have varied
439 substantially. Although the spatial/temporal heterogeneity of crop type and production can possibly
440 cause the observed change in AVHRR NDVI, this semi arid region is heavily reliant on irrigation to
441 grow more productive crops. Irrigation practices and crop selection were found to explain the NDVI
442 anomalies observed (Fig. 8).

443

444 3.4.1. *Land Cover*

445 Marked changes in land cover were found in Northern Texas, Oklahoma, and Kansas. Landsat
446 analysis revealed changes in irrigation extent. $\sim 100,000 \text{ km}^2$ was mapped and during observations
447 agriculture increased by $\sim 2,850 \text{ km}^2$, short vegetation grassland declined $\sim 4,860 \text{ km}^2$, barren lands
448 increased by $\sim 1,650 \text{ km}^2$, and water extent changed by $\sim 160 \text{ km}^2$. Center pivot agriculture expansion
449 was pervasive throughout this region (Fig. 8).

450 Expansion of irrigated agriculture is largely constrained by access to the Ogallala aquifer. Water
451 in this aquifer is considered a nonrenewable resource because it was formed from melt water from the
452 Rocky Mountains during the Pliocene era. The High Plains aquifer in this region has experienced a
453 $>30\%$ decline in ground water over the past 40 years (Scanlon et al., 2005). Standard practices consist
454 of dry land farming (completely reliant on rain) and furrow and dike irrigation (flooding fields). Using

455 center pivot irrigation over previous irrigation practices has tripled production (biomass) and consumed
456 less water (Opie, 2000). Enhanced production was due to the center pivot's ability to more evenly and
457 accurately irrigate fields. Expansion of center pivot irrigation in this region from 1972-2000 was
458 marked and evident at the Landsat resolution (Fig. 8, F and G).

459 Abiotic variability did not impact vegetation in this region. Normal precipitation ranges 30 - 50
460 cm of rain a year, when a majority of the crops (corn, wheat and sorghum) require up to 76 - 101 cm (for
461 corn) during the growing season. The deficit of precipitation relative to evaporation ranges from 20 -
462 160 cm (Covich et al., 1997). Droughts are common in this area and tend to occur every 20 years and
463 can last between 5-10 years (Opie, 2000). The most severe drought occurred in the 1930's (Great Dust
464 bowl) and the second during the 1950's (Little Dust bowl). More recent droughts, although minor in
465 comparison, have occurred during the late 1970s, late 1980s and most recently in 1996 (Covich et al.,
466 1997). The 1988 drought did not impact this region with the severity incurred in the north central
467 United States and parts of the North East (Trenberth et al., 1988). Dry spells do not impact the farmers
468 to the extent of previous years because of the development of the high plains aquifer irrigation networks,
469 which now extend for more than 16,000 km² (www.hpwd.com). A heavy reliance on ground water has
470 been developed to offset the irregular patterns of precipitation.

471

472 3.4.2. *Crop Data*

473 To verify if abiotic changes were enhancing vegetation growth we examined the NASS records.
474 Alterations in crop production were noted in the agricultural data and a trend similar to the Dakota
475 region appeared to be the case. Substitution of corn for grain, the dominant crop of the region, showed
476 marked increases in production. From 1982 to 1997 in Dallam, Sherman, Hartley and Moore Counties
477 located within the AVHRR NDVI anomaly region centered on Dalhart, Texas corn production had

478 increased > ~200% (Fig. 8, E). Counties located outside of the anomaly region experienced little to no
479 growth in corn for grain production. NDVI seasonal profiles have been shown to aid in estimating crop
480 performance and the observed anomaly trends appear to reflect this observation (Benedetti & Rossini,
481 1993; Boissard et al., 1993; Doraiswamy & Cook, 1995; Labus et al., 2002; Rasmussen, 1992). This
482 positive growth relationship between crop statistics and enhanced NDVI signature was apparent in our
483 study.

484 Change from wheat to corn production appeared to be causing the marked increase in the
485 AVHRR NDVI. Conversion to center pivot irrigators for corn production enhanced the observed
486 AVHRR NDVI anomaly. Expansion of center pivot irrigated agriculture throughout this region had a
487 marked impact on land cover in this region and was visible in Landsat (Fig. 9). The coupled influence of
488 change in crop type and more extensive irrigation networks resulted in the AVHRR NDVI anomaly.

489

490 3.5. Quebec

491 The southern Quebec study region encompasses a majority of the southern portion of the
492 province, which is mixed boreal forest. The ecotone is very similar to the Northern Saskatchewan as
493 they are both considered to be a part of the North American Boreal Shield. Many of the same tree
494 species also exist in this region and they have the same response and successional sequences. Similar to
495 Northern Saskatchewan, two species are very common: white spruce (*P. glauca*); and black spruce (*P.*
496 *marinana*). Other species present include: eastern larch (*L. laricina*); balsam fir (*A. balsamea*); jack
497 pine (*P. banksiana*); trembling aspen (*P. tremuloides*); and paper birch (*B. papyrifera*). The observed
498 AVHRR NDVI anomalies are around the Lac Saint-Jean area in the East to the Reservoir Gouin to the
499 West (Fig. 10, A). This region has experienced extensive logging and modifications to the forest cover
500 were very evident at Landsat resolution. Fire disturbance does not modify the land cover extensively in

501 this region; large fire events have only been observed further to the North. Population density occurs
502 toward the East in the Saguenay Lac Saint-Jean region where over 300,000 inhabitants are distributed
503 over 56 municipalities (Alma, 2006).

504

505 3.5.1. Land Cover

506 Land cover analysis for this region indicated marked changes in vegetation cover. $\sim 170,000 \text{ km}^2$
507 were mapped, and during observations needle leaf evergreen forests declined by $\sim 2,350 \text{ km}^2$ (-39%
508 change in area), short vegetation grassland increased $\sim 1310 \text{ km}^2$ (+37% change in area), broad leaf
509 deciduous forests increased by $\sim 5,580 \text{ km}^2$ (+15% change in area), and dwarf trees and shrubs extent
510 changed by $\sim 2,570 \text{ km}^2$ (+26% change in area) (Fig. 10). Logging and recovery from logging was
511 common throughout this region.

512 Landsat land cover trends were comparable to similar rates recorded from the Canadian Forest
513 Service which both have recorded increasing rates of logging. Fire did not have a significant role in
514 disturbance regime in this region as it did in Saskatchewan. Extensive salvage logging was initiated by
515 a wide spread spruce budworm (*C. fumiferana*) outbreak during the mid 1970s. During the last century,
516 Eastern North American forests have suffered increasing rates of spruce budworm outbreaks rising to
517 $\sim 550,000 \text{ km}^2$ in 1975 (Kettela, 1983). Blias et al. (1981; 1983), reported that a spruce budworm
518 outbreak collapsed in 1975 in Southern Quebec, and extensive mortality up to 91% of balsam fir (*A.*
519 *balsamea*), their preferred fare, occurred. Recovery of the understory was reported to be rapid of tree
520 species that comprised the original stand because they did not suffer extensive infestation. This has
521 been interpreted to be part of the successional system (Baskerville, 1975; Blias, 1985). The Canadian
522 forest service permitted extensive salvage logging to take place as much of this region is utilized for
523 cash crops in pulp and paper production. We observed in Landsat data that recovering vegetation at

524 logged sites had an enhanced near infrared reflectance that would also enhance the AVHRR NDVI (Fig.
525 10, E, F and G).

526

527 3.5.3. *Logging Rates*

528 The Canadian Forest Service has reported substantial increases in logging rates throughout the
529 province of Quebec. Total annual harvesting during the NDVI record has grown from 2,000 km² a year
530 to > 3,500 km². It has been reported by Sabol et al., (2002), that post-logging regrowth in Pacific
531 Northwest U.S. conifer forests had a higher NDVI after 3-4 years than the mature conifer stands they
532 replaced, which persisted for 10 to 30 years. We observed higher near infrared reflectance in Quebec at
533 disturbed sites, which increased NDVI. Forest age structures as suggested by Casperson et al., (2000),
534 may be responsible for the observed trend increase in this region. The successional process of *P.*
535 *glauca*, which are ubiquitous in this region, begins after logging with fast growing deciduous species.
536 These deciduous species of paper birch (*B. papyrifera*) and trembling aspen (*P. tremuloides*) typically
537 have a higher NDVI signature than the conifers that replace them. In this region regrowth following
538 logging acts as a disturbance-driving element of the observed AVHRR NDVI anomaly.

539

540 3.6. *Newfoundland and Labrador*

541 The island of Newfoundland and the Labrador coast has a unique environment with a maritime
542 boreal forest influenced by the confluence of two ocean currents, the cold Labrador and the warm Gulf
543 Stream. Its maritime climate can change drastically depending on what current is dominating flow. The
544 entire island over 100,000 km² has recorded a marked increase in NDVI over the 1992-1999 period.
545 Land use change is not a dominant factor in this region as it is sparsely populated and does not have
546 productive soil for agriculture. Over half of the population resides in St. Johns, the capital of

547 Newfoundland on the eastern coast. Newfoundland also has a fairly extensive logging operation in the
548 West where large amounts of spruce and pine are harvested for pulp and paper production. The ecotone
549 is very similar to that of the Quebec study region. The vegetation of Newfoundland consists of dense
550 mixed forest of trembling aspen (*P. tremuloides*), paper birch (*B. papyrifera*), white spruce (*P. glauca*)
551 and black spruce (*P. marinana*) in the west. The central and eastern portions of the island are open
552 lichen woodland where fertile soils have been removed and underlying rock has been exposed by
553 ancient glaciers of the past (Fig. 11).

554

555 3.6.1. Land Cover

556 Extensive logging was noted on the western coast of Newfoundland for pulp and paper
557 production. From 1982 to 1999 an additional 100 km² were logged but this is insignificant compared to
558 the 100,000-km² extent of the island (<http://pndf.ccmf.org>). Land cover results for this region indicate
559 moderate changes in vegetation cover. ~170,000 km² were mapped including Labrador, and during
560 observations needleleaf evergreen forests declined by ~6,650 km² (-10% change in cover type), short
561 vegetation grassland increased ~3,920 km² (+7% change in cover type), broadleaf deciduous forests
562 increased by ~350 km² (+12% change in cover type), and barren extent changed by ~1,360 km² (+20%
563 change in cover type) (Fig. 11, C). Logging and recovery from logging is pervasive throughout the
564 western portion of Newfoundland.

565 No other large-scale land cover trend was observed, as population density is sparse throughout
566 the region. Emergence of more deciduous species of paper birch (*B. papyrifera*), and trembling aspen
567 (*P. tremuloides*) in formally logged areas was noted from aerial over flights. However, these alterations
568 in land cover are insignificant compared to the observed NDVI anomaly, which extends over the entire
569 island. Land cover land use change is not a major factor in the observed NDVI trend; abiotic factors are

570 the dominant cause. Annual surface temperature nearly doubled over the 1990's and it appears to have
571 enhanced the NDVI record. The growing season has extended by 17 days and enabled more biomass to
572 be produced (Fig. 11, F). These marked climate changes over one decade have been reflected in the
573 NDVI record as anomalies. The intense change in surface temperature is responsible for the observed
574 anomaly in NDVI (Neigh et al., 2007).

