Characterising stand-replacing disturbance in western Alberta grizzly bear habitat, using a satellite-derived high temporal and spatial resolution change sequence

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ABSTRACT

Timely and accurate mapping of anthropogenic and natural disturbance patterns can be used to better understand the nature of wildlife habitats, distributions, and movements. One common approach to map forest disturbance is by using high spatial resolution satellite imagery, such as Landsat 5 Thematic Mapper (TM) or Landsat 7 Enhanced Thematic Mapper plus (ETM+) imagery acquired at a 30 m spatial resolution. However, the low revisit times of these sensors acts to limit the capability to accurately determine dates for a sequence of disturbance events, especially in regions where cloud contamination is a frequent occurrence. As wildlife habitat use can vary significantly seasonally, annual patterns of disturbance are often insufficient in assessing relationships between disturbance and foraging behaviour or movement patterns.

The Spatial Temporal Adaptive Algorithm for mapping Reflectance Change (STAARCH) allows the generation of high-spatial (30 m) and -temporal (weekly or bi-weekly) resolution disturbance sequences using fusion of Landsat TM or ETM+ and Moderate Resolution Imaging Spectroradiometer (MODIS) imagery. The STAARCH algorithm is applied here to generate a disturbance sequence representing stand-replacing events (disturbances over 1 ha in area) for the period 2001 to 2008, over almost 6 million ha of grizzly bear habitat along the eastern slopes of the Rocky Mountains in Alberta. The STAARCH algorithm incorporates pairs of Landsat images to detect the spatial extent of disturbances; information from the bi-weekly MODIS composites is used in this study to assign a date of disturbance (DoD) to each detected disturbed area. Dates of estimated disturbances with areas over 5 ha are validated by comparison with a yearly Landsat-based change sequence, with producer's accuracies ranging between 15 – 85 % (average overall accuracy 62 %, kappa statistic of 0.54) depending on the size of the disturbance event. The spatial and temporal patterns of disturbances within the entire region and in smaller subsets, representative of the size of a grizzly bear annual home range, are then explored. Disturbance levels are shown to increase later in the growing season, with most disturbances occurring in late August and September. Individual events are generally small in area (less than 10 ha) except in the case of wildfires, with, on average, 0.4 % of the total area disturbed each year. The application of STAARCH provides unique high temporal and spatial resolution disturbance information over an extensive area, with significant potential for improving understanding of wildlife habitat use.

Keywords: *Ursus arctos* L., Landsat, MODIS, change detection, harvesting, monitoring

1. INTRODUCTION

Spatial and temporal patterns of forest disturbance, due to both natural and anthropogenic factors can have significant and long lasting influences on resource availability, habitat suitability, and the distribution of wildlife species (Foster et al., 2003, Nielsen et al., 2004a). Forest disturbance can fragment suitable habitat reducing forest patch size, increase edges and result in increasing patch isolation; however, disturbances can also increase the availability of open habitat areas and associated resources, such as emerging grasses and herbaceous plants (Berland et al., 2008). For example, grizzly bear (*Ursus arctos* L.) habitat use has been shown to be influenced by the temporal and spatial distribution of disturbance within bear home ranges. Bears prefer a matrix of habitat types, incorporating both forest clearings and closed forest (Blanchard, 1983, Hamer and Herrero, 1987). Disturbed areas, such as fire scars, roadside verges and harvested forest areas, provide high-quality forage (Berland et al., 2008, Roever et al., 2008), while closed forest provides security when bedding (Munro et al., 2006). Grizzly bear food availability has been shown to vary across seasons and by disturbance type (Servheen, 1983), with key seasonal food resources, such as cow parsnip (*Heracleum lanatum*), particularly abundant along forest edges (Turner, 2003). As such, edges and disturbed areas impact grizzly bear habitat through changes in seasonal food availability and the bear's use of disturbed areas, as well as movement patterns, will vary over the growing season (Berland et al., 2008, Nielsen et al., 2004b). However, bears also experience increased mortality when using such areas, due to a higher risk of conflict with humans (McLellan, 1998, Nielsen et al., 2004c) and some studies indicate that bears avoid clear-cuts (Zager et al., 1983, McLellan and Hovey, 2001). This has implications for the sustainability of populations in highly disturbed areas.

As the patterns of grizzly bear foraging, movement and in particular, use of disturbed areas, will vary seasonally, the timing of disturbance events during the growing season could have implications for bear habitat use and survival. High temporal resolution disturbance information, over extensive areas, can therefore be critical in understanding patterns of wildlife habitat use recorded at very high temporal resolutions using GPS and satellite radio collars (Nielsen et al., 2008, Graham et al., 2010), with annual landscape change variables unlikely to be sufficient.

Remote sensing has been demonstrated to be an important source of information for disturbance mapping and Landsat imagery, in particular, has been widely used to monitor land cover (Wulder et al., 2008a) and map ecosystem disturbance at landscape and continental scales (Healey et al., 2005, Masek et al., 2008). Landsat imagery is characterized by 30 m spatial resolution and large per-scene areal coverage (185 km x 185 km) and, as a result, is highly suitable for detecting disturbance events over extensive areas (Healey et al., 2005). Such disturbances include permanent changes in land-use such as road construction or mining, as well as more temporary changes in canopy cover including harvesting activity and the influence of pests and disease. However, the 16-day revisit cycle of the platform limits its ability to accurately determine dates of disturbance events, especially in regions where cloud contamination is a frequent occurrence (Gao et al., 2006, Ju and Roy, 2008). For instance, in humid, cloudy regions, the probability of acquiring cloud free Landsat imagery in any given year can be as low as 10 % (Leckie, 1990) and the probability of acquiring even two images from different seasons per year is only about 53 % on a global average (Ju and Roy, 2008). As wildlife movements and habitat use are likely to be sensitive to the timing of disturbance events within the growing season, higher temporal resolution data is needed to inform on disturbance within forested environments. High temporal and spatial resolution disturbance sequences also have potential applications in assessing the influence of both anthropogenic and natural disturbances on forest ecosystems and in implementing sustainable approaches to forest management based on patterns of prevalent natural disturbances.

Fusion of high spatial resolution Landsat imagery with high temporal resolution data such as that from the Moderate Resolution Imaging Spectroradiometer (MODIS), which acquires reflectance observations at 250-1000 m resolution and has near daily global coverage, enables the generation of synthetic, Landsat-like, observations with high spatial (30 m) and temporal (potentially daily) resolution (Gao et al., 2006). Synthetic data generated using the Spatial and Temporal Adaptive Reflectance Fusion Model (STARFM) (Gao et al., 2006) has been shown to allow monitoring of seasonal patterns of vegetation change and large scale changes in land use (Hilker et al., 2009a). The Spatial Temporal Adaptive Algorithm for mapping Reflectance Change (STAARCH) (Hilker et al., 2009b) was developed to allow the detection of disturbance events at spatial scales smaller than that of a MODIS pixel, through the generation of a spatial change mask derived from Landsat and an image sequence recording the temporal evolution of disturbance events based on MODIS. The STAARCH algorithm has also been combined with STARFM (Gao et al., 2006) to allow the prediction of synthetic Landsat-like reflectance that includes disturbance events (Hilker et al., 2009b). The algorithm has been applied and tested over a single Landsat scene in west-central Alberta (Hilker et al., 2009b) but has not previously been applied in an operational context over a large spatial extent, covering multiple Landsat scenes and MODIS tiles.

In this paper, the STAARCH algorithm is applied to predict high spatial and temporal resolution disturbance over a large area of western Alberta, Canada, spanning 14 Landsat path/rows. The area represents important grizzly bear habitat and is the focus of a larger study on grizzly bear habitat use and mortality. A bi-weekly disturbance sequence for the period September 2001 to June 2008 is produced and the temporal and spatial patterns of disturbance within core and secondary grizzly bear habitat areas are examined over the entire region, and at the spatial scale of individual grizzly bear home ranges. The disturbance sequence generated provides a unique insight into seasonal disturbance trends and patterns over an extensive region.

2. METHODOLOGY

2.1 The Alberta grizzly bear study area

The Rocky Mountains and foothills in western Alberta, Canada, provide important habitat for grizzly bears, as well as other wildlife. High quality grizzly bear habitat in Alberta is under tremendous pressure related to resource extraction activities and increased human use, which may be influencing the health and distribution of bears at both individual and population levels (Garshelis et al., 2005, Nielsen et al., 2004c, Fest-Bianchet, 2010). In North America, grizzly bear habitat loss has occurred throughout the northern United States and southern Canada (Neilson et al., 2004) with only 37 % of grizzly bear range currently considered secure and the remaining area considered vulnerable (Banci et al., 1994). In addition to habitat concerns, high levels of human caused mortality, associated with access features (roads) in good quality grizzly bear habitat, represents a significant risk to long term survival of grizzly bear populations. One component of the Alberta grizzly bear recovery plan (Alberta Sustainable Resource Development, 2008), was the establishment of grizzly bear conservation areas within each population unit (management units with genetically distinct grizzly bear populations, typically separated by major highways). The Alberta government has prepared draft conservation areas (Nielsen et al., 2009) which delineate areas as with being core or secondary bear habitat. Core habitat includes areas of high habitat value coinciding with areas of low mortality risk (assessed using road density data), whereas secondary areas are locations of good habitat, but with increased road access densities. Disturbance patterns were assessed at two spatial scales, that of the entire grizzly bear study area and at a small watershed scale of approximately the size of an adult female grizzly bear home range (about 700 km^2) (Nielsen et al., 2009) (Figure 1). Our implementation of this approach was focused on these new provincial grizzly bear conservation areas.

