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Cumulative Effects of Environmental Change on Culturally Significant Ecosystems in the Inuvialuit Settlement Region

William Tyson,[1] Trevor C. Lantz,[1,2] and Natalie C. Ban[1]

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ABSTRACT. The Inuvialuit Settlement Region (ISR) in the western Canadian Arctic is experiencing environmental changes that affect subsistence harvesting practices and are of concern to local communities. In order to assess the impacts of multiple disturbances on culturally important ecosystems in the ISR, we created a cumulative disturbance map that represents relative intensity of terrestrial disturbances across the study region. We then assessed the relative level of environmental disturbance in important harvesting areas and management zones. Subsequently, we modeled nine future disturbance scenarios that included combinations of increased human impacts and more frequent and widespread wildfires. Using the conservation planning software Marxan, we assessed the potential to conserve large, contiguous areas of unaffected harvesting lands across all scenarios. Our results show that important management zones, wildlife harvesting areas, and community planning zones are all affected by environmental disturbances. Marxan optimizations show that existing disturbance levels create thresholds for current conservation potential and indicate that future disturbances will further limit conservation potential. These results suggest that conservation planners in the region must take steps to anticipate more widespread natural and human-caused disturbance in the ISR and work to maintain large contiguous landscapes that can support wildlife harvesting in the face of ongoing environmental disturbance.

Key words: Inuvialuit Settlement Region; cumulative effects; environmental change; Marxan; wildlife harvesting; conservation planning; climate change; Arctic

RÉSUMÉ. La région désignée des Inuvialuit (RDI) dans l'ouest de l'Arctique canadien connaît des changements environnementaux qui ont des incidences sur les méthodes de récolte. Ces incidences sont également à la source d'inquiétudes chez les collectivités de la région. Afin d'évaluer les incidences de perturbations multiples sur les écosystèmes de la RDI revêtant une importance culturelle, nous avons créé une carte des perturbations cumulatives représentant l'intensité relative des perturbations terrestres dans toute la région visée par l'étude. Ensuite, nous avons évalué le degré relatif de perturbation environnementale dans les zones de gestion et les aires de récolte importantes. Par la suite, nous avons modélisé neuf scénarios de perturbations futures tenant compte d'un ensemble d'incidences accrues attribuables à l'être humain et de feux irréprimés plus fréquents et généralisés. À l'aide du logiciel de planification de la conservation Marxan, nous avons évalué la possibilité de conserver de grandes zones contiguës de terres de récolte intactes dans tous les scénarios. Nos résultats montrent que les zones de gestion importantes, les aires de récolte d'animaux sauvages et les zones de planification communautaire sont toutes touchées par les perturbations environnementales. Les optimisations réalisées à l'aide de Marxan montrent que les degrés de perturbation existants créent des seuils pour potentiel de conservation actuel et indiquent que les perturbations futures auront pour effet de restreindre le potentiel de conservation. Ces résultats suggèrent que les responsables de la planification de la conservation de la région doivent prendre des mesures pour prévoir des perturbations généralisées de nature humaine et naturelle dans la RDI et travailler dans le but de maintenir de grands paysages contigus qui peuvent permettre des récoltes d'animaux sauvages à la lumière des perturbations environnementales continues.

Mots clés : région désignée des Inuvialuit; effets cumulatifs; changement environnemental; Marxan; récolte d'animaux sauvages; planification de la conservation; changement climatique; Arctique

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INTRODUCTION

Intensifying human impacts on the environment, combined with a changing climate, are dramatically altering ecosystems worldwide (Steffen et al., 2015). Habitat loss and fragmentation due to human development are well-established drivers of biodiversity loss (Noss et al., 1996; Debinski and Holt, 2000), and the interactions between these disturbances and a changing climate are accelerating ecological transformations (Brooke et al., 2008; Garcia et al., 2014). This pattern is particularly relevant in the Arctic, where increases in air and ground temperatures are well

[1] School of Environmental Studies, University of Victoria, PO Box 1700 STN CSC, Victoria, British Columbia V8W 2Y2, Canada
[2] Corresponding author: tlantz@uvic. ca

above the global average (Serreze et al., 2000; ACIA, 2005; Burn and Kokelj, 2009), and human development is occurring in previously unaffected ecosystems (Johnson et al., 2005; Kiggiak – EBA Consulting Ltd., 2011). On the surface, individual changes may seem small and insignificant, but when these are combined with other disturbances, the cumulative effects of environmental perturbations can significantly alter ecosystem function (Spaling, 1994). Cumulative environmental impacts are often measured over large spatial and temporal scales and refer to the accumulation of current, previous, or near future disturbances that affect valued ecosystem components (Hegmann et al., 1999).

Cumulative landscape change has the potential to affect communities that are linked to their local environment through subsistence harvesting (Berkes and Jolly, 2001; Parlee et al., 2012; Shanley et al., 2013), particularly in Arctic indigenous communities, where a high reliance on local landscapes for food security intensifies the impact of environmental change on human health and community well-being (Corell, 2006; Furgal and Seguin, 2006). An emerging sub-field of cumulative effects research seeks to understand the impacts of environmental change on culturally valued ecosystem components (Ehrlich and Sian, 2004; Mitchell and Parkins, 2011; Parlee et al., 2012; Spyce et al., 2012). However, to date very little research has explored the overlap between cumulative environmental change and landscape-scale patterns of subsistence use (Mitchell and Parkins, 2011).

To address this gap, we explored the cumulative effects of multiple environmental disturbances on culturally important ecosystems in the Inuvialuit Settlement Region (ISR) in the western Canadian Arctic. Ecosystems in the ISR provide critical habitat for a suite of marine and terrestrial species (Yukon Ecoregions Working Group, 2004; Ecosystem Classification Group, 2009, 2012). This region is also the traditional territory of the Inuvialuit, who rely on the land for hunting, trapping, whaling, and fishing (Usher, 2002; Alunik et al., 2003; Furgal and Seguin, 2006). The ISR has also felt the impact of industrial development associated with hydrocarbon exploration and is experiencing environmental transformations associated with climate change (Burn and Kokelj, 2009; Pearce et al., 2011). The impacts of these perturbations have raised concern among residents, many of whom depend on the land for subsistence use, about the ecological and cultural effects of landscape change (Bennett and Lantz, 2014). However, we are not aware of research that quantifies the cumulative impact of environmental change on culturally significant landscapes in the ISR.