575 Newfoundland has temperature-constrained environment where precipitation is non-limiting.
576 Muskegs are a common feature in the landscape held by ancient glacial rock and rejuvenated by frequent
577 precipitation events. The climate of Newfoundland varies drastically because of its northern maritime
578 exposure on all fronts. During the last decade, the Gulf Stream has dominated the Labrador Current
579 allowing warm waters to reach Newfoundland's shores (Afanasyev et al., 2001). These warm currents
580 are driving an observed increase of 3.5°C in 1992 to 7°C in 1999 in mean annual temperature (Fig. 11,
581 E).

582 A typical warm weather promotes growth and photosynthesis in this mixed boreal forest. The
583 growing season has extended by over 17 days from 1982 to 1999, reducing snow cover and enabling
584 more vegetation productivity (Neigh et al., 2007). Similar to the northern Saskatchewan study region,
585 growth is often limited in coniferous forest by mineral poor soils with productivity controlled by nutrient
586 cycling through litter fall and decomposition (Cole & Rapp, 1981). Enhanced temperature accelerates
587 decomposition enabling more nutrients to be released into the soil (vanCleve et al., 1983). Culminating
588 with this fact, black spruce (*P. mariana*), the dominant stand species in this region, has an optimum
589 temperature for photosynthesis of 15°C, with a 90% rate maintained between 9°C and 23°C (Vowinckel
590 et al., 1975). Warmer temperatures reduced snow cover and extended growing season length. An in
591 depth quantitative analysis of climate influenced vegetation productivity is beyond the scope of this

592 paper; the role of increasing temperature to vegetation productivity will be investigated with simulation
593 modeling in the future.

594

595 **4. Synthesis**

596 Six different areas displaying marked changes in NDVI values for the period from 1982 to the
597 present have been examined using multi-temporal Landsat data and other ancillary data sources to
598 provide attribution for the changes. These results indicate a complex interaction between anthropogenic
599 changes and direct biophysical impacts. In some areas, especially in northern latitudes, the changes
600 appear to be the result solely of biophysical impacts. In the Mackenzie Delta it appears that temperature
601 increases are the prime drivers. In Newfoundland the immediate cause of increases in NDVI appears to
602 be related to regional increases in water temperatures in the adjacent ocean. In contrast in northern
603 Saskatchewan the proximate driver of increases in NDVI is forest regrowth following frequent large
604 forest fires, though the latter may be affected by temperature increases associated with global warming
605 superimposed on cyclical fluctuations in fire frequency.

606 In the other examined areas the impact of anthropogenic influences was more direct. In Quebec
607 the anomalies arise from the regeneration of extensive logged areas of evergreen forests leading to
608 forests dominated by deciduous species. In southern Saskatchewan and the Dakotas the increases in
609 NDVI derive from increased agricultural activity following the increased precipitation rainfall after an
610 extensive drought prior to 1992. But further south in the High Plains of the Oklahoma Panhandle, the
611 area's increases in NDVI are related to large increases in pivot irrigation relying on ground water.

612 The pattern of NDVI anomalies over the time period considered therefore arises from a variety
613 of interacting factors. Some of these changes appear to be driven by long-term climate change but most
614 appear associated with climate variability on decadal and shorter time scales along with direct

615 anthropogenic land cover conversions. Interactions between the three types of drivers of change
616 demonstrate the difficulty of interpreting changes in NDVI. Furthermore this indicates the complex
617 nature of changes in the carbon cycle within North America. Coarse scale analysis of changes could
618 well fail to identify the important local scale drivers controlling the carbon cycle and to identify the
619 relative roles of disturbance and climate change.

620

621 **5. Conclusion**

622 North American vegetation dynamics driven by a number of different biophysical phenomena
623 have been revealed in this research. Discrete events over the past two decades have induced change in
624 ecosystem functioning that have been identified with multi-resolution satellite imagery. We find that:
625 (1) Multi-resolution data provides information critical to the state of knowledge of vegetation dynamics
626 in North America; (2) land cover land use change driven by humans had a marked impact to North
627 American photosynthetic capacity; (3) natural abiotic and anthropogenic events can modify vegetation
628 dynamics in concert or singularly; (4) coupled processing of multi-resolution data can be performed
629 efficiently to extract synoptic information of ecosystem state; and (5) information about vegetation
630 dynamics enhances ecosystem models to emulate altered terrestrial biogeochemistry and land surface
631 energy exchange.

632 Investigation through multi-scalar and multi-temporal data revealed land cover dynamics during
633 the 1980s and 1990s. In correspondence to Hicke et al., (2002), Neigh et al., (2007), and Zhou et al.,
634 (2001), changes in temperature and precipitation have also been found to be marked contributors to
635 vegetation change. Human activities were observed to have an impact to vegetation productivity
636 altering the relationship between the biota and the physical environment. The unique contribution of this
637 study is how regional land cover land use change altered vegetation dynamics at the continental scale in

638 North America. Continued investigation is needed to extrapolate how natural and anthropogenic
639 changes impact the North American carbon cycle. Future work will investigate areas of large-scale
640 NDVI decreases within the 1982 to 2005 period of our study.

641

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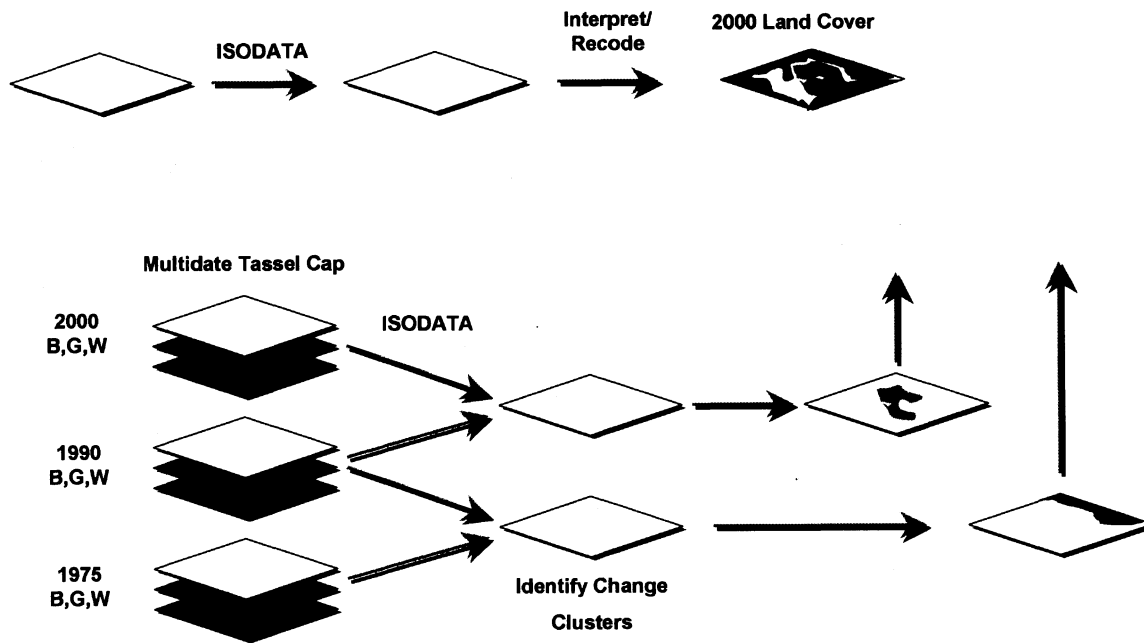


Fig. 1. Diagrammatic representation of the land cover classification method developed to extract thematic information from multi-temporal Landsat data. Channels 3,4 and 5 from Landsat-7 were first processed in an unsupervised method into ~50 classes that subsequently were aggregated into the 9 International Geosphere Biosphere Program land cover types. Subsequently, all reflective channels were used to produce a multi-date "tassel cap" transformation for each time period and then subjected to an unsupervised aggregation to produce areas of change for each of the three time periods. The three time periods were then compared to identify changes from 2000 to 1990 and 1990 to 1970s, respectively. This approach was used in the Mackenzie River delta, Northern Saskatchewan, Southern Quebec, and Newfoundland study areas.