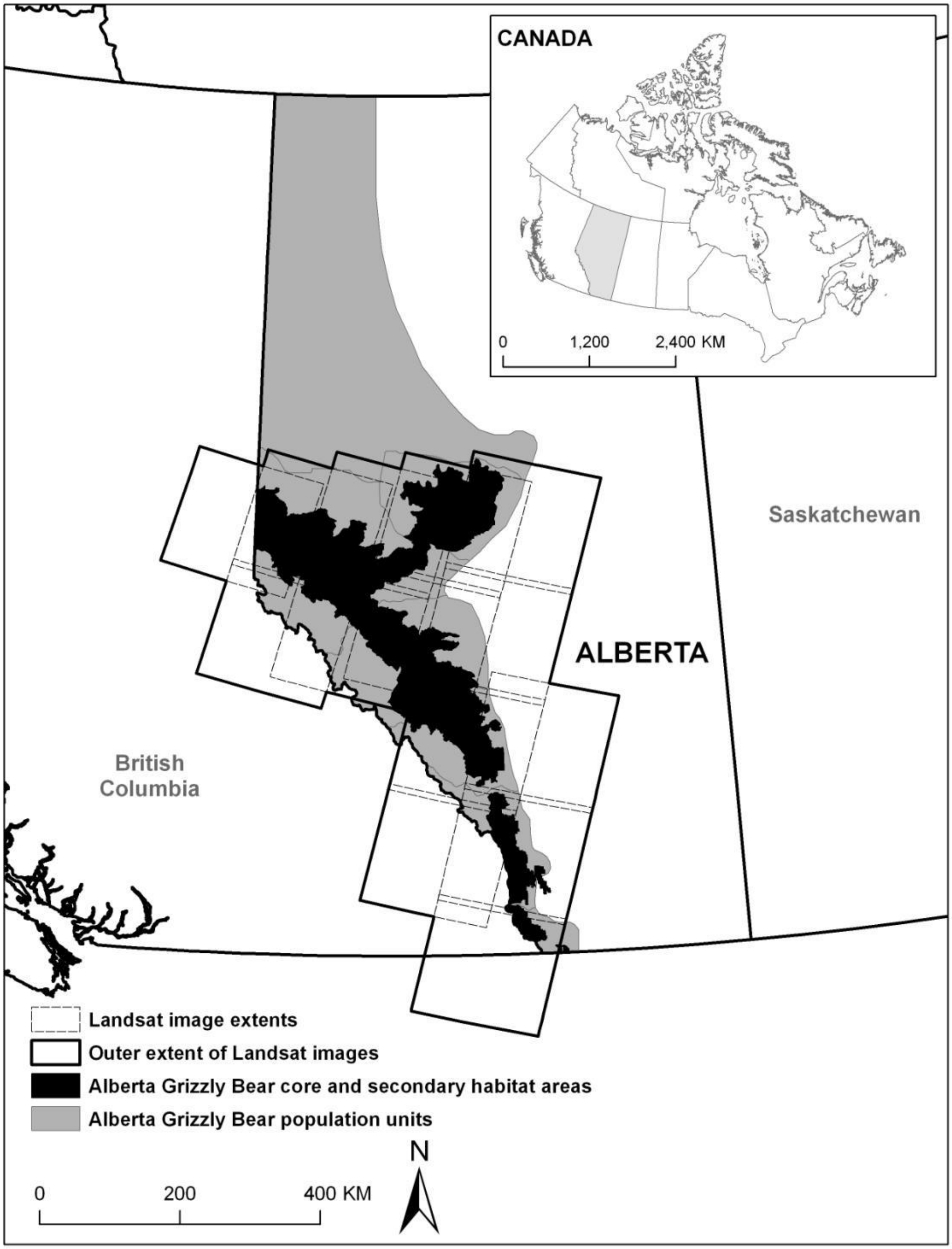


Figure 1: Location of the Grizzly Bear population units and core and secondary habitat areas within western Alberta, Canada, based on Nielsen et al., 2009.

The focus of this paper is on stand-replacing disturbance events. The spatial extent of individual stands will vary as a result of past disturbance patterns and management. Disturbance events must be of sufficient magnitude to result in a detectable change in spectral properties of a 30 m Landsat TM pixel, but the exact disturbed area or percentage of trees removed to result in such a change will vary with disturbance type. For example, the early stages of insect infestation may affect a significant number of trees but cause little change in spectral properties, while the loss of a smaller area of forest for road construction may result in a larger spectral response. In this paper, the term ‘stand-replacing’ is used simply to emphasize the focus on disturbance events greater than 1 ha in area, causing permanent or temporary changes to land cover, that are large enough to be observable at medium scales, as opposed to lower magnitude disturbances such as the loss of individual trees within a stand to windthrow, pests or disease. In some cases, even such large disturbances may divide an existing stand rather than lead to a full ‘stand-replacement’.

2.2 Implementation of the STAARCH Algorithm

A detailed description of the STAARCH algorithm and its use for producing high spatial- and temporal-resolution disturbance maps can be found in Hilker et al. (2009b). Briefly, STAARCH is a change detection algorithm designed to map forest disturbance events at a 30 m spatial resolution and at weekly or bi-weekly time intervals, using a combination of Landsat TM/ETM and MODIS observations (Hilker et al., 2009b). As an auxiliary dataset, the STAARCH algorithm also uses a land cover classification product to normalize disturbance observations to the respective land cover type. The two main outputs of STAARCH are: 1) a spatial change mask of forest disturbance at 30 m spatial resolution; and, 2) an image sequence which records the temporal evolution of these disturbance events. Spatial change characteristics are assessed on the basis of two Landsat scenes recorded at the beginning and at the end of an observation period. The change detection utilizes a disturbance index (Healey et al., 2005) derived from a tasselled cap transformed image space of each of the two Landsat scenes (Kauth and Thomas, 1976, Crist and Cicone, 1984). Change predictions are restricted to cloud free areas and clouds are detected automatically using a Landsat based cloud filter (based on Irish et al., 2006). The date of disturbance (DoD) is then determined from a time series of tasselled cap transformed MODIS images (Lobser and Cohen, 2007). The algorithm uses a smoothing and filtering technique of several subsequent MODIS scenes to define the time of disturbance as the time interval with the maximum increase in the MODIS disturbance index (Hilker et al., 2009b). The algorithm used in this study has been slightly improved over the originally published version (Hilker et al., 2009b) in that it now features a median filter to automatically remove outliers in the disturbance sequence. Additionally, the cloud detection algorithm (Irish et al., 2006) has been extended to now also mask cloud cover in the MODIS imagery in addition to using the MODIS quality flags to prevent the algorithm from assigning dates of disturbance to cloudy areas.

The temporal resolution of the STAARCH disturbance prediction depends on the density of the input data. For this study, we chose a bi-weekly input of 8-day MODIS composites (MOD 09 product, 500 m resolution) to predict disturbance events between 2001 and 2008 at a 16-day interval. Landsat 5 TM data for 14 path/rows covering the area of interest, acquired between July and October 2001, June and August 2004 and July and September 2008 were obtained from the USGS GLOVIS archive (http://glovis.usgs.gov/). An additional, intermediate Landsat scene (from 2004) was included due to the extended time period considered in this study. Images were selected to minimise cloud cover (where possible to below 30%) and the temporal separation between adjacent scenes across the study area. All images were atmospherically corrected using a dark object subtraction (DOS1 in Song et al., 2001). MODIS 8-day composites from 2001 to 2008 were re-projected to Universal Transverse Mercator (UTM) projection using the MODIS re-projection tool, clipped to the extent of the Landsat imagery and re-sampled to a 30 m spatial resolution. Land cover data was obtained from the Landsat-7 land cover classification of Canada that was produced for the Earth Observation for Sustainable Development of Forests (EOSD) initiative (Wulder et al., 2008b), representing circa year 2000 conditions. The STAARCH algorithm was implemented separately on each Landsat path/row to produce 14 disturbance sequences. Once combined, the sequences serve to collectively cover the majority of the Alberta grizzly bear core and secondary habitat area, with change predictions made at 16-day time steps.