To investigate the cumulative effects of environmental change on wildlife harvesting areas in the ISR, as well as the vulnerability of these areas to future disturbance, we quantified the amount of environmental change that has occurred in culturally significant ecosystems across the mainland ISR over the past 50 years. We also assessed future impacts by developing nine scenarios of increased disturbance and used Marxan software (Ball et al., 2009) to explore the impact of increasing environmental disturbance on the amount of contiguous habitat and the spatial configuration of intact wildlife harvesting areas. This research was one component of a larger initiative exploring the cumulative impacts on culturally important landscapes, which also involved interviews with knowledgeable hunters (Tyson, 2015) to examine the effects of a changing Arctic on hunting and trapping in the region. While the research presented here did not take place in direct consultation with the Inuvialuit Government, it has the potential to inform ongoing research, monitoring, and management efforts in the ISR.

METHODS

Study Area

This study focuses on the southern ISR, which we define as the mainland portion of the region (Fig. 1). Vegetation structure in this region changes with increasing latitude and can be divided into four broad zones: high boreal forest, low subarctic, high subarctic, and low Arctic tundra (Timoney et al., 1992). The northern portion of the ISR is characterized largely by shrub tundra, while subarctic boreal forest extends through the southern portion of the Mackenzie Delta and southeastern ISR (Burn and Kokelj, 2009; Ecosystem Classification Group, 2012). Alpine tundra dominates the Richardson Mountains to the west (Yukon Ecoregions Working Group, 2004). There are four small communities in the study area: Inuvik (Pop. 3463), Aklavik (Pop. 633), Tuktoyaktuk (Pop. 854), and Paulatuk (Pop. 313) (Statistics Canada, 2011). Beyond the municipal boundaries of these communities, human impacts to the land stem largely from a history of hydrocarbon exploration in the region (Burn and Kokelj, 2009). To quantify the cumulative impact of natural and human-caused disturbance in the region, we applied a grid of 25 km^2 cells over the entire planning region (Fig. 1). This grid divided the 131 331 km^2 area into 5815 unique planning units (PUs). While most units were 25 km^2, instances where the grid overlapped the edge of the study area created some planning units of irregular shape and size. This irregularity was accounted for in all calculations.

DISTURBANCES

Current Disturbances

To assess cumulative impacts to terrestrial ecosystems in the region, we obtained spatial data on disturbances from a variety of sources and used them to estimate the proportion of each PU directly affected by the disturbance. Seismic lines were mapped using polyline coverage available for both the Yukon (Yukon Highways and Public Works, 2014) and Northwest Territories (WWF, 2002). We used air photos with a resolution of ~0.5 m from the Tuktoyaktuk