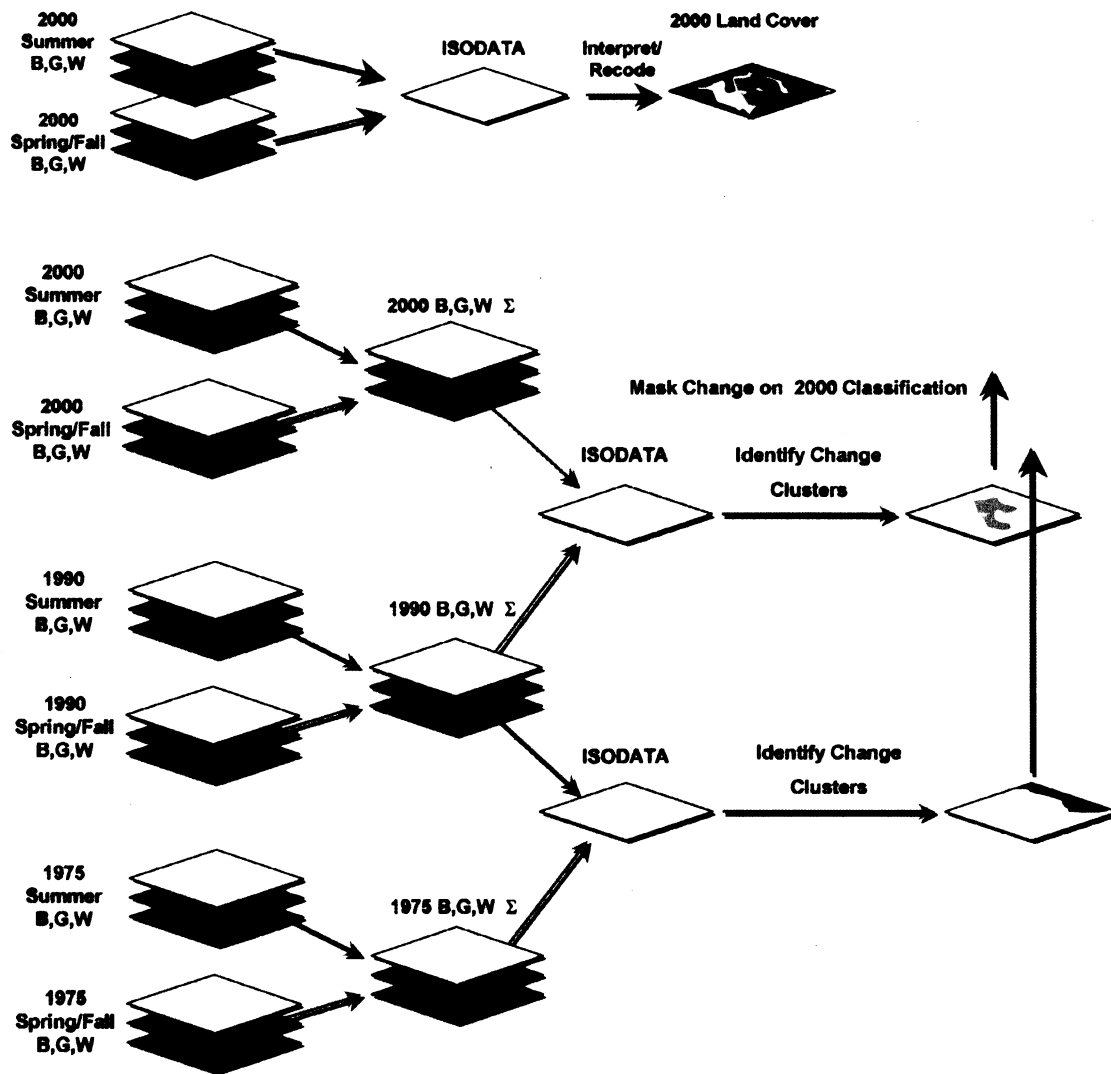


Fig. 2. Land cover change classification algorithm diagramming steps to extract thematic data from Landsat data for the Southern Saskatchewan and Oklahoma “Panhandle” agricultural study areas. Method two was adapted for regions with irrigated agriculture to capture inter annual variability in crop productivity. Performing a transformation on multi-date tasseled cap images captures active irrigated agriculture and distinguishes between fallow agriculture and native grasslands.

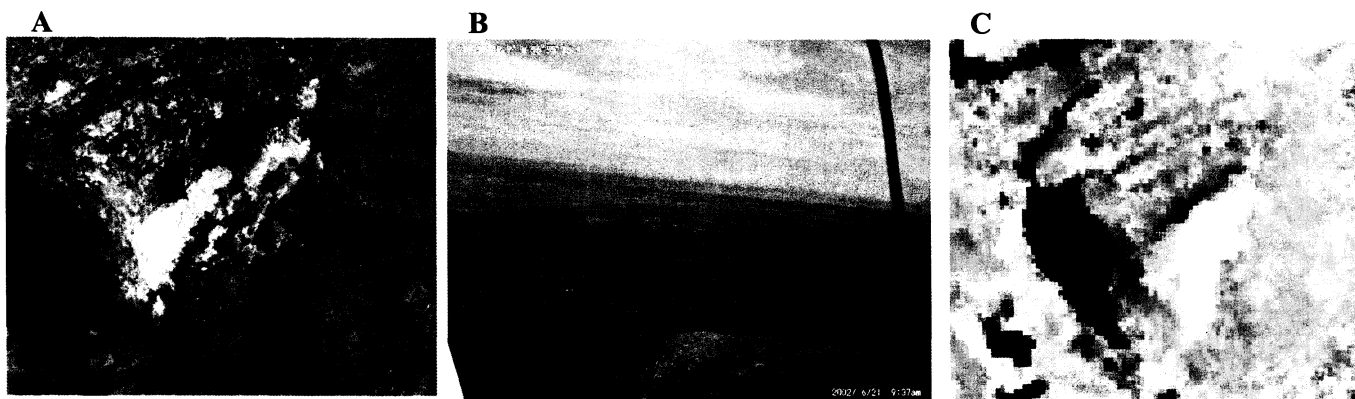


Fig. 3. An example of our validation efforts from Newfoundland. (A) A black and white geo-referenced digital air photo was obtained from the Canadian Government (id A26784_21, 8/03/1985). (B) A low altitude oblique aerial photograph taken by the authors with the GPS coordinates of the location of the camera. (C) A Landsat multi-spectral image using bands 4, 5, and 3 to represent red, green, and blue colors, respectively (path 4 row 26, 8/05/2001). The same geographic features, mountains and water bodies, were found to be useful for merging these types of data from North America study regions.

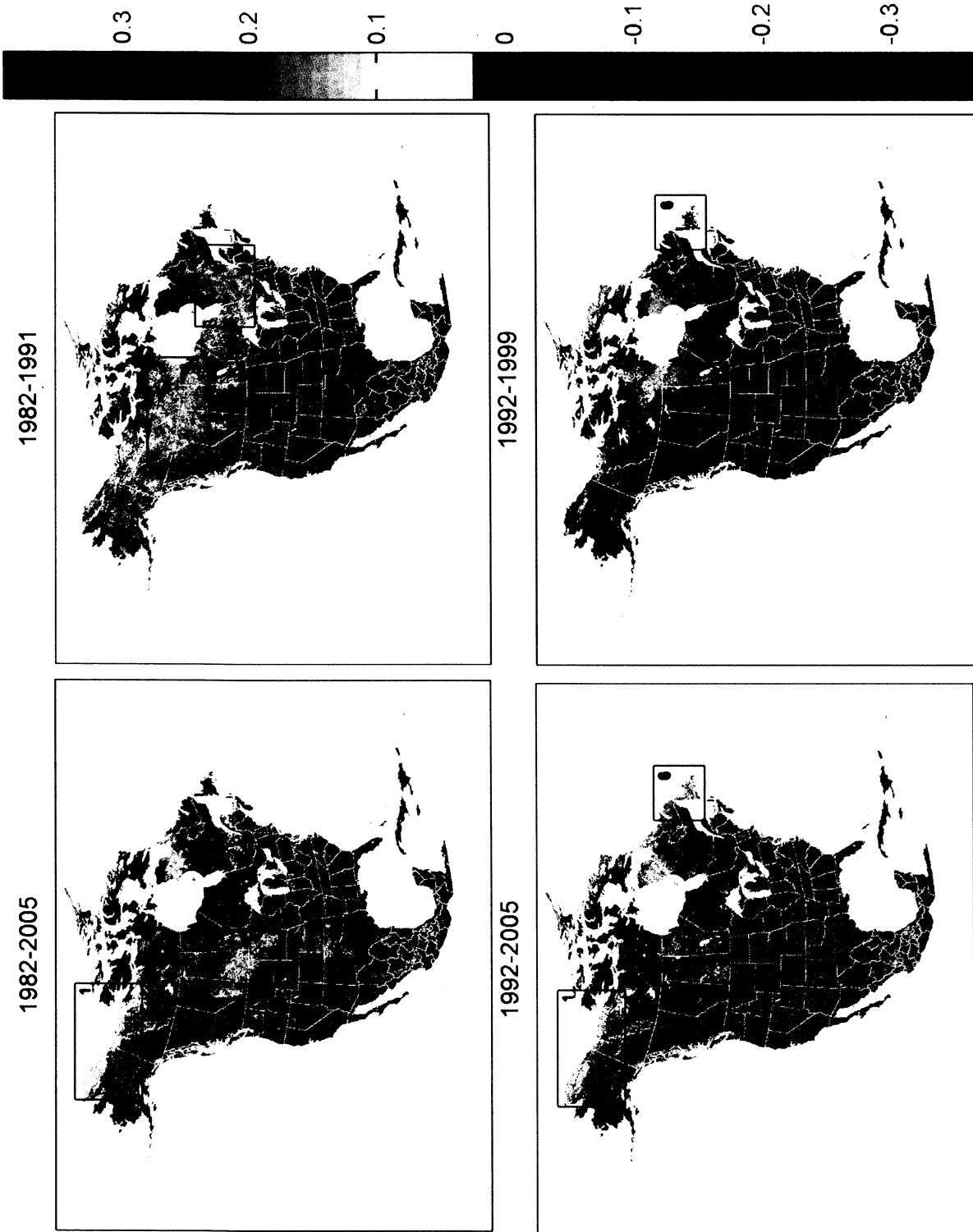


Fig. 4. May to September annual AVHRR NDVI trends for selected periods between 1982 and 2005. Areas were selected for more detailed study where NDVI increases were greater than 0.1 NDVI units for the various time periods for regions > 2,000 km² and high resolution remote sensing and ground data were available. Six regions met these criteria among 4 different time periods: (1) The Mackenzie River Delta area; (2) Northern Saskatchewan; (3) Southern Saskatchewan; the (4) Oklahoma panhandle and adjacent areas; (5) Southern Quebec; and (6) Newfoundland.