2.3 Validation of the STAARCH predicted disturbance sequence

The validation protocol implemented in this study was developed under the assumption that if the date of stand-replacing disturbance events can be correctly predicted to yearly time-steps, then the level of accuracy should be transferable to higher temporal resolutions, as the algorithm and sensor properties remain constant (Hilker et al., 2009b). It is acknowledged that this assumption is reasonable only for stand replacing disturbance events for which the spectral changes due to disturbance are expected to be much greater than seasonal changes in vegetation cover and where changes occur over a relatively discrete time period. The effect of seasonal variation is minimized through the land cover normalization process (Hilker et al., 2009a). The capacity of STAARCH to correctly predict the year of changes was assessed using two scenes (located: Worldwide Reference System-2 (WRS-2) Path 44 / Row 22 (55˚32’16.4” N 118˚25’35.0” W) and Path 43 / Row 24 (55˚42’47.8” N 118˚47’1.9” W)). These Landsat scenes were selected as they were central to the study area and the input Landsat data was largely cloud free. The scenes were subset to ensure only areas common to all three (2001, 2004, and 2008) Landsat input scenes were included, resulting in a validation area of 19,396 km^2 for Path 44 / Row 22 (hereafter referred to as area A) and 18,646 km^2 for Path 43 / Row 24 (area B).

To provide a validation dataset, intermediate Landsat scenes from the summers of 2002, 2003, 2005 and 2007 were acquired from the USGS GLOVIS portal (http://glovis.usgs.gov). Cloud-free images were selected where possible (all validation scenes used had less than 15 % cloud cover). No cloud-free 2006 scenes were available for either validation Path/Row. The change detection component of STAARCH was then run over each one year time period (or two year period from 2005 to 2007) to generate change masks from the Landsat pairs and provide a year of occurrence (period from summer of one year until summer of the next) for each disturbance event. Where changes were detected for the same area in multiple years (approximately 20 % of pixels), the earlier year was used. Individual changes were then converted to polygons and any areas of less than 5 ha (20 % of a MODIS pixel) were excluded. The DoD from the full STAARCH implementation (running from 2002 to 2004 and 2004 to 2008) was then classified to the same yearly time periods and the area correctly and wrongly assigned to each yearly period assessed using a confusion matrix. As with the validation data, areas under 5 ha were excluded from the analysis. Only areas detected as changed or disturbed in both the validation and change sequence layers were included. Accuracy statistics (Overall accuracy, Producer's accuracy and kappa statistic) were then calculated for each Path/Row subset.

To determine the influence of the size of the disturbed area on accuracy of the DoD predictions, change polygons were classified into one of six area classes (1 to 5 ha, 5 to 10 ha, 10 to 15 ha, 15 to 20 ha, 20 to 40 ha and over 40 ha) based on the area detected by STAARCH. Overall accuracy of the predicted yearly time period was calculated for each class. For comparison, polygons with areas of 1 to 5 ha were also included in this analysis. These small disturbance events (equivalent to only 4 – 20 % of the area of a MODIS pixel), are likely to have significantly lower accuracy in terms of the date of disturbance assigned, but are retained in the final disturbance sequence as they contain valuable information on spatial aspects of disturbance patterns, with spatial extent determined from the higher resolution Landsat TM imagery. This analysis is therefore included to give an indication of the accuracy that can be expected in terms of temporal characteristics of these small disturbed areas.

2.4 Processing of the STAARCH change sequence

Following generation of change sequences for all Landsat path/rows from 2001 to 2004 and 2004 to 2008, the two temporal sequences were combined and converted to polygons (areas of disturbance occurring at the same date). To ensure consistency between scenes, only disturbances within the time period common to all path/rows (22nd September 2001 to 18th June 2008) were included. All changes over 1ha in area (4 % of a MODIS pixel) are included in the layer, with smaller areas of change either merged with neighbouring polygons (when present) or removed in the case of isolated areas. Areas were marked as null if STAARCH was unable to assign a date to a disturbance, due to frequent cloud within the MODIS image sequence (less than 0.5 % of disturbance polygons). Sequences for all path/rows were then combined. Within areas of overlap, the scene with the least cloud and snow in the input Landsat imagery was given preference. At boundaries of Landsat scenes, adjacent change polygons were merged only if they shared the same DoD.

2.5 Characterisation of disturbance patterns across the grizzly bear study area

The temporal (bi-weekly and yearly) and spatial distribution of disturbance events was examined for the entire grizzly bear study area and, in more detail, for ten individual grizzly bear core or secondary habitat areas. The selected areas were distributed across the 5 Grizzly Bear population units (two per population unit) covered by the STAARCH change sequence (Clearwater, Livingstone, Swan Hills, Yellowhead, and Grand Cache) to ensure an even geographical distribution. For each area, the mean distance to the nearest road (based on the

Alberta road network for February 2008) was calculated and used to stratify the area for each population unit as having a high or low relative likelihood of being disturbed (by anthropogenic factors). One area was then selected randomly from those in each mean road distance strata, for each population unit. For comparison with disturbance characteristics, the mean elevation, the percentage of the areas classed as forested (based on an available land cover classification representing 2005 conditions (McDermid et al., 2008)) and the percentage of the area identified as disturbed during the previous decade were calculated. The latter was derived from a difference map produced using the LEDAPS (Landsat Ecosystem Disturbance Adaptive Processing System) Change Product showing forested areas in 1990 and the EOSD land cover classification for 2000 (Wulder et al., 2008b).

For the full grizzly bear study area described above, we calculated total disturbed area for each bi-weekly period between 2001 and 2008. The same values were also calculated for the selected focus core and secondary habitat areas to allow examination of the temporal pattern of disturbance events. The distribution of disturbance events by patch area was also examined. Within the focus areas, the percentage of the total area disturbed in the 2001-2008 period, the number of disturbance events and the mean, maximum, and standard deviation of patch area were calculated. Area weighted mean shape index of the disturbance events was also calculated for the selected areas (Rempel, 2008). Area weighted mean shape index is based on the ratio of patch perimeter to the minimum perimeter for a compact (circular) shape of the equivalent area. It is equal to 1 when patches are circular and increases with increasing patch shape irregularity (McGarigal and Marks, 1995).

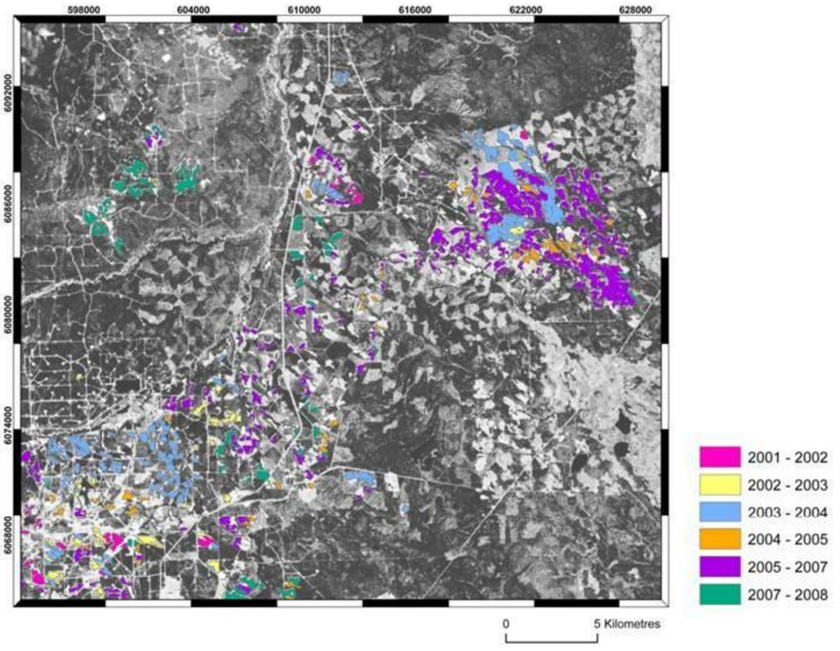
Finally, unequal-variance t-tests were used to assess whether there were significant differences in the percentage of the total habitat area disturbed (2001-2008) in designated core and secondary habitat areas, using all habitat areas over the entire study area.

3. RESULTS

3.1 Validation of the disturbance sequence

Yearly changes detected in the validation data set using intermediate Landsat scenes were compared to results of the STAARCH algorithm, classified to the equivalent periods (Figure 2). STAARCH was able to predict the yearly period of disturbance for validation area A with an overall accuracy of 67 % (Table 1). The accuracy for validation area B was somewhat lower (overall accuracy of 56.7 %). Changes and disturbance events covering large areas were generally detected with higher accuracy (Figure 3), with a clear trend of increasing accuracy as event size increased. Accuracies of over 50 % were obtained for disturbances over 10 to 15 ha in area (40 to 60 % of a MODIS pixel). As a single exception for validation area B, accuracy declined for the largest disturbance size class (Figure 3); however, the small number of events of this extent should be considered when interpreting this finding.