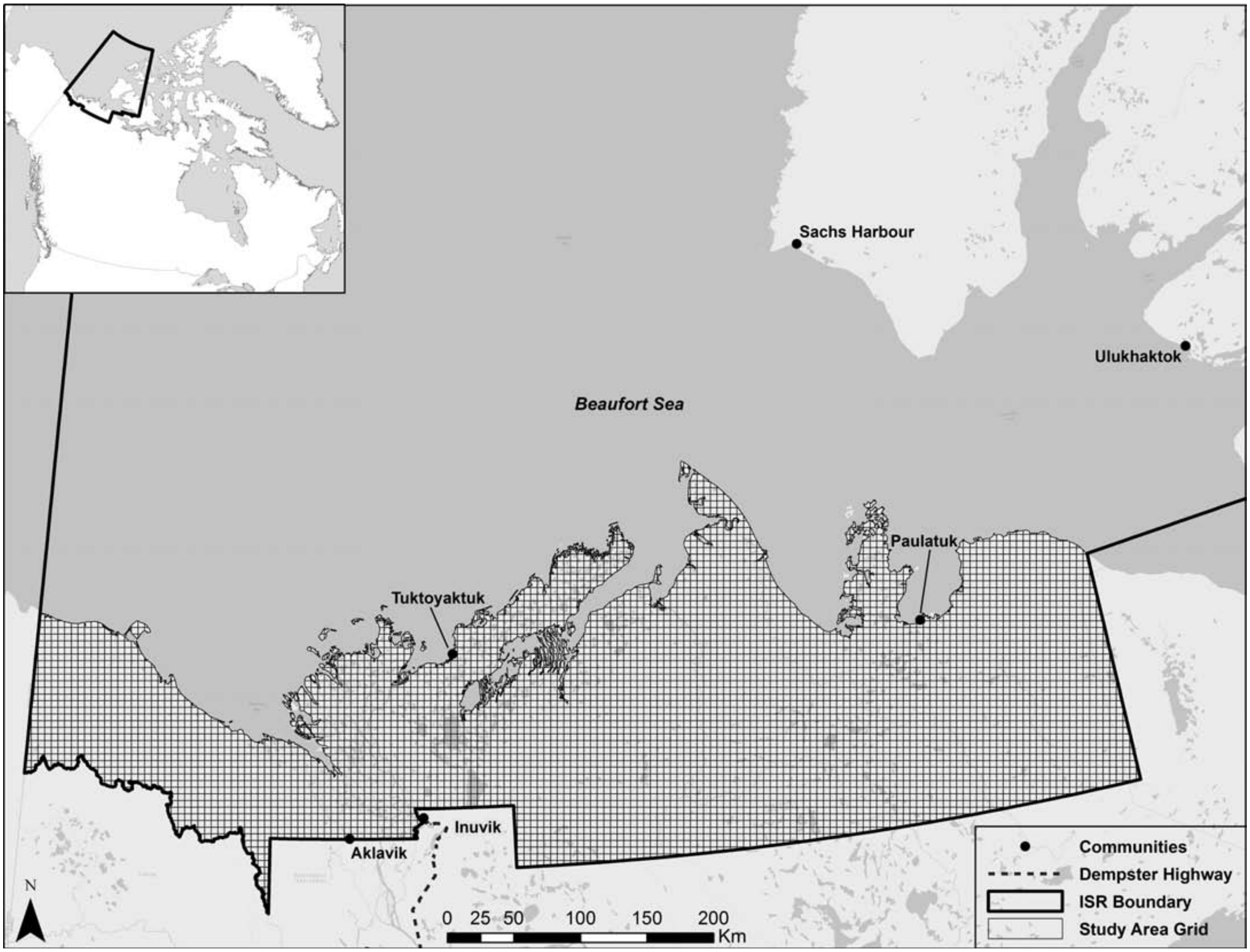

FIG. 1. Study area map. We defined our study area as the mainland ISR, which covers an area of 131 331 km^2. This area includes the communities of Inuvik, Aklavik, Tuktoyaktuk, and Paulatuk. We applied a grid of 25 km^2 cells to the region, creating 5815 unique planning units (PUs), which were used to tabulate levels of environmental disturbance.

Coastlands (NWT Geomatics, 2004) to estimate the width of a typical seismic line. Subsequently, we buffered polylines to create shapefiles that extended 3.5 m on either side of the line features, the average width of seismic lines we measured in air photos. Similarly, to map the Ikhill Pipeline, which extends from Inuvik to a gas field approximately 49 km to the north, we used aerial imagery to determine that the right of way typically extends 7.5 m on either side of the pipeline (NWT Geomatics, 2004). We combined aerial imagery of Inuvik, Tuktoyaktuk, Aklavik, and Paulatuk (NWT Geomatics, 2004) with data on municipal boundaries (Government of Canada, 2010) to estimate the spatial footprint of each settlement and used these data to delimit the footprints of each settlement as the maximum north, east, south, and west extent of community infrastructure. Point locations of drilling mud sumps (locations of buried drilling fluids and other waste from resource exploration) were obtained from the Environmental Studies Research Fund sumps database (INAC, 2005). To estimate the total area of each PU affected by sumps, we multiplied the number of sumps per planning unit by the mean sump area visible in aerial imagery (22.3 ha) (NWT Geomatics, 2004).

The area of each PU affected by natural disturbances was also estimated using GIS data. Historic wildfires were mapped using the Yukon and Northwest Territories historic fire databases (WWF, 2002; Department of Community Services, 2014). We mapped the area affected by a severe storm surge along the Beaufort coast by using data on vegetation change presented in Lantz et al. (2015). The footprint of retrogressive thaw slumps (areas of ground subsidence and erosion due to permafrost thaw) in each PU was estimated using a broad-scale map of slump density in the NWT (Segal et al., 2016). This dataset portrays the density of slumps in 225 km^2 cells as no slumps, low density (1 – 5), medium density (6 – 14), or high density (15 or more). To use these data to estimate slump coverage in each PU, we assumed that, on average, low-density grid cells contained three slumps, medium-density grid cells contained 10

TABLE 1. Percent of the different landscape zones affected by fires in three scenarios created to model wildfire frequency over the next 50 years. Simulation 1 is the baseline scenario, in which fire rates in each zone remain constant. Simulations 2 and 3 assume that increasing fuel loads, warming temperatures, and more frequent lightning will yield disturbance regimes similar to those in lower-latitude vegetation zones, with fire rates increasing in a stepwise manner.

Fire simulation	High boreal	Low subarctic	High subarctic	Low Arctic
1 (Baseline)	20	3.7	0	0
2 (Moderate)	20	20	3.7	0
3 (High)	20	20	20	3.7

slumps, and high-density grid cells contained 20 slumps. We then multiplied the number of slumps in each cell by the mean slump size in the region (3.02 ha) (Segal et al., 2016). This produced an estimate of the total area disturbed by slumps in each 225 km^2 grid cell. The percentage of each 225 km^2 grid cell affected by slumps was then attributed to every 25 km^2 PU that occurred within its boundary. In instances where a 25 km^2 PU was split by the boundary of multiple 225 km^2 grid cells, the 225 km^2 grid cell that contained the largest portion of the PU area was used to determine the percentage of PU affected by slumps.

Future Disturbances

To explore the impact that more frequent wildfires and increasing industrial development might have on the footprint of disturbances in the region, we generated spatial data representing scenarios of increased industrial activity and wildfire over the next 50 years. We restricted the modeling of future human impacts to either development that is already in progress or potential development that has publicly available plans. This approach limited our modeling to an all-season road that is currently being built from Inuvik to Tuktoyaktuk (Kiggiak – EBA Consulting Ltd., 2011); the proposed route of the Mackenzie Valley Pipeline, which enters the ISR near Inuvik and runs northwest to the Beaufort Sea (Joint Review Panel, 2010); and an area of existing mineral claims near Paulatuk (WWF, 2002). The future road was mapped at a width of 20 m on the assumption that it will be similar in size to the Dempster Highway (Gill et al., 2014). The pipeline was mapped by applying a right of way with the same width as the Ikhill Pipeline. To simulate the impacts of future mineral exploration in the Paulatuk area, we used the boundaries of existing mineral claims in the region (WWF, 2002). In the absence of data on the level of planned development, we modeled a scenario in which mineral extraction had direct impact on approximately 20% of the area in each PU affected.

To simulate future natural disturbances, we focused on wildfire because it can be modeled in a systematic fashion on the basis of historical fire rates (WWF, 2002; Department of Community Services, 2014) and known vegetation zones (Timoney et al., 1992). Although other types of ecological disturbances are likely to increase across the ISR (Fraser et al., 2014; Lantz et al., 2015), we chose to limit the scope of our modeling to fire because simulation was relatively straightforward and yielded scenarios ranging from low to high disturbance. The spatial extent of future wildfire was estimated by generating disturbances using the Geospatial Modeling Environment (GME) software (Beyer, 2014). The first step in this process involved parameterizing GME to simulate fires with a size and frequency that were consistent with historical wildfires in each of the vegetation zones in the region (WWF, 2002; Department of Community Services, 2014). We first calculated the size and density of historic wildfires in the high boreal, low subarctic, high subarctic, and low Arctic vegetation zones described by Timoney et al. (1992). Using the spatial boundaries for each of these vegetation zones (Timoney et al., 1992) and data on historical fire frequency (WWF, 2002; Department of Community Services, 2014), we adjusted the frequency of ignition, the rate of spread, and the time that a fire was active on the landscape until GME yielded outputs that mimicked the percentage of area disturbed by fire over the past 50 years in each vegetation zone (online Appendix 1: Table S1).