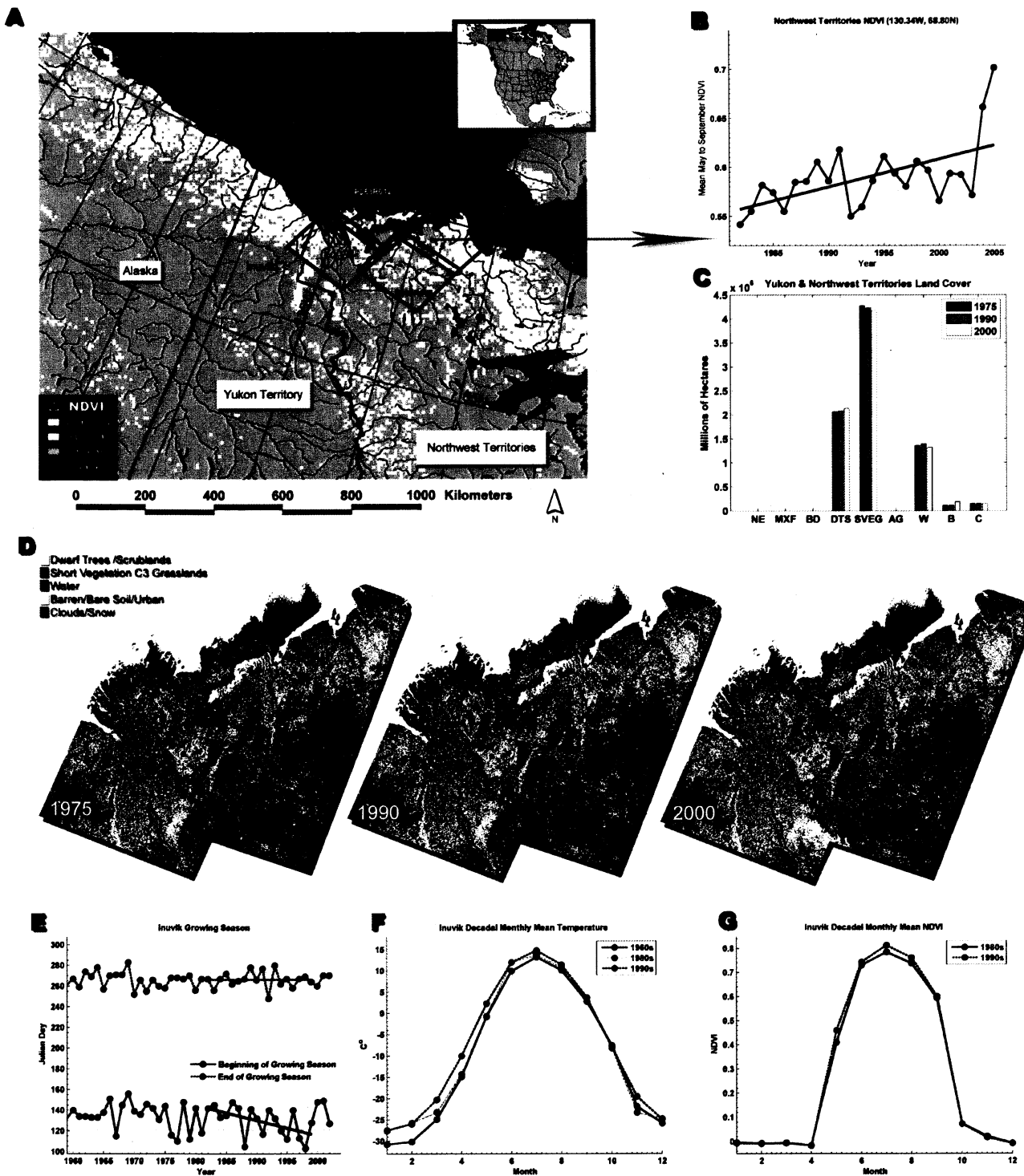


Fig. 5. A diagrammatic representation of the Yukon and Northwest Territories study area identified in Fig. 4. (A) Shows the Landsat scenes we have used in our study, (B) shows the NDVI time series for the area indicated by the arrow from Fig. 4, (C) shows the changes in the IGBP land cover classes for dwarf trees and shrub lands, short vegetation grasslands, water extent, cloud cover, and barren lands determined from the 1970s, 1990, and 2000 Landsat image, (D) shows the actual Landsat data for the three periods after the tasseled cap transformation was performed, (E) shows the change in growing season length from 1960 to 2002, (F) shows the increase in monthly mean temperature calculated by decade for the 1960s, 1980s and 1990s; and (G) shows the increase in monthly mean NDVI calculated by decade for 1980s, and 1990s. NDVI increase in this area (G) resulted from a longer growing season (E) due to increase surface air temperature (F).

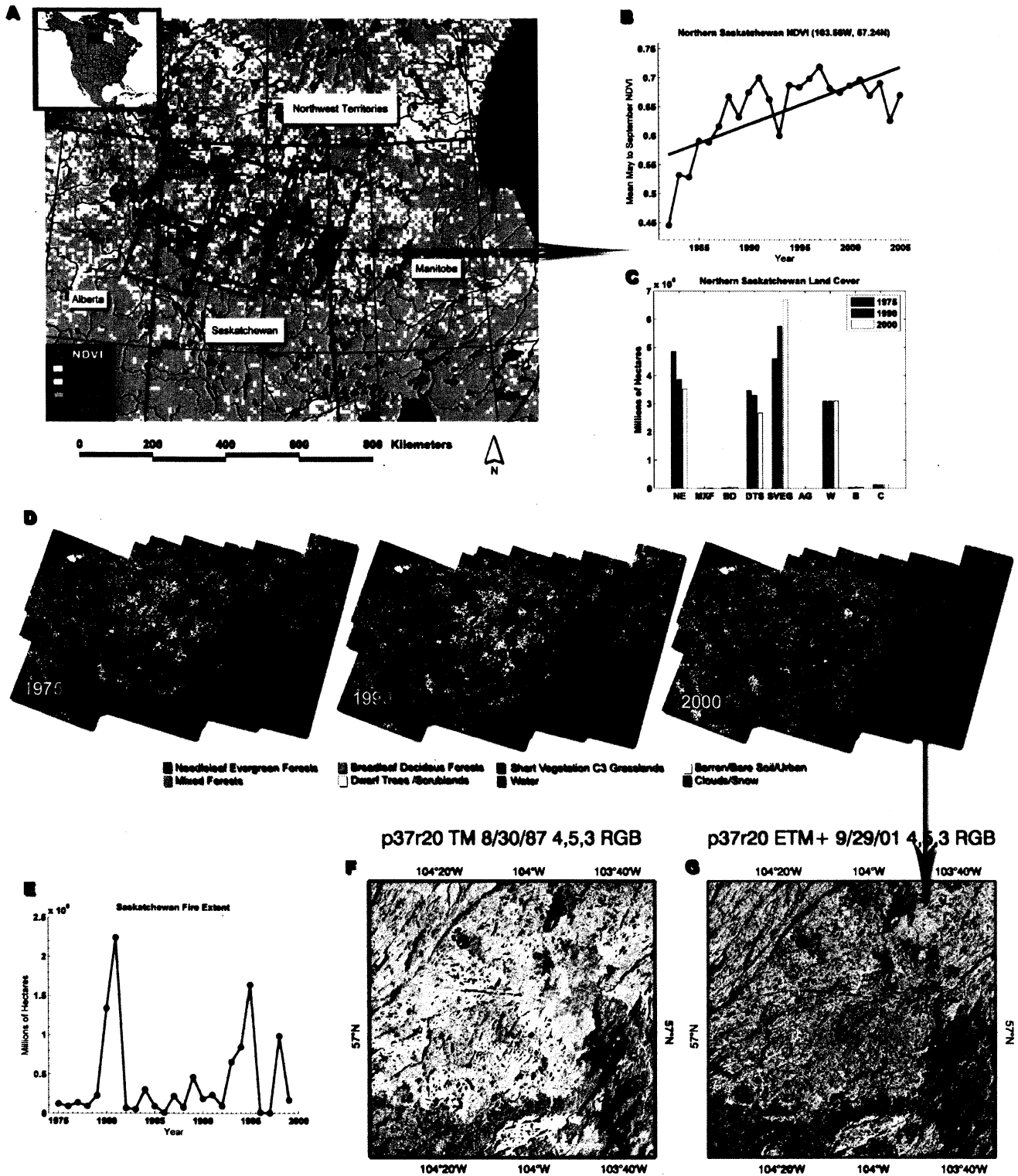


Fig. 6. The Northern Saskatchewan study area is identified in (A) with the Landsat scene areas superimposed upon the map. (B) Shows the NDVI time series while (C) shows how the 3 images have changed between the 1970s and 1990 and 1990 to 2000 time periods, respectively. (D) Is a representation of the Landsat data for the three periods using a tasseled cap transformation and (E) shows the fire frequency by year. (F and G) are the unprocessed data for one Landsat scene showing the areas that were affected by fire from locations indicated by arrows from (A to B) and (D to G). With the exception of 1980-1981 and 1995, fire was not a widespread phenomenon in this region. NDVI increase in this area resulted from fire in 1980, 1981 and 1995.

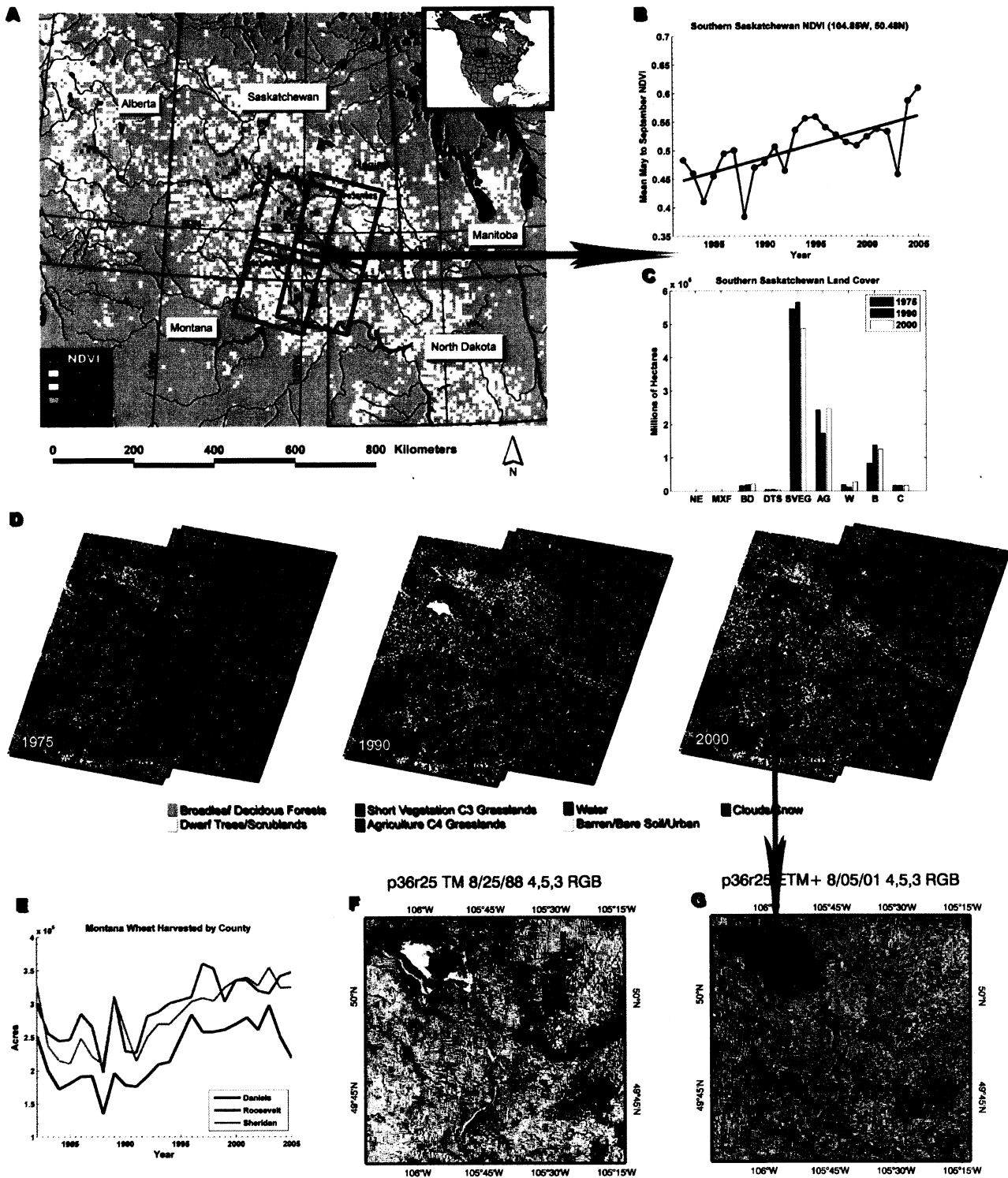


Fig. 7. The area in Southern Saskatchewan identified in Fig. 4 as having experienced a marked NDVI increase from 1982 to 2005. Superimposed upon (A) an image showing the areas of 1982 to 2005 NDVI increase are the 4 Landsat scenes used to investigate higher spatial resolution land cover and land use changes. (B) Shows the NDVI trends with time for the area represented by the arrow, (C) shows the changes in land cover for the three Landsat time periods, (D) shows the classified areas from the three GeoCover time periods, (F) is a Landsat scene near the peak of the drought period, (G) is a Landsat image during the period of recovery from drought, and (E) is a plot of total wheat yield by year for the areas in Montana covered by Landsat data in Fig. 7a. The areas indicated in this figure exhibited NDVI trends because of increasing precipitation.