(a) STAARCH



(b) Validation data

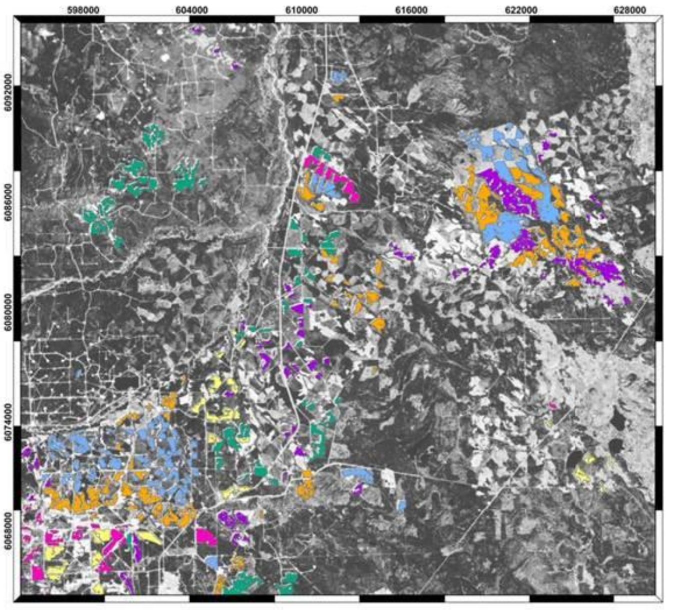


Figure 2: (a) An example of yearly classified STAARCH disturbances within validation area A. (b) Validation data set for the same area, derived by producing change masks from intermediate Landsat scenes. Yearly periods run from summer to summer, with exact date

Table 1. STAARCH DoD sequence accuracy statistics. Maximum and minimum producer's accuracies are the accuracies of the most and least accurate yearly periods.

Validation area (Path / Row)	Overall accuracy (%)	Kappa statistic	Minimum Producer's accuracy (%)	Maximum Producer's accuracy (%)
A (44 / 22)	67.0	0.59	41.7 (2004 – 2005)	85.0 (2005 – 2007)
B (43 / 24)	56.7	0.48	14.5 (2003 – 2004)	76.6 (2007 – 2008)

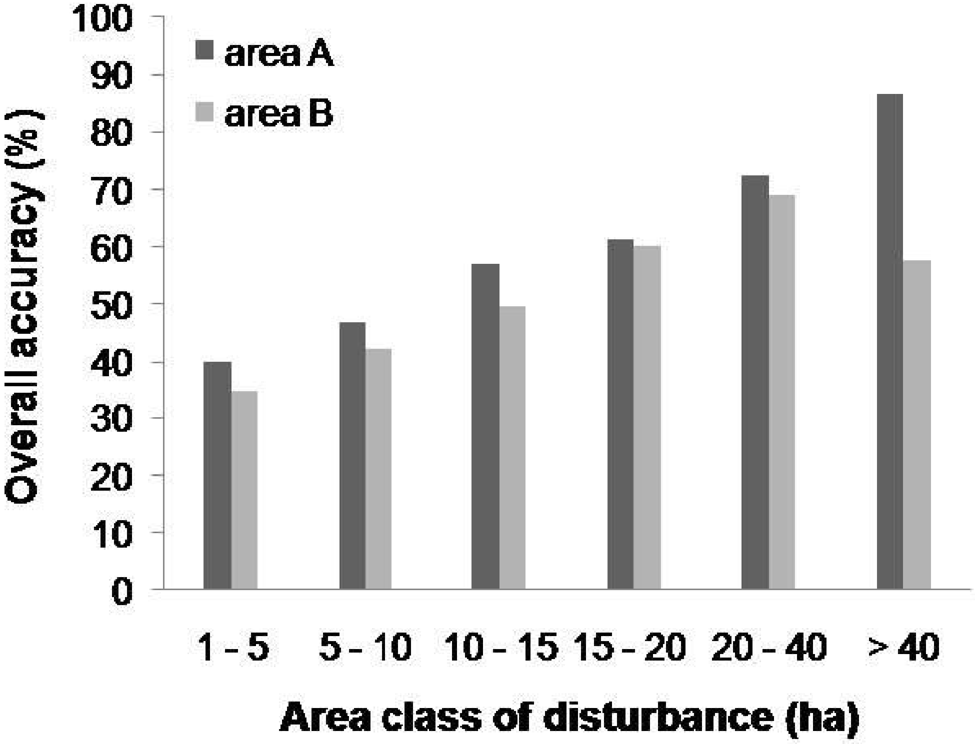


Figure 3: Overall accuracy of classified date of disturbance predictions according to area of the disturbance. The percentage of total disturbed area for the entire study area accounted for by events in each 'area class' were: 1-5 ha = 48 %, 5-10 ha = 23 %, 10-1

3.2 Disturbance patterns over the Alberta grizzly bear study area.

The STAARCH algorithm most frequently predicted disturbances as occurring in the first few dates of the growing season (representing both disturbances during those periods and those occurring outside of the sequence, such as winter harvesting and snow-related crown damage) as well as late in the season, during late August and September (Figure 4). Large amounts of disturbance (on average, 23 677 ha year^{-1} or 0.4 % of the total area) occurred in all years, but 2003 had noticeably higher predicted disturbance levels than other years (Figure 5). On average, 22 % of disturbance (by area) occurred in the first two dates of each year. If these two dates are taken to represent winter disturbance, this equates to a mean of 1140 ha disturbed area per month between October and March, compared to a rate of 4316 ha per month from May to September (suggesting winter disturbance rates are approximately 26 % of those in the summer).

The majority of individual disturbance events were small in terms of area (mean patch size of 3.84 ha, standard deviation of 7.2 ha) with most (94 % of events or 70 % of total disturbed area) covering between 1 and 10 ha. A smaller number of larger disturbance events also occurred, with the largest covering an area of 1028 ha. 75 discrete disturbance events with areas of over 50 ha occurred during the period examined, accounting for 4 % of the total area disturbed. The percentage of the total area disturbed was not significantly different for areas classed as core habitat from those classed as secondary (t=1.046, d.f.=82, P=0.299), although mean percentage disturbed was slightly higher for secondary areas (3.56 % compared to 3.11 %).

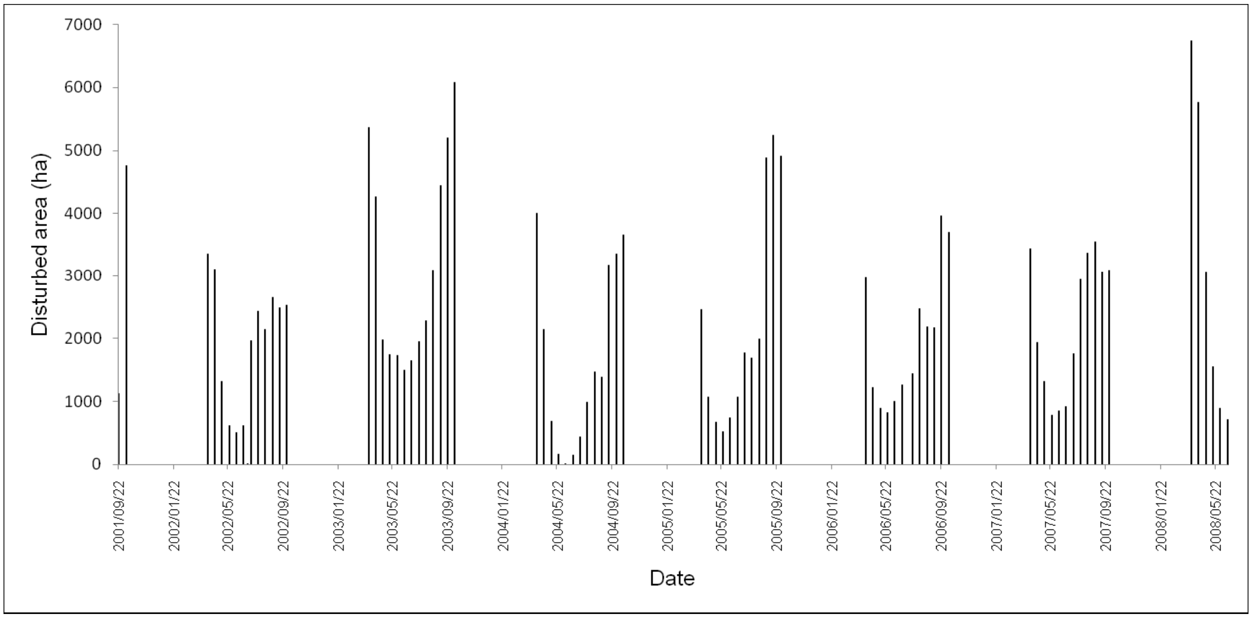


Figure 4: Total disturbed area within the grizzly bear study area by date. Dates are given as yyyy/mm/dd.