We then created three "future fire" scenarios intended to reflect the impacts on fire frequency of rising air temperatures (Serreze et al., 2000; ACIA, 2005) and increasing fuel accumulation (Lantz et al., 2013; Fraser et al., 2014). Scenarios were based on the assumption that the future size and density of fires in a given zone would be similar to the patterns now common in the vegetation zones immediately to the south (Table 1). The Mackenzie Delta was excluded from fire simulations because the high density of rivers and lakes limits the potential for large or frequent fires (Burn and Kokelj, 2009). To simplify our model, we chose not to increase rates of fire in the boreal forest zone of our study area, which is at the northern limit of the biome and comprises only a small percentage of our study area, because we were primarily concerned with changes to Arctic ecosystems. Consequently, given the forecasted changes in fire frequency in this biome (de Groot et al., 2013), our scenarios in the boreal portion of the study area should be viewed as conservative.

Using these data layers, we constructed nine future disturbance scenarios that involved combinations of fire and anthropogenic disturbance (Table 2). In each future scenario, current disturbances were combined with potential future disturbances to represent a range of possible disturbance levels over the next 50 years. The modeled intensity of each disturbance and its persistence on the landscape are described in the following section.

Weighting

The intensity of a disturbance's environmental impact varies according to the ecological variable being measured, the nature of the disturbance, the ecosystem component(s)

TABLE 2. Scenarios based on combinations of current and future disturbances. All future disturbance scenarios included current disturbances and the simulated impacts of more widespread fire or anthropogenic disturbance. Disturbance intensity increases in each scenario with the introduction of either increased fire occurrence or increased human activity in the study area.

				Anthropogenic disturbance			Fire			
	Scenario	Thaw slumps Existing	Storm surge Existing	Existing	Planned	Potential	Historic	Baseline	Moderate increase	Large increase
Current	1	X	X	X			X			
Future	2	X	X	X				X		
	3	X	X	X	X			X		
	4	X	X	X	X	X		X		
	5	X	X	X					X	
	6	X	X	X	X				X	
	7	X	X	X	X	X			X	
	8	X	X	X						X
	9	X	X	X	X					X
	10	X	X	X	X	X				X

it affects, and the conditions of the landscape on which it occurs (Duinker et al., 2013). There is no standard method for weighting disturbances on the basis of their intensity and frequency, and cumulative effects research typically weights disturbances differently depending on the ecosystem component in question (Johnson et al., 2005; Gunn et al., 2011; Raynolds et al., 2014). We developed a weighting scheme that accounts for differences in 1) the impact that disturbances have on vegetation structure, soils, and ground temperature (disturbance severity) and 2) the time it takes to recover following disturbance (recovery time). This relative scheme was developed using existing data on the impacts of disturbances on vegetation, soils, and permafrost conditions (Table 3).

Disturbances were weighted in relation to each other by multiplying a severity score by a recovery score for each disturbance type (Table 3). Severity scores ranged from 1 (minimal ecological alteration) to 10 (total land transformation). Recovery time was ranked using a scale ranging from 0 to 1 to represent the length of time a disturbance persists on the land. If a disturbance, such as a community development, is likely to persist over a 50-year period, it received a score of 1. If a disturbance, such as seismic lines, is likely to show significant recovery of vegetation structure and ecological processes over a 50-year period, it received a score between 0.1 and 0.9. Lower scores represented a less persistent disturbance that is likely to exhibit significant recovery over a 50-year period. To calculate cumulative disturbance scores for each PU, we multiplied the percentage of area affected by each disturbance by the disturbance weight and summed these scores in each PU.

$$\text{Disturbance Score} = \sum_{Dist=1}^{n} \left(\frac{Disturbance\ Area}{Planning\ Unit\ Area} \right) \times Disturbance\ Weight$$

In simulated future scenarios, all existing disturbances were included, but we recalculated the original disturbance score by multiplying again by the recovery score (Table 3). This approach allowed us to simulate the cumulative impacts of disturbances over time, while also acknowledging the decreasing impact of current disturbances in the future.

ANALYSIS ZONES

We examined the spatial pattern of current landscape disturbance by mapping disturbance scores across the study area (Fig. 1) and comparing disturbance levels between different analysis zones (Table 4). We defined our analysis zones using areas of importance that were outlined in community conservation plans for the region (IJS, 2008a–d). These analysis zones consist of individual planning areas (PAs) that are designated for each community; priority management zones, which are areas of high cultural or ecological significance that are managed to avoid environmental disturbance (IJS, 2008a–d); and caribou harvesting zones. While many other types of harvesting are common in the region, we chose to analyze caribou harvesting zones as an example of species-specific use areas because caribou are harvested in multiple communities (Usher, 2002; Alunik et al., 2003; Joint Secretariat, 2003), are the focal point of research and management efforts (Adamczewski et al., 2009; Environment and Natural Resources, 2011; Gunn et al., 2011), and because conservation plans provided consistent data across the study area. In every analysis zone, we measured the percentage of PUs containing environmental disturbance and the number of unique disturbance types occurring in PUs. We also measured the percentage of PUs containing high levels of environmental disturbance, which we defined as a disturbance score ≥ 80 (the equivalent of half the PU being affected by wildfire). The impact of current and future disturbances on multiple harvesting values was examined in our Marxan analysis.

Marxan Analysis

The spatial prioritization software Marxan (Ball et al., 2009) was used to analyze the impact of each disturbance scenario on the area and contiguity of undisturbed PUs in the study area. Marxan is spatial planning software designed to find a near-optimal solution to a conservation problem by maximizing the acquisition of valued habitat while minimizing the cost associated with protecting these lands. In our analysis, we used the cumulative disturbance score as

TABLE 3. Disturbances mapped in the study area and their recovery score, severity score, weight, and future weight, which were used to calculate the disturbance score in each planning unit. To represent continued recovery in future disturbance scenarios, existing disturbance weights were multiplied by the recovery score.