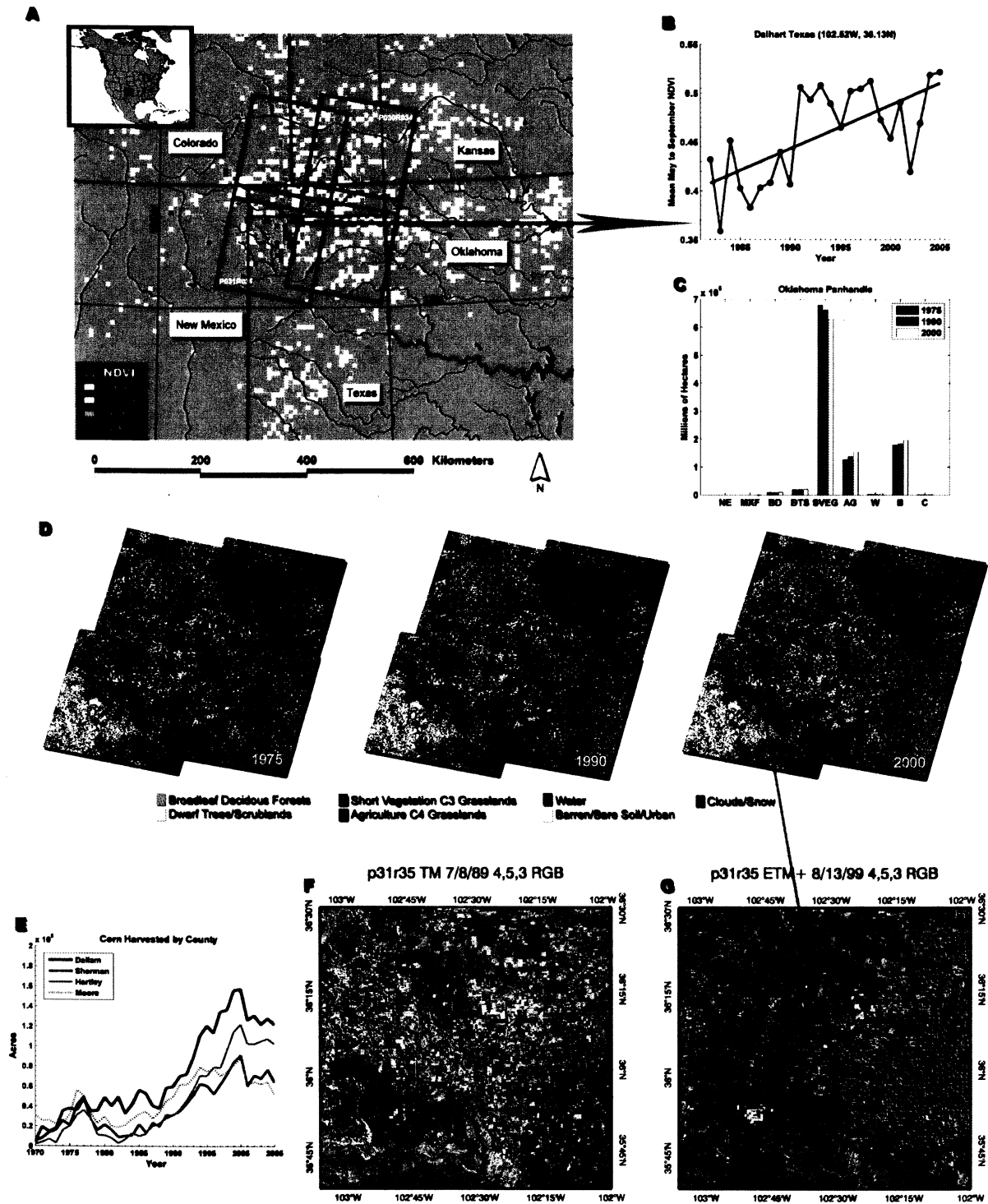


Fig. 8. An area of expanded irrigated agriculture in the “Panhandle” area of Colorado, Kansas, New Mexico, Oklahoma, and Texas that was identified in Fig. 4 as having experienced a marked NDVI increase from 1982 to 2005. (A) Is a diagrammatic representation of the areas of NDVI increase from 1982 to 2005 with an overlay of the 4 Landsat scenes used for the detailed spatial analyses, (B) is the 1982 to 2005 NDVI trend with time for the area indicated by the arrow, (C) shows the decrease in natural vegetation to irrigated agriculture over the 1970s to 2000 time period, (D) shows the isoclustered Landsat data for the three time periods using two dates per time period, (E) are data of corn harvested by county from 1970 to 2005, (F) is an unprocessed Landsat image from 1989 and (G) from 1999. Landsat area (F and G) is from arrow indicated from (A to B). Note the expansion of center-pivot irrigated agriculture from 1989 to 1999, the increasing NDVI, and the increasing corn yields over the same time period in this semi-arid area.

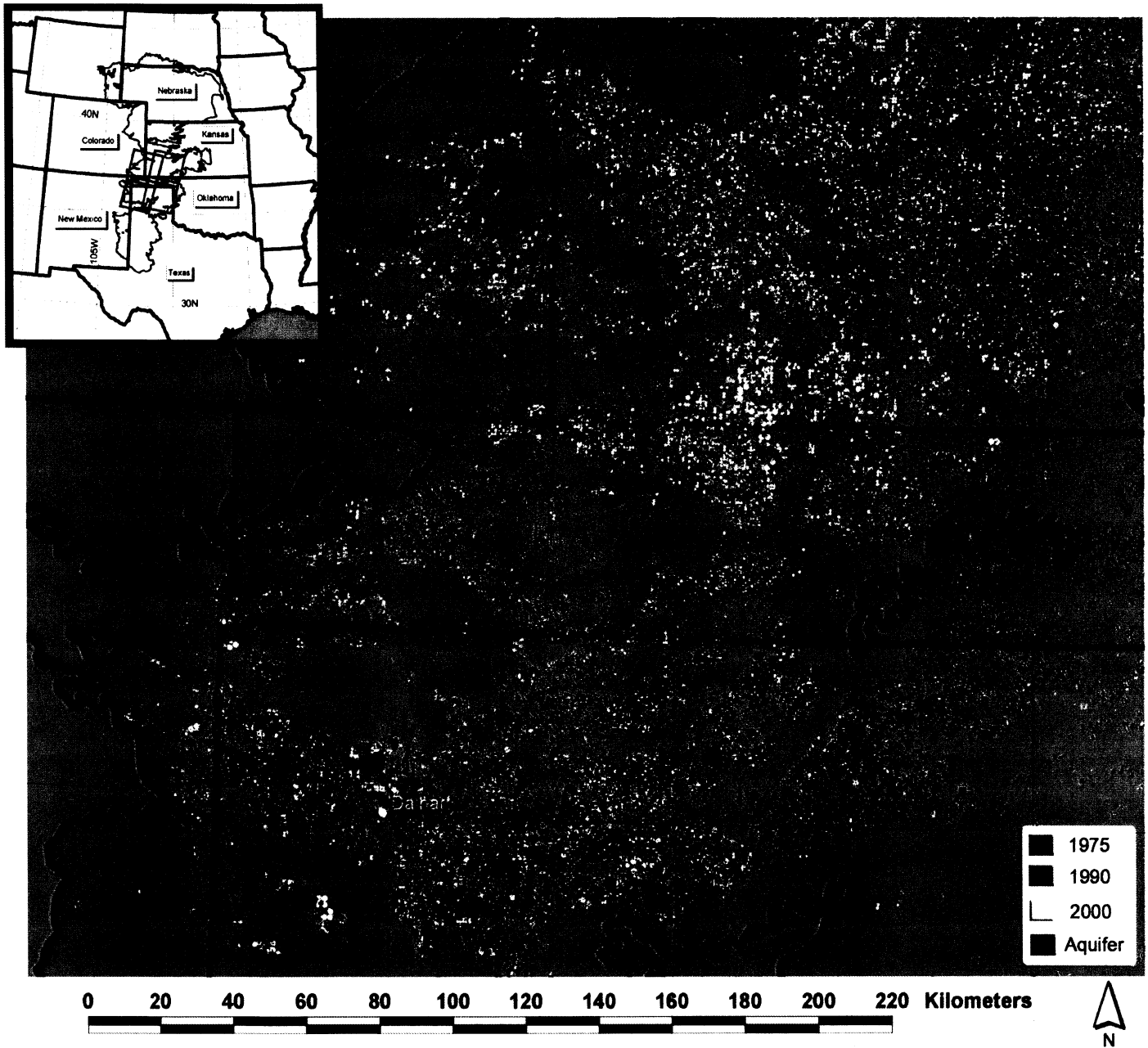


Fig. 9. A land cover classification of the Oklahoma “Panhandle” and adjacent areas, that shows the expansion of irrigated agriculture in this area from 1975 to 2000 based upon the analyses of Landsat data for these 3 time periods. Brown indicates agriculture land in 1975; red represents expansion in 1990, and yellow in 2000. Blue polygons represent the bounds of the Ogallala Aquifer. Our investigation of Landsat time series revealed expansion of agriculture land within the bounds of the Ogallala Aquifer; this change in agriculture extent and intensity coincides with the trend in AVHRR NDVI.