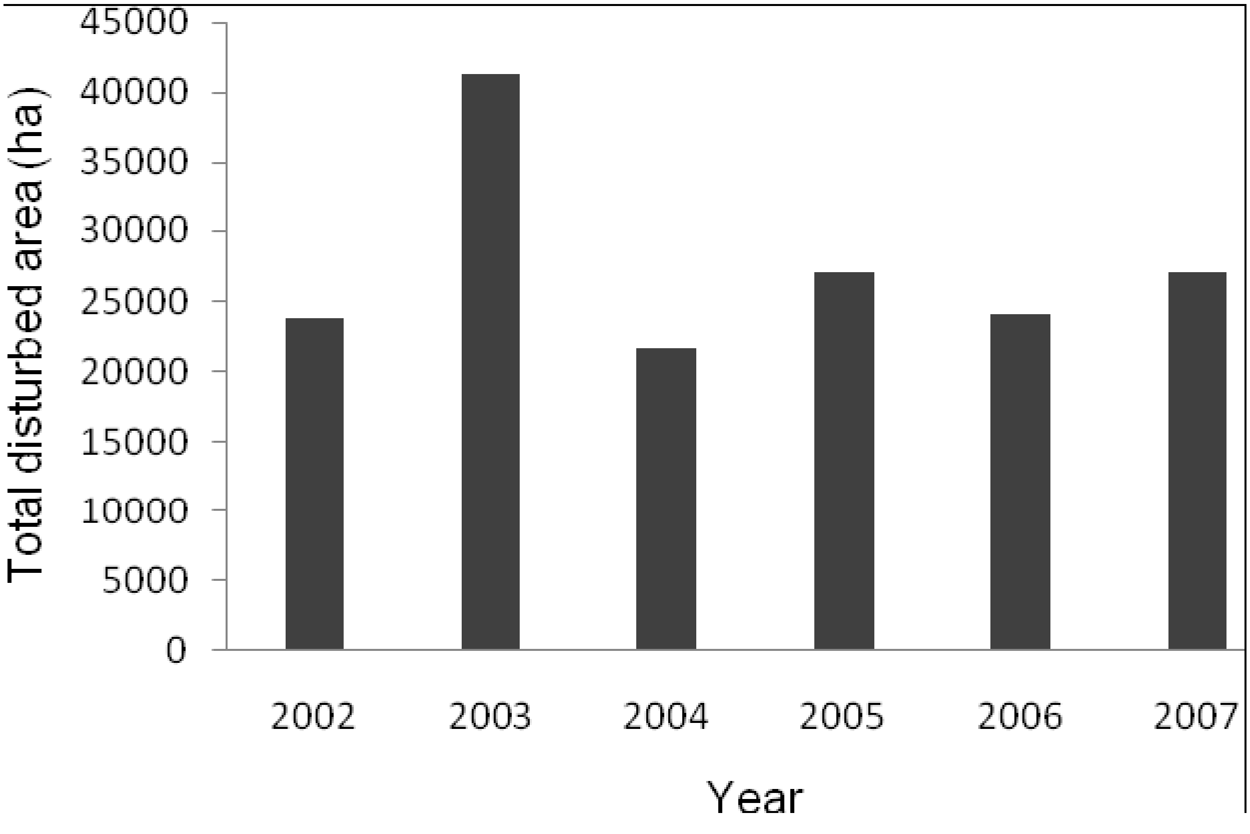


Figure 5: Disturbed area within the grizzly bear study area by year.

3.3 Disturbance patterns within the selected grizzly bear core and secondary habitat areas.

The selected core and secondary habitat areas (Figure 6), spanned a range of habitat types and exhibited a range of ecological and disturbance characteristics (Table 2). The units ranged from 36 to 87 % forested, with the least forested units typically being located furthest from roads and at high mean altitudes (for example Y103, the least forested unit, is, on average, 9784 m from the nearest road and at an altitude of 2149 m). All areas showed some evidence of disturbance during the previous decade (1990s) with the percentage of the area influenced ranging from 0.1 to 7.4 %.

Examples of disturbance sequences for some of the selected areas are presented in Figure 7. The large disturbed area in C118 corresponds to a burnt area, whilst a pattern more typical of harvesting activity is apparent in C123 and G10 (as well as S13, Y61 and to a lesser extent S6, not shown). G35 and L143 are relatively undisturbed during the period of the change sequence (as are L145A and Y103, not shown). Seasonal patterns of disturbance for many of the areas (for example, S13, S6, Y61 and Y103) follow the trend evident for the entire study area, with larger areas classed as disturbed during April (representing changes outside of the growing season) and in August and September (Figure 8). This seasonal trend is less evident in units G35, L143 and L145A, where disturbance levels are low overall and disturbance occurs largely early in the season.

Table 2. Characteristics of the selected focus core and secondary habitat areas. Percent disturbed in the 1990s is the percent of the total area.

Habitat area	Grizzly Bear Population Unit	Habitat type	Total area (ha)	Mean distance to roads (m)	Percent of unit forested	Percent disturbed in 1990s	Mean elevation (m)
C118	Clearwater	Core	39610	2565	47.8	1.83	1958
C123	Clearwater	Secondary	36010	606	77.1	0.10	1490
G10	Grande Cache	Secondary	73252	472	75.1	4.86	940
G35	Grande Cache	Core	33925	3914	70.7	7.36	1527
L143	Livingstone	Core	22755	877	79.5	1.28	1666
L145A	Livingstone	Core	29252	2666	25.2	3.10	2261
S13	Swan Hills	Core	57964	941	74.8	3.00	827
S6	Swan Hills	Secondary	42116	618	87.4	4.04	919
Y61	Yellowhead	Core	64849	570	76.3	4.26	1411
Y103	Yellowhead	Core	48929	9784	35.7	1.19	2149

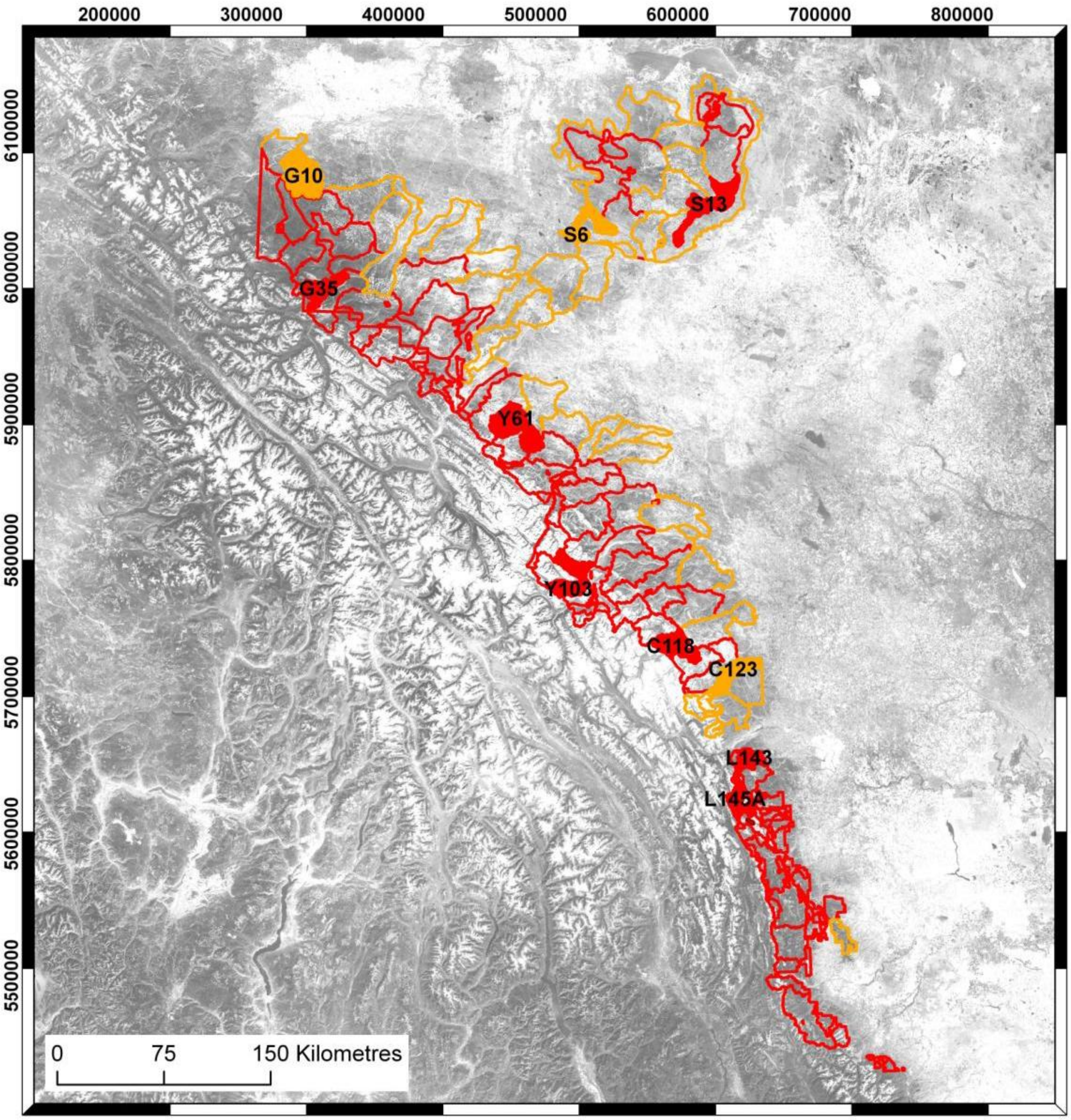


Figure 6: Map of core (red) and secondary (yellow) Grizzly Bear habitat areas showing the focus areas selected for in-depth analysis.