Disturbance	Disturbance weighting: Recovery	Severity	Weight	Future weight	Impacts of disturbance	Sources
Thaw slumps	0.5	7	3.5	3.5[1]	Alters the chemistry of soils, lakes, and rivers; transforms vegetation structure and permafrost conditions	Lantz and Kokelj, 2008; Kokelj et al., 2013; Thienpont et al., 2013
Fire	0.4	4	1.6	0.64	Transforms vegetation structure, community composition, and permafrost conditions	Racine et al., 2004; Jandt et al., 2008; Joly et al., 2010; Lantz et al., 2010; Bret-Harte et al., 2013
Tundra seismic lines	0.2	1	0.2	0.04	Alters permafrost conditions and vegetation structure; reduces lichen cover	Kemper and Macdonald, 2009; Williams et al., 2013
Forested seismic lines	0.4	3	1.2	0.48	Alters permafrost conditions and vegetation structure; reduces lichen cover	Kemper and Macdonald, 2009; Williams et al., 2013
Drilling mud sumps	0.5	10	5	0.25	Alters topography, permafrost conditions, and vegetation structure and composition	Johnstone and Kokelj, 2008; Kokelj et al., 2010
Pipeline	1	2	2	2	Permanent right of way; alters vegetation structure and composition and can cause ground subsidence	Walker et al., 1987; Williams et al., 2013
Municipality	1	10	10	10	Permanent settlement	NWT Geomatics, 2004
Saline storm surge	0.5	10	5	5	Soil salinization kills vegetation and results in long-term modifications to habitat quality	Pisaric et al., 2011; Kokelj et al., 2012; Lantz et al., 2015
Mineral development	1	10	10	10	Permanent infrastructure	WWF, 2002
Road	1	10	10	5	Permanent right of way that alters vegetation, soil, and permafrost	Myers-Smith et al., 2006; Gill et al., 2014

[1] Since we estimated that active slumps will continue to occupy a similar area, the future weight of thaw slumps was not adjusted.

TABLE 4. Impacts to planning units (PUs) across multiple analysis zones. We calculated the percentage of disturbed PUs and the percentage of PUs containing high disturbance levels (disturbance score ≥ 80) in every analysis zone. We also assessed the degree to which disturbance types overlapped by measuring the percentage of PUs in each analysis zone affected by 1, 2, 3, 4, and 5 different disturbance types. PA = planning area.

Analysis zone	PUs containing environmental disturbance (%)	PUs containing high environmental disturbance (%)	Percent of PUs affected by 1–5 different disturbance types: 1	2	3	4	5
Entire study area	55.0	1.6	39.2	13.1	1.6	1.0	0.1
Aklavik PA	66.37	2.5	26.5	12.2	1.6	1.0	0.1
Inuvik PA	71.43	2.7	26.4	12.2	1.6	1.0	0.1
Tuktoyaktuk PA	69.60	2.9	23.3	9.3	1.0	0.8	0.1
Paulatuk PA	40.32	0.1	14.8	1.9	0.1	0.0	0.0
Most significant management zones	56.11	1.8	20.9	8.0	0.8	0.6	0.02
Particularly significant management zones	49.14	2.5	6.7	2.6	0.4	0.2	0.02
Seasonally significant management zones	56.47	0.6	18.3	4.2	0.7	0.4	0.03
Caribou harvesting zones	64.30	1.7	24.1	9.5	1.1	0.7	0.02

the cost layer, so that Marxan would prioritize the selection of lands with the lowest disturbance score. Forty terrestrial harvesting areas identified in Inuvialuit Community Conservation Plans (IJS, 2008a–d) were selected as the use values that Marxan simulations attempted to conserve. These use areas varied in size, and significant overlap occurred among many values. To identify near-optimum spatial configurations of wildlife harvesting areas, multiple Marxan optimizations were run for each disturbance scenario. Marxan selections began by identifying the near-optimal spatial output that selected at least 50% of PUs in each harvesting area. Subsequent iterations targeted a higher percentage of each harvesting area. Optimizations were run until the threshold for each disturbance scenario was reached, and Marxan failed to achieve the targeted percentage of wildlife harvesting areas. Each of these optimizations comprised 100 runs, in which Marxan attempted to select the targeted percentages for each use value while incurring the lowest possible cost (i.e., minimizing the disturbed terrain selected) and maintaining contiguity. Marxan parameters were set so that optimizations prioritized maintaining a low overall cost and avoided areas of high disturbance intensity (online