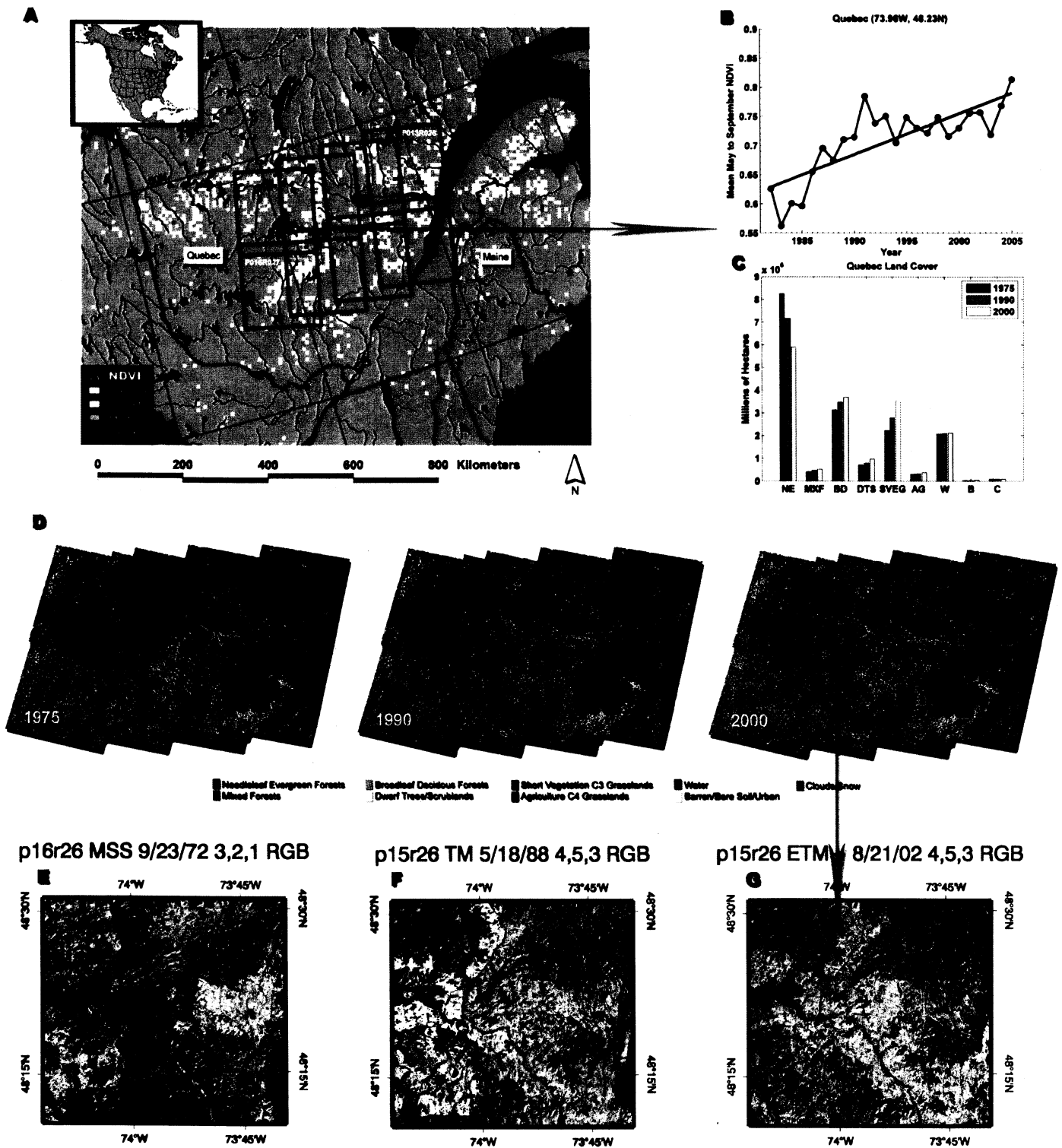


Fig. 10. (A) An area in southern Quebec that was identified in Fig. 4 has been extensively logged. (B) Shows the NDVI over time for the May to September time periods, (C) show the changes in land cover and land use associated with the logging, (D) shows the actual isoclustered Landsat data used for the 3 time periods. (E), (F), and (G) are the unclassified Landsat images from the 1972, 1988, and 2002 time periods, respectively. Landsat areas coincide with arrow from (A to B) where AVHRR NDVI increased from 1982 to 2005 (B). Note the decrease in NDVI in 1982-1983 due to logging/desiccation of forest from insects and the subsequent increase in NDVI as recovery and regeneration progressed.

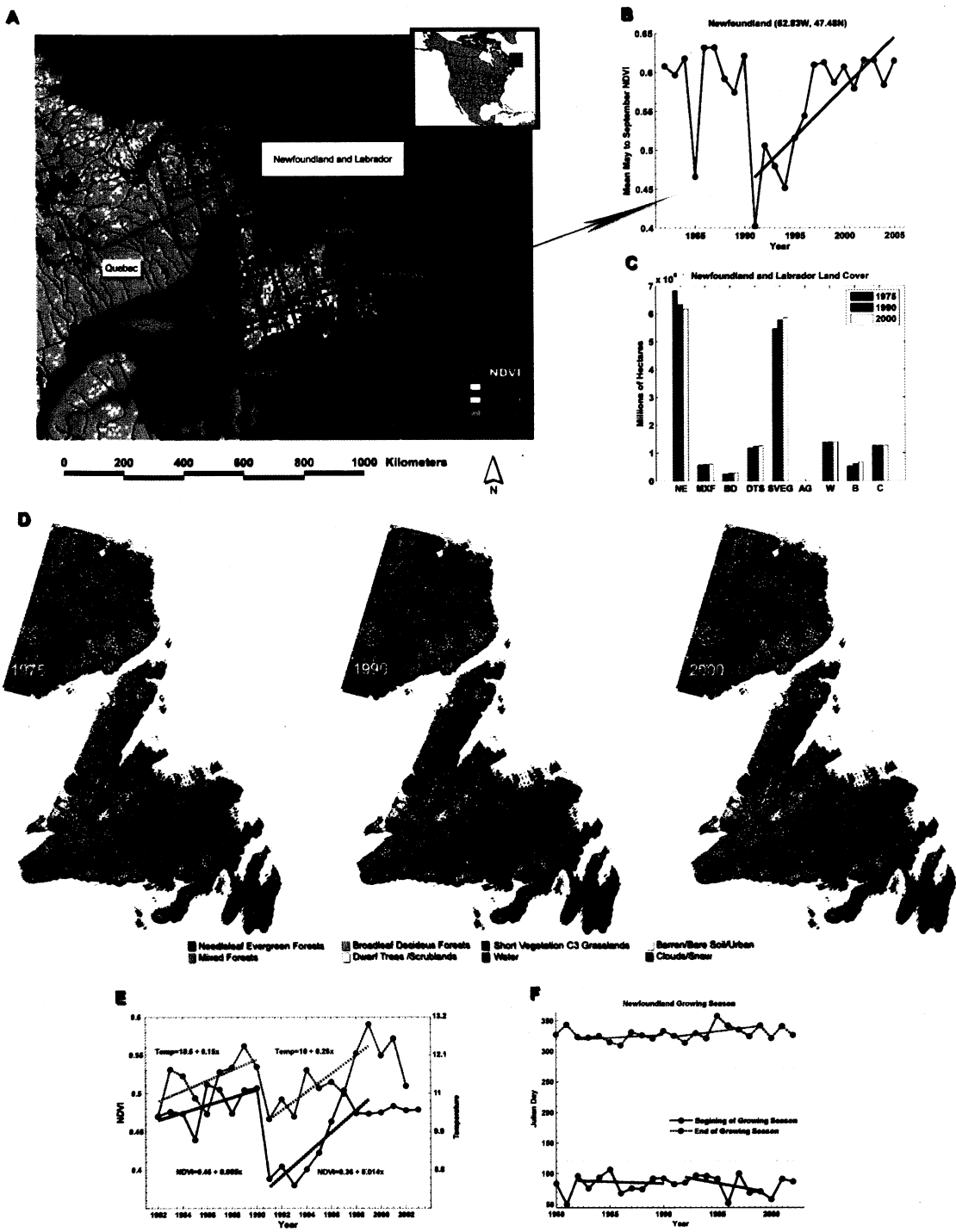


Fig. 11. The Newfoundland and Labrador areas that experienced marked increases in NDVI from 1992 to 1999 are noted in (A) with the Landsat images used for spatial understanding superimposed as an overlay. (B) The NDVI trend with time from 1982 to 2005 that shows a marked drop in NDVI in 1991 followed by a recovery from 1992 to the present. (C) Shows that few land cover changes have occurred while (D) shows the actual isoclustered Landsat data for the 1970s, 1990, and 2000, respectively. (E) Shows the trend in temperature and NDVI is synchronous in this maritime environment and (F) shows that the growing season had increased by ~17 days from 1992-1999.

Table 1
 Class Definitions for evaluation protocol

Class	Criteria
(NE) Needleleaf Evergreen Forests	Needleleaf Evergreen Trees > 3 m in height, Continuous Canopy > 30%
(MXF) Mixed Forests	Mixed Needleleaf Evergreen and Deciduous Trees > 3 m in height, Continuous Canopy > 30%
(BD) Broadleaf Deciduous Forests	Broadleaf Deciduous Trees > 3 m in height, Continuous Canopy > 30%
(DTS) Dwarf Trees/Scrublands	Trees and Shrubs >1 and < 3 m in height, Continuous Canopy >30%
(SVEG) Short Vegetation C3 Grasslands	Herbaceous Vegetation < 1 m in height, Sparse Canopy Density <50%
(AG) Agriculture C4 Grasslands	Annual Crops, Sparse Canopy Density < 50%
(W) Water	Open Water Surfaces > 20%
(B) Barren/Bare Soil/Urban	Human Built Structures, Roads, Bare Soil > 20%
(C) Clouds/Snow	Clouds, Cloud Shadow, and Snow Cover > 20%

Table 2
Error Matrices for Yukon

		Air Photo & IKONOS Reference Data									
		Ne	Mbn	Bd	Dts	Sveg	Ag	W	B	C	Map %
MSS	Ne	0	0	0	0	0	0	0	0	0	0.0
Mapped Data	Mbn	0	0	0	0	0	0	0	0	0	0.0
	Bd	0	0	0	0	0	0	0	0	0	0.0
	Dts	0	0	0	1494	161	0	33	0	0	26.0
	Sveg	0	0	0	118	1096	0	46	248	0	53.8
	Ag	0	0	0	0	0	0	0	0	0	0.0
	W	0	0	0	17	4	0	5281	0	0	17.1
	B	0	0	0	0	0	0	0	262	0	1.4
	C	0	0	0	0	0	0	0	0	0	1.8
Producer's Accuracy	-	-	-	-	91.7	86.9	-	98.5	51.4	0	-
User's Accuracy	-	-	-	-	88.5	72.7	-	99.6	100.0	-	-
Sample %	-	-	-	-	18.4	13.5	-	64.9	6.3	-	-
<i>Overall Accuracy 92.8%</i>											
<i>Kappa Statistic 87.4%</i>											
TM	Ne	0	0	0	0	0	0	0	0	0	0.0
Mapped Data	Mbn	0	0	0	0	0	0	0	0	0	0.0
	Bd	0	0	0	0	0	0	0	0	0	0.0
	Dts	0	0	0	376	620	0	9	0	0	26.1
	Sveg	0	0	0	194	9269	0	19	248	0	53.2
	Ag	0	0	0	0	0	0	0	0	0	0.0
	W	0	0	0	0	38	0	19967	0	0	17.5
	B	0	0	0	0	22	0	0	262	0	1.4
	C	0	0	0	0	0	0	0	0	0	1.8
Producer's Accuracy	-	-	-	-	66.0	93.2	-	99.8	51.4	-	-
User's Accuracy	-	-	-	-	37.4	95.3	-	99.8	92.3	-	-
Sample %	-	-	-	-	1.3	31.0	-	66.8	1.7	-	-
<i>Overall Accuracy 96.3%</i>											
<i>Kappa Statistic 92.2%</i>											
ETM	Ne	0	0	0	0	0	0	0	0	0	0.0
Mapped Data	Mbn	0	0	0	0	0	0	0	0	0	0.0
	Bd	0	0	0	0	0	0	0	0	0	0.0
	Dts	0	0	0	2648	145	0	0	0	0	26.8
	Sveg	0	0	0	233	2611	0	10	175	0	52.5
	Ag	0	0	0	0	0	0	0	0	0	0.0
	W	0	0	0	0	0	0	4454	0	0	16.6
	B	0	0	0	25	0	0	0	326	0	2.3
	C	0	0	0	0	0	0	0	0	0	1.8
Producer's Accuracy	-	-	-	-	91.1	94.7	-	99.8	65.1	-	-
User's Accuracy	-	-	-	-	94.8	86.2	-	100.0	92.9	-	-
Sample %	-	-	-	-	26.4	26.0	-	44.4	5.0	-	-
<i>Overall Accuracy 94.5%</i>											
<i>Kappa Statistic 91.8%</i>											