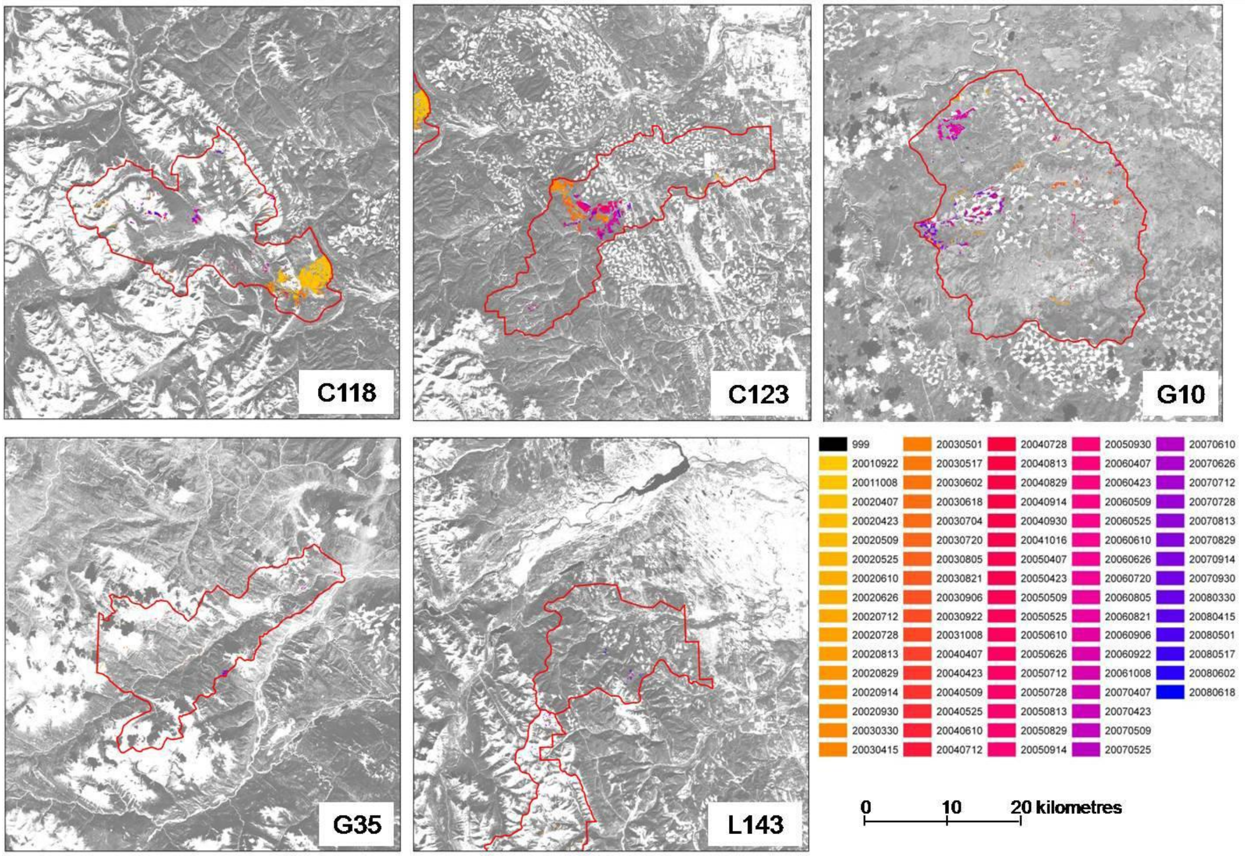


Figure 7: Pattern of disturbance from STAARCH for a subset of the selected Grizzly Bear habitat areas. Red lines represent habitat area boundaries.

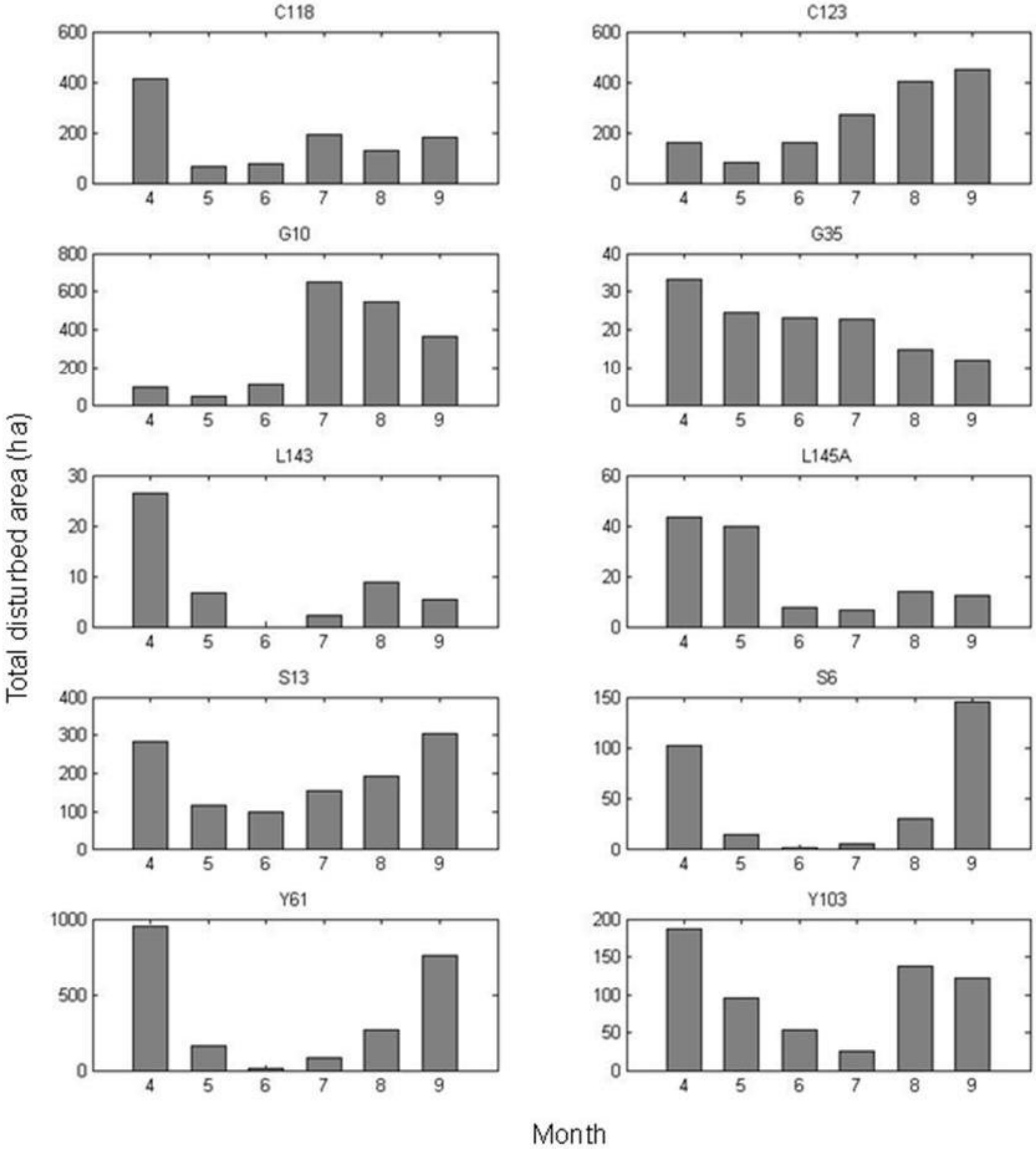


Figure 8: Distribution of disturbance by month (April – September) for focus habitat areas.

Disturbance events occurred within the areas during all years (2002-2007), with many areas experiencing highest disturbance in 2003 (C123, G35 (although at low levels overall), S6, S13) (Figure 9). Large areas of C118 were classed as disturbed in 2002 (and late 2001, not shown in

Figure 9) due to the Dogrib Creek Fire (September to October, 2001). Other areas show a general trend of increasing levels of disturbance late in the time-series (Y103, G10 and L143).