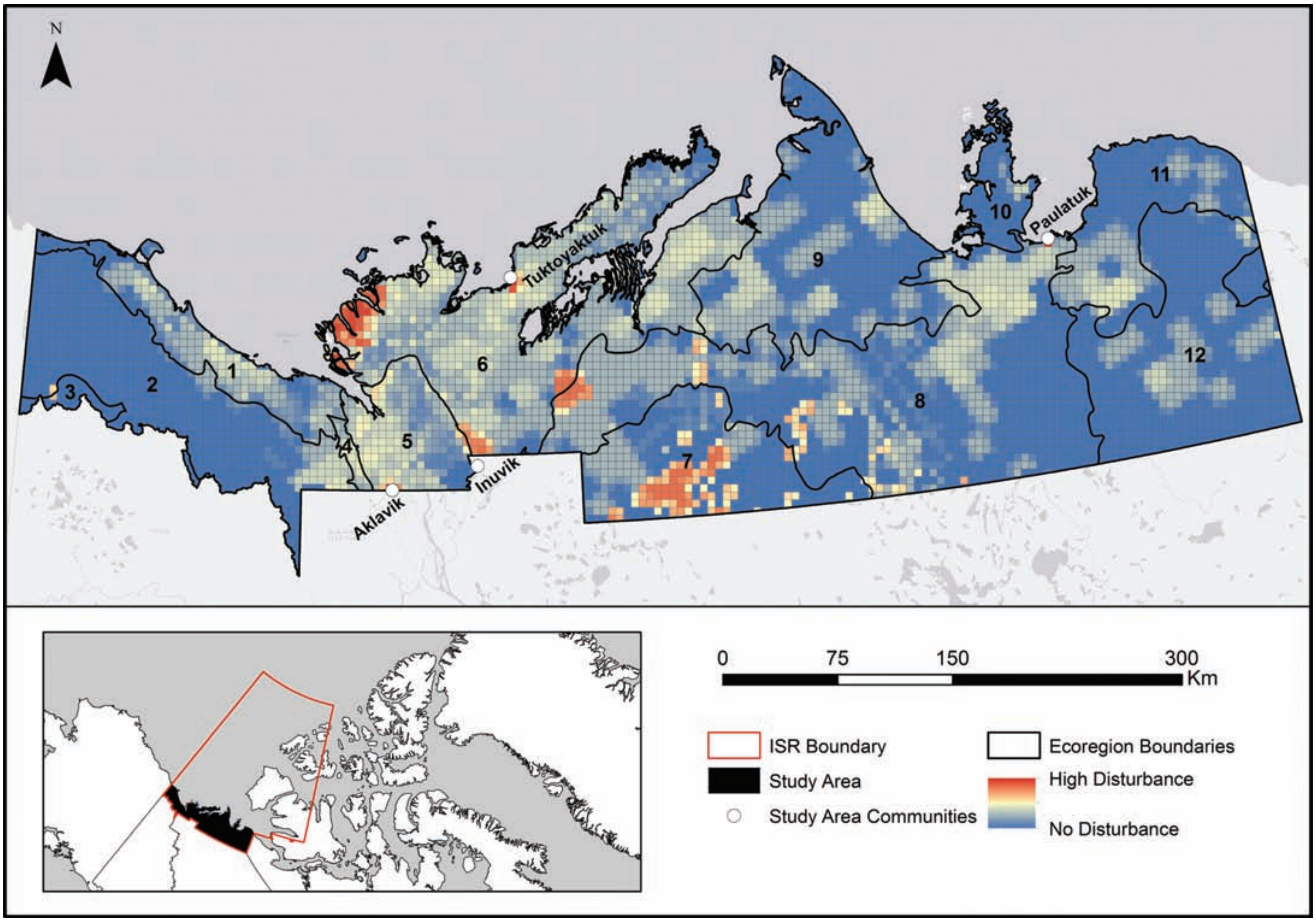

FIG. 2. Current disturbance levels in the study region and their distribution across major ecoregions: 1: Yukon Coastal Plain, 2: British Richardson Mountains, 3: Old Crow Basin, 4: Peel Plateau, 5: Mackenzie Delta, 6: Tuktoyaktuk Coastal Plain, 7: Great Bear Lake Plain, 8: Dease Arm Plain, 9: Anderson River Plain, 10: Amundsen Gulf Lowlands, 11: Coronation Hills, 12: Bluenose Lake Plain. Inset in the bottom left corner shows the study area location in black and the entire ISR boundary in red.

Appendix 1: Table S2). For a full list of Marxan parameters and the 40 terrestrial harvesting areas used in this analysis, see online Appendices 2 and 3.

We compared Marxan outputs across all simulations to investigate the impact of changing disturbance levels on the availability of community-defined harvesting areas. In order to measure the connectivity in each output, we compared the average number of PU edges per PU for all Marxan solutions in each disturbance scenario. To measure the level of disturbance in Marxan outputs, we measured the average cost per PU. Patterns were analyzed between all 10 disturbance scenarios and across each conservation target of use values.

RESULTS

Current Disturbance Footprint

Our compilation of GIS data shows that disturbance has impacts on most areas of the southern ISR, but it also reveals substantial spatial variation in the intensity of these impacts (Fig. 2). Over half of PUs contained at least one disturbance type, while 14.8% of PUs contained two or more disturbances (Table 4). Slumping and historic seismic lines were the most widespread disturbance types (Table 5), and disturbance intensity was low to moderate in most of the study region (Fig. 2). Large expanses of undisturbed areas existed in the Richardson Mountains, Amundsen Gulf Lowlands, Anderson River Plain, Bluenose Lake Plain, the eastern Dease Arm Plain, and Coronation Hills (Fig. 2). Well-defined hotspots of high-intensity disturbances were found in the Tuktoyaktuk Coastal Plain, the western Dease Arm Plain, and the Great Bear Lake Plain (Fig. 2), which represented a low percentage of total PUs (Table 4).

The percent of PUs disturbed also varied among community PAs, management zones, and key wildlife harvesting areas. The percentage of disturbed PUs in Aklavik, Inuvik, and Tuktoyaktuk PAs was higher than the disturbance rate for the entire study area, while the Paulatuk PA contained a much lower percentage of disturbed PUs (Table 4). Management zones that have been identified as most significant, particularly significant, or seasonally significant in the community conservation plans each contained disturbance levels similar to those of the study area as a whole, while specific caribou harvesting zones contained a greater percentage of disturbed cells than the whole study area (Table 4).

Future Disturbances and Marxan Simulations

Simulations of future fires and increased human activity created nine distinct future disturbance scenarios (Fig. 3). Comparing the spatial distribution of disturbances in future scenarios to the baseline scenario revealed that the frequency and intensity of environmental disturbances in the region increased throughout all 10 scenarios (Fig. 3). Scenarios 2, 5, and 8 involved major shifts in fire occurrence and displayed the greatest increase in disturbance levels across the study area (Fig. 3). Increasing human disturbance alone (Scenarios 3, 4, 6, 7, 9, and 10) resulted in a much smaller increase in regional impacts (Fig. 3).

When disturbance scenarios were used to modify the cost layer in Marxan optimizations, we observed two distinct thresholds where Marxan could not achieve conservation targets. In disturbance scenarios 1 to 7, failure rates were 100% when optimizations attempted to conserve 82% of all use values. In Scenarios 8 to 10, the failure threshold was 76% (Table 6). At targets of 50% and 75%, Marxan also encountered a significant failure rate in disturbance scenarios 8 to 10 (Table 6).