Table 3
Error Matrices for Northern Saskatchewan

		Air Photo & IKONOS Reference Data									
		<i>Ne</i>	<i>Mbn</i>	<i>Bd</i>	<i>Dts</i>	<i>Sveg</i>	<i>Ag</i>	<i>W</i>	<i>B</i>	<i>C</i>	Map %
MSS	<i>Ne</i>	399	0	0	125	5	0	0	0	0	29.9
Mapped Data	<i>Mbn</i>	0	0	0	0	0	0	0	0	0	0.0
	<i>Bd</i>	0	0	0	0	0	0	0	0	0	0.2
	<i>Dts</i>	13	0	0	426	28	0	0	0	0	21.4
	<i>Sveg</i>	5	0	0	26	149	0	0	0	0	28.4
	<i>Ag</i>	0	0	0	0	0	0	0	0	0	0.0
	<i>W</i>	2	0	0	0	0	0	836	0	0	19.1
	<i>B</i>	0	0	0	0	0	0	0	0	0	0.2
	<i>C</i>	0	0	0	0	0	0	0	0	0	0.8
Producer's Accuracy		95.2	-	-	73.8	81.9	-	100.0	-	-	-
User's Accuracy		75.4	-	-	91.2	82.8	-	99.8	-	-	-
Sample %		23.1	-	-	31.9	10.1	-	46.2	-	-	-
Overall Accuracy		89.9%									
Kappa Statistic		89.7%									
TM	<i>Ne</i>	3694	0	0	125	159	0	0	0	0	23.8
Mapped Data	<i>Mbn</i>	0	0	0	0	0	0	0	0	0	0.0
	<i>Bd</i>	0	0	0	0	0	0	0	0	0	0.2
	<i>Dts</i>	19	0	0	426	89	0	0	0	0	20.3
	<i>Sveg</i>	72	0	0	26	1315	0	0	0	0	35.5
	<i>Ag</i>	0	0	0	0	0	0	0	0	0	0.0
	<i>W</i>	1	0	0	0	38	0	2114	0	0	19.1
	<i>B</i>	0	0	0	0	22	0	0	0	0	0.2
	<i>C</i>	0	0	0	0	0	0	0	0	0	0.8
Producer's Accuracy		97.6	-	-	73.8	81.0	-	100.0	-	-	-
User's Accuracy		92.9	-	-	79.8	93.1	-	98.2	-	-	-
Sample %		50.2	-	-	7.6	21.5	-	28.0	-	-	-
Overall Accuracy		97.6%									
Kappa Statistic		89.7%									
ETM	<i>Ne</i>	3538	0	0	31	161	0	0	0	0	21.7
Mapped Data	<i>Mbn</i>	0	0	0	0	0	0	0	0	0	0.0
	<i>Bd</i>	0	0	0	0	0	0	0	0	0	0.1
	<i>Dts</i>	7	0	0	95	151	0	0	0	0	16.5
	<i>Sveg</i>	57	0	0	24	1993	0	0	0	0	41.3
	<i>Ag</i>	0	0	0	0	0	0	0	0	0	0.0
	<i>W</i>	0	0	0	0	0	0	2126	0	0	19.1
	<i>B</i>	0	0	0	0	0	0	0	0	0	0.2
	<i>C</i>	0	0	0	0	0	0	0	0	0	0.8
Producer's Accuracy		98.2	-	-	63.3	86.5	-	100.0	-	-	-
User's Accuracy		94.9	-	-	37.5	96.1	-	100.0	-	-	-
Sample %		46.5	-	-	1.9	29.7	-	27.4	-	-	-
Overall Accuracy		94.7%									
Kappa Statistic		92.0%									

Table 4
Error Matrices for Southern Saskatchewan & Dakotas

		Air Photo & IKONOS Reference Data									
		<i>Ne</i>	<i>Mbn</i>	<i>Bd</i>	<i>Dts</i>	<i>Sveg</i>	<i>Ag</i>	<i>W</i>	<i>B</i>	<i>C</i>	Map %
MSS	<i>Ne</i>	0	0	0	0	0	0	0	0	0	0
Mapped Data	<i>Mbn</i>	0	0	0	0	0	0	0	0	0	0
	<i>Bd</i>	0	0	230	65	52	80	0	0	0	1.8
	<i>Dts</i>	0	0	0	98	0	0	4	57	0	0.5
	<i>Sveg</i>	0	0	74	7	11631	952	13	63	0	58.8
	<i>Ag</i>	0	0	83	19	0	7634	1018	69	0	26.1
	<i>W</i>	0	0	0	45	0	0	2163	0	0	2
	<i>B</i>	0	0	4	0	60	133	67	1166	0	9
	<i>C</i>	0	0	0	0	0	0	0	0	0	0
Producer's Accuracy	-	-	-	58.8	41.9	99.0	86.8	66.2	86.1	-	-
User's Accuracy	-	-	-	53.9	61.6	91.3	86.5	98.0	81.5	-	-
Sample %	-	-	-	1.7	1.0	51.2	38.4	14.2	5.9	-	-
<i>Overall Accuracy 88.9%</i>											
<i>Kappa Statistic 82.8%</i>											
TM	<i>Ne</i>	0	0	0	0	0	0	0	0	0	0
Mapped Data	<i>Mbn</i>	0	0	0	0	0	0	0	0	0	0
	<i>Bd</i>	0	0	169	0	21	35	0	0	0	0.9
	<i>Dts</i>	0	0	0	0	0	0	0	0	0	1.9
	<i>Sveg</i>	0	0	15	0	10253	97	1	256	0	65.1
	<i>Ag</i>	0	0	61	21	364	1785	3	29	0	13.5
	<i>W</i>	0	0	0	0	39	0	10	0	0	0.3
	<i>B</i>	0	0	0	0	28	0	0	2019	0	18.1
	<i>C</i>	0	0	0	0	0	0	0	0	0	0.1
Producer's Accuracy	-	-	-	69.0	0.0	95.8	93.1	71.4	87.6	-	-
User's Accuracy	-	-	-	75.1	0.0	96.5	78.9	20.4	98.6	-	-
Sample %	-	-	-	1.6	0.1	70.4	12.6	0.1	15.2	-	-
<i>Overall Accuracy 93.6%</i>											
<i>Kappa Statistic 86.4%</i>											
ETM	<i>Ne</i>	0	0	0	0	0	0	0	0	0	0
Mapped Data	<i>Mbn</i>	0	0	0	0	0	0	0	0	0	0
	<i>Bd</i>	0	0	149	16	11	50	0	0	0	2.2
	<i>Dts</i>	0	0	0	0	0	0	0	0	0	0.4
	<i>Sveg</i>	0	0	31	14	3466	288	0	103	0	52.5
	<i>Ag</i>	0	0	25	0	86	2311	0	25	0	26.7
	<i>W</i>	0	0	0	0	0	0	651	0	0	2.9
	<i>B</i>	0	0	2	0	100	5	0	653	0	13.5
	<i>C</i>	0	0	0	0	0	0	0	0	0	1.8
Producer's Accuracy	-	-	-	72.0	0.0	94.6	89.1	100.0	83.6	-	-
User's Accuracy	-	-	-	65.9	0.0	90.2	94.4	100.0	85.9	-	-
Sample %	-	-	-	2.9	0.4	50.7	35.9	9.0	10.8	-	-
<i>Overall Accuracy 91.2%</i>											
<i>Kappa Statistic 86.7%</i>											

Table 5
 Error Matrices for Oklahoma Panhandle

		Air Photo & IKONOS Reference Data									
		Ne	Mbn	Bd	Dts	Sveg	Ag	W	B	C	Map %
MSS	Ne	0	0	0	0	0	0	0	0	0	0
Mapped Data	Mbn	0	0	0	0	0	0	0	0	0	0
	Bd	0	0	131	0	0	0	0	0	0	0.9
	Dts	0	0	112	55	0	0	0	0	0	1.9
	Sveg	0	0	31	17	28109	400	0	1100	0	66.8
	Ag	0	0	0	7	119	2434	0	52	0	12.4
	W	0	0	0	0	0	0	16	57	0	0.3
	B	0	0	2	0	1843	57	5	6926	0	17.6
	C	0	0	0	0	0	0	0	0	0	0.1
Producer's Accuracy	-	-	-	47.5	69.6	93.5	84.2	76.2	85.1	-	-
User's Accuracy	-	-	-	100.0	39.2	94.8	93.2	21.9	78.4	-	-
Sample %	-	-	-	0.7	0.2	79.8	7.7	0.1	21.6	-	-
<i>Overall Accuracy 90.8%</i>											
<i>Kappa Statistic 78.9%</i>											
TM	Ne	0	0	0	0	0	0	0	0	0	0.0
Mapped Data	Mbn	0	0	0	0	0	0	0	0	0	0.0
	Bd	0	0	164	0	1	0	0	0	0	0.9
	Dts	0	0	0	0	0	0	0	0	0	1.9
	Sveg	0	0	24	0	8720	45	0	122	0	65.1
	Ag	0	0	22	0	417	773	0	49	0	13.5
	W	0	0	6	0	0	0	99	0	0	0.3
	B	0	0	0	0	447	1	0	2849	0	18.1
	C	0	0	0	0	0	0	0	0	0	0.1
Producer's Accuracy	-	-	-	75.9	-	91.0	94.4	100.0	94.3	0	-
User's Accuracy	-	-	-	99.4	-	97.9	61.3	94.3	86.4	0	-
Sample %	-	-	-	1.7	-	76.0	6.5	0.8	24.0	0	-
<i>Overall Accuracy 91.7%</i>											
<i>Kappa Statistic 83.1%</i>											
ETM	Ne	0	0	0	0	0	0	0	0	0	0
Mapped Data	Mbn	0	0	0	0	0	0	0	0	0	0
	Bd	0	0	55	0	0	0	0	0	0	1.0
	Dts	0	0	0	0	0	0	0	0	0	2.0
	Sveg	0	0	47	0	2340	12	0	2110	0	62.0
	Ag	0	0	0	0	0	3255	0	10	0	15.2
	W	0	0	0	0	0	0	22	0	0	0.4
	B	0	0	0	0	50	37	0	10351	0	19.2
	C	0	0	0	0	0	0	0	0	0	0.1
Producer's Accuracy	-	-	-	53.9	-	97.7	98.5	100.0	83.0	-	-
User's Accuracy	-	-	-	100.0	-	51.9	99.7	100.0	99.2	-	-
Sample %	-	-	-	0.6	-	14.9	20.6	0.1	77.8	-	-
<i>Overall Accuracy 87.6%</i>											
<i>Kappa Statistic 77.3%</i>											