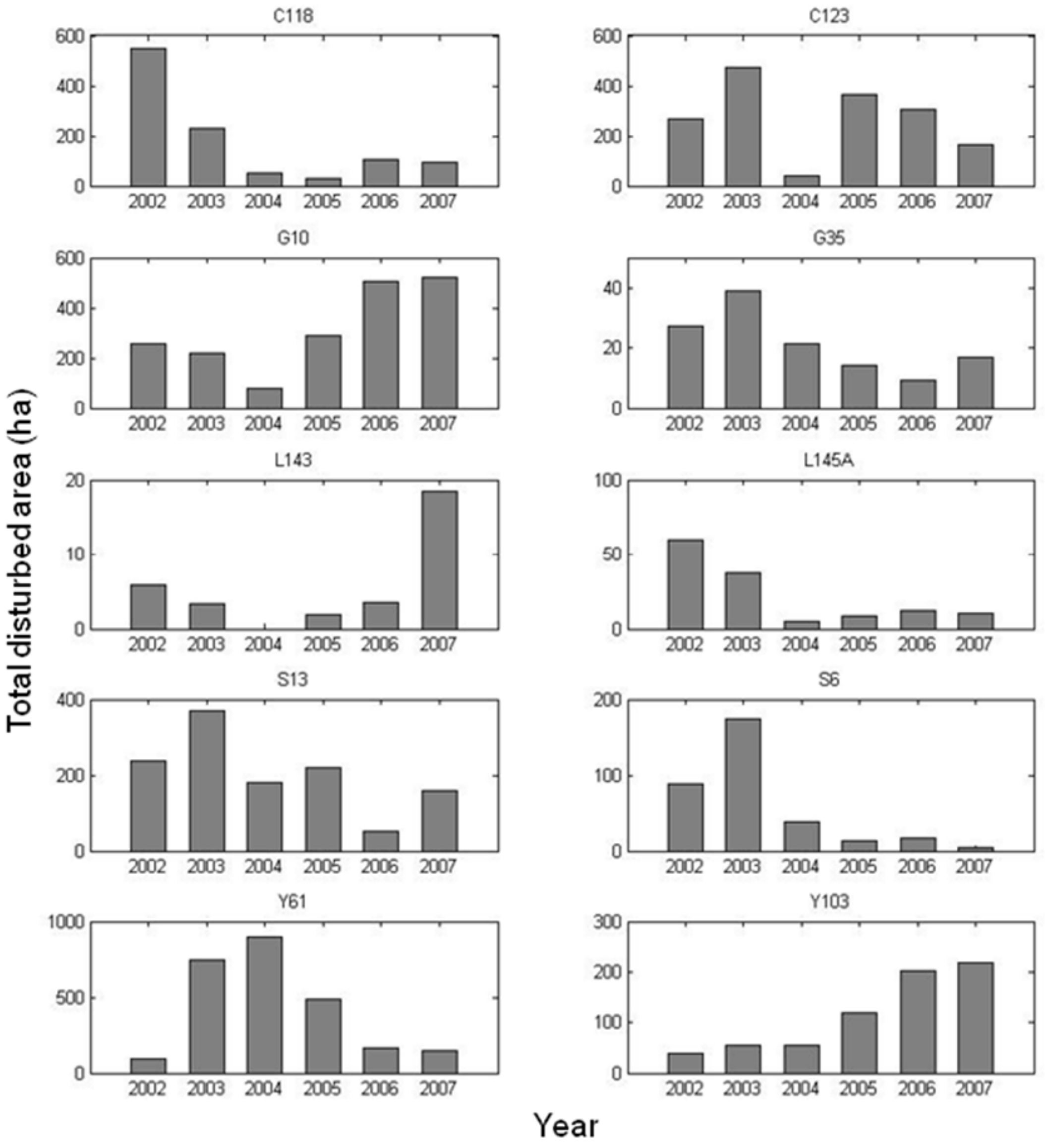


Figure 9: Distribution of disturbance by year (2002-2007) for selected core and secondary habitat areas.

Notable variation occurred between selected habitat areas in the percentage of the total area disturbed between 2001 and 2008 (from 0.26 % for L143 to 5.26 % for C118) (Table 3). Some areas that were significantly disturbed during the 1990s (Table 2), showed very low levels of disturbance from 2001-2008 (for example, S6 and G35), while others showed an increased level of disturbance (especially C118 and C123). L143 remained relatively undisturbed in both time periods, while the area disturbed in Y61 was high throughout, most likely due to continued harvesting activity (with peak levels occurring in 2004).

The average area covered by individual disturbance events (patches) was also variable (Table 3). The largest patches occurred in unit C118 (mean area of 6.68 ha and maximum of 787.8 ha), due to large burnt areas disturbed during a single bi-weekly period. Large patches also occurred in those units where significant harvesting appears to have occurred during the period (C123, G10, S13 and Y61), with G10 and Y61 also having a very large number of individual disturbance events (515 and 746, respectively). In general, both the percentage of the areas disturbed and the mean disturbance patch size increases as the mean distance of the areas from roads decreases and mean elevation decreases (Table 2); however, these trends are not statistically significant. Units G35, Y103, L145A and L143 are all relatively undisturbed with only small patches of disturbance occurring and are located at high elevation and relatively isolated from the road network. In contrast, the most disturbed areas (G10, Y61 and C123) are at low elevation and typically close to roads. The exception to this trend is C118, which was significantly disturbed by a fire, but is relatively remote, with an average elevation of 1958 m and mean distance to roads of 2565 m. This unit is also unique in having more complex patch shapes (area weighted mean shape index of 4.68) than other areas. Significant negative correlations occurred between the percentage of forest cover within the habitat area and the mean distance to roads (R=-0.66, P=0.037), and elevation (R=-0.84, P=0.002). Forest cover declined as elevation increased, with the road network also becoming less dense in these low forest cover areas.

Table 3. Disturbance characteristics (22nd Sept. 2001 – 18th June 2008) for the selected habitat areas.

Habitat area	% of total area disturbed	Number of disturbance events	Mean area of patches (ha)	Maximum patch size (ha)	Patch size standard deviation (ha)	Area weighted mean shape index
C118	5.26	312	6.68	787.8	45.84	4.68
C123	4.58	295	5.59	80.0	7.39	2.01
G10	2.72	515	3.87	79.5	5.49	2.07
G35	0.44	77	1.95	6.5	1.13	1.80
L143	0.26	27	2.16	6.3	1.46	2.11
L145A	0.50	73	1.98	6.8	1.12	1.75
S13	2.38	396	3.48	32.6	3.75	2.04
S6	0.83	111	3.16	17.7	3.03	1.89
Y61	4.48	746	3.89	33.7	3.93	1.91
Y103	1.45	304	2.33	13.8	1.78	1.94

4. DISCUSSION

4.1 Accuracy of predicted dates of disturbance

This paper describes the disturbance patterns throughout a large Grizzly bear study area located in western Alberta, as derived from the STAARCH algorithm. High temporal resolution, bi-weekly, disturbance sequences were generated over an 8 year time period across 14 Landsat path rows at a 30 m spatial resolution. The validation approach shows that the algorithm was able to predict dates of stand replacing disturbances in the landscape with a mean overall accuracy of 62 %. Accuracy was somewhat lower than in a previous validation of the algorithm (87-89 % accuracy, Hilker et al., 2009b). This difference is most likely a result of the increased time period and much larger spatial extent of this study, as well as the larger variety of land cover and disturbance types likely to occur in the validation scenes (the validation was not restricted solely to forest). However, it should be noted that due to the large area under investigation and a lack of comparable ground data, it was only possible to validate the year of disturbance, whilst bi-weekly predictions were made under the assumption that if the year is correct, the bi-weekly disturbance period is also correctly assigned. This is a reasonable assumption for stand-replacing disturbances, where resulting spectral changes are likely to outweigh seasonal reflectance changes, as the underlying sensor properties and prediction algorithm remain the same at a yearly or bi-weekly interval (Hilker et al., 2009b). The data to assess actual disturbance date is not readily available, especially in the sample sizes desired.

The prediction accuracy for the DoD also varied with the size of the disturbance polygon. This is to be expected, as changes impacting larger areas will have a greater influence on the spectral characteristics of MODIS pixels and DoDs will therefore be easier to detect. For disturbances of below 5 ha, dates should be used with caution. The accuracy of predicted DoD for Area B was lower than that for Area A. This was largely due to the influence of the Tokumm-Verendrye fire in Kootenay National Park, which burned over 5000 ha of the validation area between July and September 2003, but was dated slightly earlier (May-July) and wrongly assigned to the previous annual period. The smoothing applied to the disturbance index curves (as described in section 2.1) potentially reduces the precision with which the exact bi-weekly period of disturbance can be identified, as disturbance predictions are based on the input of more than one 8 day MODIS composite. However, the smoothing does also reduce the likelihood of incorrect DoDs being assigned due to noise in individual MODIS scenes (such as variation resulting from cloud cover). One further limitation of STAARCH, besides cloud contamination, is its restriction to observations made only during the growing season, which cause winter disturbances to be assigned to the first cloud free spring observation (Hilker et al., 2009b). This unavoidable limitation, which was implemented to avoid prediction inaccuracies due to extensive snow cover, is less relevant in the context of mapping grizzly bear habitats due to the dormancy of the bears. For other species that remain active during the winter, this may be a greater consideration.

It was not a focus of this study to validate the spatial extent of disturbances identified by the STAARCH algorithm, as reference disturbance data at comparable spatial resolutions and temporal and spatial coverages were not available. However, a smaller-scale application of the STAARCH algorithm in the same region (Hilker et al., 2009b) demonstrated that the Landsat-based disturbance detection applied in STAARCH successfully detected 93 % of the total disturbed area when compared to a validation data set. When applied over a larger area (western Alberta), as in this study, some errors will result where cloud or snow cover is present in the satellite imagery. Cloud cover within the Landsat imagery could result in areas of disturbance not being detected by the algorithm (the ground surface must be visible in both the start and end Landsat images for changes to be detected). In a few cases (<0.5 % of the disturbed area), very frequent cloud in the MODIS imagery prevented a DoD from being assigned, even though a change was detected in the Landsat. Despite the limitations described above, it is demonstrated here that the STAARCH algorithm allows the production of an accurate, high temporal (bi-weekly) and spatial (30 m) resolution disturbance sequence over a very large area, providing information of significant importance for resource management, conservation and wildlife research.

4.2 Disturbance patterns in western Alberta

4.2.1 Temporal patterns

As the STAARCH algorithm was only implemented over the growing season (April to September), disturbances occurring outside this period are automatically assigned to be the first observation of the following growing season (either the first date or the date of the first cloud-free MODIS scene), adding to any disturbances actually occurring within these bi-weekly periods. As is apparent in Figure 4, significant areas of disturbance did occur outside of the growing season (on average, 22 % of total disturbed area), leading to DoD for large areas being assigned to the first few bi-weekly periods. Caution should therefore be taken in inferring rates of disturbance for periods early in the season and these periods are generally better viewed as identifying disturbance events over the proceeding winter, such as winter harvesting or avalanche disturbance. However, the rate of disturbance over winter months was significantly lower than that during the summer, suggesting human activity such as road building and harvesting is reduced, while the likelihood of fire in winter will also be low (Beverley et al., 2009).