The average measure of solution edges per PU and the average cost per PU increased in scenarios with greater disturbance. Increases in cost and edge ratios were much larger in scenarios that included shifts in fire frequency, compared to scenarios that simulated increased human activity (Figs. 4 and 5). As conservation targets increased, the magnitude of differences between cost scores and the edge to PU ratios among simulations also increased (Figs. 4 and 5). The impact of disturbance on habitat contiguity was also evident in mapped Marxan outputs, where scenarios with a higher level of disturbance produced outputs containing fewer intact solutions and much longer edges (Fig. 6).

DISCUSSION

Current Disturbance Levels

This study highlights the importance of assessing cumulative effects in regions with a strong reliance on subsistence harvesting. Our analysis shows that the Inuvialuit Settlement Region (ISR) is more affected by natural and human disturbances than is suggested in Community Conservation Plans that call for the avoidance of disturbances across large management areas (IJS, 2008a–d). This finding underscores the potential to overlook cumulative impacts that occur in large regions. Our mapping shows significant overlap between widespread disturbances and wildlife harvesting areas, important management zones, and community planning areas. We found that this overlap is substantial enough to limit the availability of undisturbed harvesting zones, and reduces conservation potential in the region. To our knowledge, this is the first comprehensive assessment of cumulative effects in the ISR, and it suggests that a wide range of perturbations have already affected Inuvialuit land use.

TABLE 5. Percentage of planning units (PUs) in the study area affected by each disturbance type.

Disturbance type	PUs affected (%)
Thaw slumps	38.8
Tundra seismic lines	24.7
Forested seismic lines	3.2
Historic wildfire	3.0
Drilling mud sumps	1.7
Ikhill Pipeline	1.7
Storm surge footprint	0.9
Community footprint	0.2

Our findings also highlight the importance of broad-scale cumulative effects assessments for conservation planning in the region. Numerous co-management organizations in the ISR have the mandate to protect biodiversity and traditional harvesting (INAC, 1984), and monitoring of cumulative effects has been incorporated into regional management across the Northwest Territories and Canada (Government of Canada, 1998; MVEIRB, 2004; Duinker and Greig, 2006; Ehrlich, 2010). To date, however, few initiatives have effectively translated the general consensus regarding the significance of cumulative effects into effective monitoring and management practices (Duinker and Greig, 2006; Gunn et al., 2011). This gap is alarming because the combination of climate change impacts and industrial development represents a significant threat to northern food security and biodiversity (Corell, 2006; Furgal and Seguin, 2006; Fuller et al., 2008). To avoid crossing thresholds where subsistence harvesting is severely impaired or no longer possible, strategies for monitoring and managing cumulative environmental impacts are needed (Parlee et al., 2012). The method for weighting disturbances presented here provides a means to include both widespread, low-intensity disturbances (e.g., seismic lines), and high-intensity impacts (e.g., salt-water vegetation kill) in a cumulative effects assessment. The maps produced can be used to evaluate conservation potential across a gradient of disturbed to undisturbed landscapes and as inputs for spatial planning activity (Ball et al., 2009; Moilanen et al., 2009, 2011).

Arriving at clear definitions of thresholds remains a challenge in cumulative effects management, and approaches range from restrictions on any development in pristine landscapes (Ehrlich, 2010) to explicit levels of allowable impacts on specific valued ecosystem components (Gunn et al., 2011). Regardless of the methods for defining a threshold, if land-use planning evaluates projects on a case-by-case basis, it risks exceeding acceptable disturbance