Table 6
Error Matrices for Quebec

		Air Photo & IKONOS Reference Data									
		Ne	Mbn	Bd	Dts	Sveg	Ag	W	B	C	Map %
MSS	Ne	4534	9	1	11	89	0	12	0	0	47.9
Mapped Data	Mbn	0	48	0	0	0	0	0	0	0	2.4
	Bd	17	36	671	0	0	0	0	0	0	18.2
	Dts	19	0	5	101	0	0	4	0	0	4.1
	Sveg	164	14	135	1	566	0	0	0	0	12.9
	Ag	12	0	0	0	0	0	0	0	0	1.8
	W	0	0	0	0	0	0	844	0	0	12.1
	B	0	0	0	0	0	0	0	0	0	0.2
	C	0	0	0	0	0	0	0	0	0	0.5
	Producer's Accuracy	95.5	44.9	82.6	89.4	86.4	-	98.1	-	-	-
	User's Accuracy	97.4	100.0	92.7	78.3	64.3	-	100.0	-	-	-
	Sample %	67.0	0.7	9.9	1.5	8.4	-	12.5	-	-	-
	Overall Accuracy	92.6%									
	Kappa Statistic	86.8%									
TM	Ne	1520	0	84	70	34	0	12	0	0	41.6
Mapped Data	Mbn	8	24	18	0	11	0	0	0	0	2.7
	Bd	70	3	263	0	6	0	0	0	0	20.2
	Dts	4	0	0	138	0	0	4	0	0	4.6
	Sveg	3	3	0	10	742	0	0	0	0	16.2
	Ag	0	0	0	0	0	0	0	0	0	1.9
	W	0	0	0	0	0	0	1405	0	0	12.2
	B	0	0	1	0	0	0	0	0	0	0.2
	C	0	0	0	0	0	0	0	0	0	0.5
	Producer's Accuracy	94.7	80.0	71.9	63.3	93.6	-	98.8	-	-	-
	User's Accuracy	88.3	39.3	76.9	94.5	97.9	-	100.0	-	-	-
	Sample %	37.2	0.6	6.4	3.4	18.1	-	34.3	-	-	-
	Overall Accuracy	92.3%									
	Kappa Statistic	89.3%									
ETM	Ne	1532	0	23	0	1	0	0	0	0	34.2
Mapped Data	Mbn	0	163	84	0	18	0	0	0	0	3.0
	Bd	114	33	558	0	7	0	0	0	0	21.4
	Dts	10	0	7	277	43	0	0	0	0	5.6
	Sveg	7	6	71	27	790	0	0	0	0	20.5
	Ag	0	0	0	0	0	0	0	0	0	2.2
	W	0	0	0	0	0	0	669	0	0	12.3
	B	0	0	0	1	0	0	0	0	0	0.3
	C	0	0	0	0	0	0	0	0	0	0.5
	Producer's Accuracy	92.1	80.7	75.1	90.8	92.0	-	100.0	-	-	-
	User's Accuracy	98.5	61.5	78.4	82.2	87.8	-	100.0	-	-	-
	Sample %	38.4	4.1	14.0	6.9	19.8	-	16.8	-	-	-
	Overall Accuracy	89.8%									
	Kappa Statistic	86.8%									

Table 7
Error Matrices for Newfoundland

		Air Photo & IKONOS Reference Data									
		Ne	Mbn	Bd	Dts	Sveg	Ag	W	B	C	Map %
MSS	Ne	79	10	17	0	932	0	0	0	0	39.1
Mapped Data	Mbn	5	12	72	45	111	0	0	0	0	3.3
	Bd	0	0	74	144	8	0	0	1	0	1.5
	Dts	1	0	16	54	222	0	0	0	0	6.8
	Sveg	19	53	406	379	5617	0	0	2	0	31.2
	Ag	0	0	0	0	0	0	0	0	0	0
	W	0	0	0	2	17	0	5751	0	0	7.9
	B	0	4	0	9	53	0	0	0	0	3
	C	0	4	3	5	183	0	45	6	0	7.2
	Producer's Accuracy	76.0	14.5	12.6	8.4	78.6	-	99.2	0.0	-	-
	User's Accuracy	7.6	4.8	32.6	18.4	86.7	-	99.7	0.0	-	-
	Sample %	0.7	0.1	0.6	0.5	48.5	-	49.6	0.0	-	-
		<i>Overall Accuracy 80.7%</i>									
		<i>Kappa Statistic 68.4%</i>									
TM	Ne	7289	361	76	13	385	0	11	12	0	36.1
Mapped Data	Mbn	444	1220	54	21	210	0	15	3	0	3.4
	Bd	8	151	351	65	49	0	3	2	0	1.6
	Dts	160	194	86	90	35	0	5	4	0	7.1
	Sveg	1648	256	361	252	6856	0	79	187	0	33
	Ag	0	0	0	0	0	0	0	0	0	0
	W	29	0	4	4	12	0	13116	4	0	8
	B	15	46	36	13	472	0	2	1235	0	3.5
	C	57	4	3	5	183	0	45	6	0	7.2
	Producer's Accuracy	75.5	54.7	36.1	19.4	83.6	-	98.8	85.0	-	-
	User's Accuracy	89.5	62.0	55.8	15.7	71.1	-	99.6	67.9	-	-
	Sample %	24.8	4.1	1.2	0.3	22.7	-	43.5	4.1	-	-
		<i>Overall Accuracy 83.2%</i>									
		<i>Kappa Statistic 77.3%</i>									
ETM	Ne	1867	153	0	8	50	0	5	1	0	35.1
Mapped Data	Mbn	7	137	0	11	0	0	0	0	0	3.4
	Bd	0	0	0	0	0	0	0	0	0	1.7
	Dts	14	0	0	213	32	0	0	0	0	7.2
	Sveg	1	0	0	47	1700	0	0	11	0	33.4
	Ag	0	0	0	0	0	0	0	0	0	0.0
	W	0	0	0	0	0	0	451	0	0	8.0
	B	0	0	0	0	16	0	0	30	0	3.8
	C	0	0	0	0	0	0	0	0	0	7.2
	Producer's Accuracy	98.8	47.2	-	76.3	94.5	-	98.9	71.4	-	-
	User's Accuracy	89.6	88.4	-	82.2	96.6	-	100.0	65.2	-	-
	Sample %	42.5	3.12	-	4.9	38.7	-	10.3	0.7	-	-
		<i>Overall Accuracy 92.5%</i>									
		<i>Kappa Statistic 88.8%</i>									

Table 8

Landsat scenes used in investigation, bold indicates duplicates for overlap.

	WRS1	MSS	WRS2	TM	ETM	MSS-2	TM-2	ETM-2
Yukon	64011	7/13/76	61011	6/30/88	9/2/00			
	67011	7/6/78	61011	6/30/88	9/2/00			
	64012	9/4/78	61012	7/18/92	7/19/00			
	67012	7/6/78	61012	7/18/92	7/19/00			
	67011	7/6778	63011	6/28/91	9/19/01			
	67012	7/6/78	63012	6/30/92	8/31/00			
	71012	7/20/76	63012	6/30/92	8/31/00			
Northern Saskatchewan	39019	9/16/76	37019	8/30/87	9/29/01			
	40020	9/6/73	37020	8/30/87	9/29/01			
	41019	9/21/79	39019	9/2/89	6/10/02			
	41019	9/21/79	37019	8/30/87	9/29/01			
	41020	8/4/76	38020	6/2/93	9/4/01			
	42020	9/21/74	39020	6/6/92	6/10/02			
	42020	9/21/74	38020	6/2/93	9/4/01			
	43019	8/5/78	41019	8/5/91	6/5/01			
	43019	8/5/78	39019	9/2/89	6/10/02			
	44020	5/25/73	41020	9/11/87	6/2/00			
44020	5/25/73	39020	6/6/92	6/10/02				
Southern Saskatchewan	38025	7/23/76	35025	7/1/88	7/26/00	9/18/79	9/3/88	4/21/00
	38026	7/13/78	35026	8/11/91	7/8/99	5/15/79		9/28/91
4/21/00 & North Dakota	39025	7/18/79	36025	8/25/88	8/5/88	9/19/79	10/12/88	5/20/02
	39026	7/18/79	36026	9/3/91	8/5/01	9/19/79	7/17/91	10/8/01
Oklahoma Panhandle	32034	6/14/79	30034	7/25/92	7/5/99	9/30/79	4/4/92	11/26/99
	32035	6/14/79	30035	9/27/92	7/5/99	9/30/79	4/4/92	11/26/99
	33034	7/13/77	31034	7/8/89	7/14/00	5/15/78	10/28/89	5/11/00
	33035	7/13/77	31035	7/8/89	8/13/99	4/18/78	10/28/89	5/11/00
Quebec	14026	8/12/78	13026	8/27/89	7/19/01			
	14026	8/12/78	15026	5/18/88	8/21/02			
	14027	8/1/75	13027	8/27/89	8/23/02			
	16026	9/23/72	14026	8/26/86	6/5/00			
	15027	10/31/75		14027	6/10/87	5/20/00		
	16026	9/23/72	15026	5/18/88	8/21/02			
	16027	6/10/75	15027	5/13/86	6/15/01			
	17026	4/30/76	16026	8/3/90	8/25/01			
17027	6/2/75	16027	8/3/90	8/25/01				
Newfoundland & Labrador	02026	5/27/75	02026	10/12/93		10/13/02		
	02027	8/19/76	02027	10/12/93		7/01/99		
	03026	8/8/75	03026	7/31/87	10/1/01			
	03027	5/15/74	03027	9/9/90	10/1/01			
	04025	7/14/73	04025	8/25/88	10/11/02			
	04026	7/14/73	04026	8/31/90	8/5/01			
	04027	9/24/73	04027	8/31/90	9/1/01			
	05023	8/22/76	05023	9/20/89	9/16/02			
	05024	9/02/74	05024	8/6/90	9/16/02			
	06025	9/13/72	05025	8/6/90	8/12/01			
	05026	8/22/76	05026	8/9/91	6/6/01			

Table 8 (continued)

Landsat scenes used in investigation, bold indicates duplicates for overlap.

	WRS1	MSS	WRS2	TM	ETM
Newfoundland	06026	9/26/73	05026	8/9/91	6/6/00
& Labrador	05027	6/4/74	05027	8/9/91	6/6/00
	06023	6/30/76	06023	8/18/92	9/20/01
	08023	10/3/72	06023	8/18/92	9/20/01
	08022	7/8/75	06023	8/18/92	9/20/01
	06024	10/19/72		06024	6/15/92 9/20/01
	07024	7/19/73	06024	6/15/92	9/20/01

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