Generally it was observed, that over the entire region and for many of the focus areas, disturbance levels peaked towards the end of the growing season, in late August and September. These represent the driest months, during which harvesting activity and the construction of roads and well-sites is likely to be underway. Fire risk may also be greatest during these months due to the drier conditions. These results do contrast to some extent with those of Stocks et al. (2003) who demonstrated that over the period 1959 to 1997, for the whole of Canada, the largest areas burned in June and July, predominantly due to lightning-caused fires. However, in the more southern regions of Canada the fire season is both longer (Stocks et al., 2003) and more likely to be human-caused and actively controlled than in northern regions. Beverley et al. (2009) also demonstrated that the majority (77%) of lightning-caused fires in the Swan Hills area of the Alberta foothills occurred between June and mid-August, but that human-caused fires begin in April and peak in early May. These results suggest that if fire was the main driver of the observed seasonal trends in disturbance then the peak in disturbed area should occur earlier in the season rather than in September. Similar data were not readily available for other disturbance types such as harvesting. To fully determine the cause of the seasonal trends it would be necessary to categorise the type of each disturbance event, which is beyond the scope of the current study but is the focus of ongoing research effort (Hilker et al., 2010).

Particularly high rates of disturbance were predicted as occurring during 2003. Close to, but outside of the core and secondary habitat areas that are the focus of this study, three large fires occurred during 2003 (based on Large Fire Database (Stocks et al., 2003)), including the Tokumm-Verendrye fire in Kootenay National Park which burned over 17000 ha (Parks Canada 2008). If drought conditions were present, making western Alberta susceptible to fires, it is possible that a number of smaller fires (below 200 ha and therefore not recorded in the Large Fire Database) also occurred within the core and secondary habitat areas during 2003, perhaps accounting for the increased disturbance rate. There is no overall trend of increasing disturbance levels through the time period considered in this study, although disturbance levels do increase over time for a number of the individual core and secondary habitat areas studied in detail (G10, L143 and Y103). Increasing disturbance rates towards the end of the period may have been expected as a result of growing forest disturbance by mountain pine beetle

(*Dendroctonus ponderosae* Hopkins). However, the beetle only reached Alberta in significant numbers from 2006 and typically influences individuals or patches of trees (Safranyik et al., 2010). The direct influence on spectral response in the Landsat imagery is therefore unlikely to be sufficient, at least in the early stages of infestation, to be detected as disturbed area (Wulder et al., 2006). Mitigation harvesting activities as a result of the outbreak should be detected in the change sequence, but were unlikely to represent a large enough area over the study area as a whole to influence the overall temporal trend, as beetle infested trees were generally limited to the north-western most area in 2007 (Safranyik et al., 2010). This mitigation harvesting may account for the increased disturbance in habitat area G10, which is located in this region.

4.2.2 Spatial patterns

The majority of disturbance events were small (<10 ha), suggesting only limited areas are cleared in each bi-weekly period by harvesting or other disturbances such as road construction. However, as is apparent in Figure 7, areas of disturbance were frequently not isolated and progressive clearance of adjacent areas may result in larger areas of disturbance over the course of several months or years. Further research is needed to characterise these processes of disturbed area expansion and merging. However, such a pattern is consistent with the predominant form of forestry in the area, which utilises a two-pass harvest design with small clear-cuts of less than 40 ha arranged in a checkerboard pattern within a stand (Nielsen et al., 2008). Oil and gas exploration activities such as well-sites or seismic cut-lines also generally influence small discrete areas and will therefore add to the predominance of small disturbance events.

The overall rate of disturbance, 0.4 % of total area per year, suggests a return interval for stand-replacing scale disturbance events of around 250 years. However, this figure applies to the total area rather than the forested area, where disturbance events might be expected to be concentrated. When only forested area is considered (therefore assuming all disturbance is within forest areas), the rate is 0.67 % or an interval of 150 years. Andison (1998) estimated a natural fire return interval in the Alberta foothills region of 80-100 years, but noted that in 1995, based on forest age-class distributions, disturbance may be overdue when compared to the natural baseline, as a result of intensive fire suppression and low harvesting rates. Fire suppression may therefore account for the higher return interval observed during the 2001-2008 period. However, although disturbance levels may not be as high as historic rates, the magnitude of the impact of permanent land cover changes, such as road construction and mining, on wildlife habitat may be significantly greater and longer lasting.

Individual core and secondary areas had distinctly different spatial and temporal disturbance patterns and experienced variable levels of natural and anthropogenic disturbance. Some remained relatively undisturbed throughout the period. The high variability highlights the importance of examining disturbance patterns over large areas, as reliance on small-scale field-based studies could lead to misleading conclusions. In some cases (such as S6 and G35) high disturbance levels in the 1990s, most likely due to harvesting, declined to relatively low rates from 2001-2008, suggesting forest harvesting activities within these areas decreased. However, disturbance rates in other areas (such as C123) increased significantly, with large areas influenced by harvesting. The temporal distribution and patch size of disturbance events appears to be influenced by the dominant disturbance type, with small patches resulting from harvesting and much larger areas being disturbed in a single bi-weekly period where wildfires occurred. The least disturbed areas were generally located in inaccessible, isolated areas (away from road networks) and at high elevations. These areas contain large proportions of core grizzly bear habitat in conservation areas. However, relationships between potential indicators of disturbance such as road densities and observed disturbance levels in the focus habitat areas were weak. There was also no significant difference between disturbance rates in core and secondary units (across the entire study area), which were designated based primarily on road density. Relationships were found between the percentage of the landscape area that was forested and the mean distance to the nearest road and elevation. Highly forested habitat areas were typically located at low elevations and had high densities of roads. Very high elevation areas are more likely to be dominated by barren areas or open vegetation that may be less susceptible to disturbance. Co-variance between such parameters makes determining the drivers of disturbance patterns difficult, but suggests that wildlife species restricted to highly forested areas may be at greatest risk from human activities, due to the high accessibility of such areas. Such patterns require further investigation.

4.2.3 Impacts on grizzly bear habitat use and mortality

In past studies, grizzly bears have been shown to be attracted to disturbed areas and to select them preferentially, especially following emergence from the den (Berland *et al*. 2008, Nielsen *et al*. 2004a). Grizzly bear foraging behaviour varies during the growing season, with three distinct phases identified (hypophagia (1st May to 15th June), early hyperphagia (16th June to 15th August) and late hyperphagia (16th August to 15th October)) (Berland *et al*. 2008). Munro *et al*. (2006) and Berland *et al*. (2008) assigned foraging behavioural categories to each of those phases, which in turn are linked to certain habitat requirements and vegetation types, including closed forest, regenerating forest and open areas. Bears may therefore benefit from home ranges containing a mosaic of different forest seral stages and land cover types, with disturbed areas especially favoured during hypophagia (Berland *et al*. 2008, Nielsen *et al*. 2004b). The disturbance patterns described in this study, with a pre-dominance of small area disturbance events at an overall rate below that likely to occur historically, could potentially benefit generalist wildlife species such as grizzly bears (Nielsen et al., 2008). However, such benefits are very likely to be outweighed by higher mortality due to the increased levels human-bear conflict and vehicle collisions resulting from human activity within core and secondary forest habitat (McLellan, 1998, Nielsen et al., 2008).

The seasonal timing of disturbance events was concentrated in the late hyperphagia phase. The implications of this and of spatial patterns in disturbance for bear movements and habitat use are difficult to determine without considering the type and nature of disturbance events explicitly. The impact of road construction or mining will be very different to temporary cover changes due to harvesting activities or avalanches, both in terms of impact on available forage resources and risk of mortality when bears utilise such areas. Ongoing research is therefore examining the potential for identifying and attributing the cause of disturbance, using patch characteristics extracted from the change sequence (for example, examining whether burnt areas have more complex shapes than harvested areas and if disturbances from road creation are more elongated). This is a non-trivial task that was beyond the scope of this study, but would allow more detailed analysis of the influence of disturbance agents on wildlife habitat and behaviour through the combination of seasonal disturbance information with high resolution data on wildlife movements, to provide models of habitat use that can be applied in determining conservation and forest management objectives.

5. CONCLUSION

The STAARCH algorithm has significant potential for providing disturbance information over extensive areas, at a high spatial and temporal resolution, and was implemented here to produce a unique disturbance sequence over a large area of western Alberta, Canada. Dates of disturbance events, to a bi-weekly period, can be predicted from blending of Landsat 5 TM and MODIS imagery with accuracy increasing with the size of the disturbance. The validated disturbance sequence allowed the characterization of patterns of change, in terms of annual and seasonal trends and patch size distribution, across western Alberta grizzly bear habitat areas, revealing significant disturbance levels throughout the period, highly variable disturbance patterns at the scale of grizzly bear home ranges and increased disturbance rates late in the growing season.

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