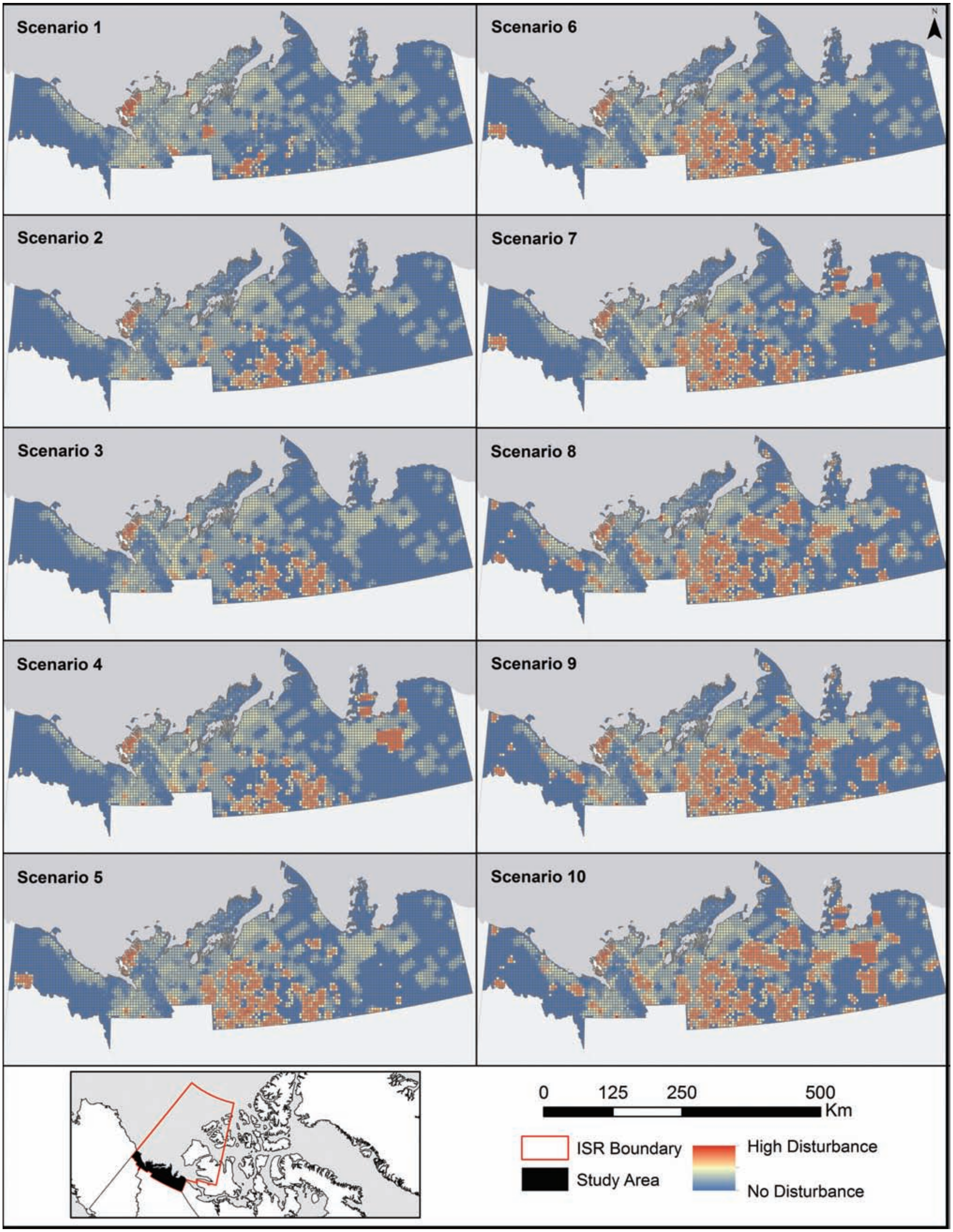

FIG. 3. Spatial output of each disturbance scenario. Scenario 1: current disturbance levels, 2: baseline future fire rates, 3: baseline future fire rates and road and pipeline development, 4: baseline future fire rates and road, pipeline, and mineral development, 5: moderate increase in future fire rates, 6: moderate increase in future fire rates and road and pipeline development, 7; moderate increase in future fire rates and road, pipeline, and mineral development, 8: high future fire rates, 9: high future fire rates and road and pipeline development, 10: high future fire rates and road, pipeline, and mineral development. Inset in the bottom left corner shows the study area location in black and the entire ISR boundary in red.

TABLE 6. Percent of Marxan runs in which the solution failed to conserve the targeted percentage for at least one use value for lack of available planning units (PUs) with a low enough disturbance score for inclusion. Two distinct thresholds exist at which Marxan solutions are unable to meet conservation targets for all use areas: the failure threshold is 82% of use values conserved in scenarios 1 to 7, but 76% in scenarios 8 to 10. Scenario 1: current disturbance levels, 2: baseline future fire rates, 3: baseline future fire rates and road and pipeline development, 4: baseline future fire rates and road, pipeline, and mineral development, 5: moderate increase in future fire rates, 6: moderate increase in future fire rates and road and pipeline development, 7: moderate increase in future fire rates and road, pipeline, and mineral development, 8: high future fire rates, 9: high future fire rates and road and pipeline development, 10: high future fire rates and road, pipeline, and mineral development.

	Scenario	Fails at 50% target	Fails at 75% target	Fails at 76% target	Fails at 82% target
Increasing Disturbance	1	2	0	0	100
↓	2	2	0	0	100
	3	2	0	0	100
	4	4	0	0	100
	5	1	0	0	100
	6	1	0	0	100
	7	2	0	0	100
	8	18	32	100	100
	9	17	28	100	100
	10	20	27	100	100

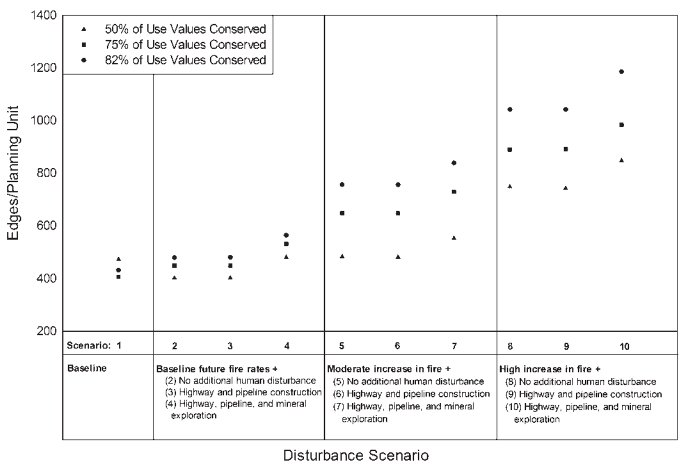

FIG. 4. Average edge score per planning unit (PU) for all Marxan analyses. Three sets of simulations were run for each disturbance scenario, attempting to reach conservation targets of 50%, 75%, and 82%. We averaged the Marxan edge score per PU to assess the contiguity of solutions. Symbols show the mean connectivity score and 95% confidence intervals around the mean. Scenarios that attempted to conserve 82% of use values all failed to meet targets for at least one value. Connectivity scores for these outputs represent the mean score of unsuccessful solutions.

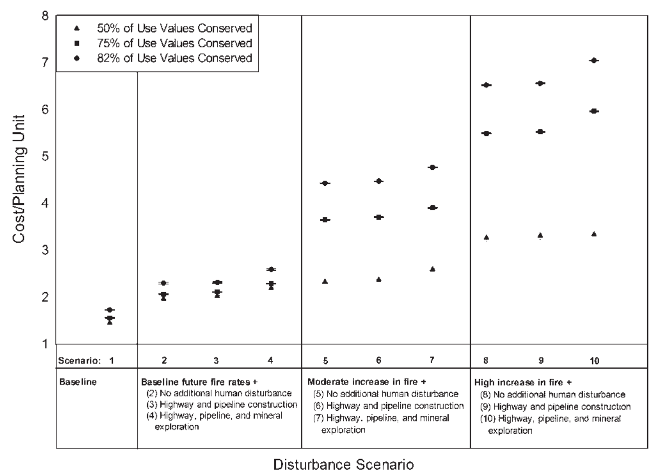

FIG. 5. Average cost scores per planning unit (PU) for Marxan solutions from each of the 10 disturbance scenarios and three conservation targets (50%, 75%, 82%). Symbols show the mean cost per PU for each solution and 95% confidence intervals around the mean. Note: scenarios that attempted to conserve 82% of use values all failed to meet targets for at least one value. Cost scores for these outputs represent the mean disturbance score of unsuccessful solutions.

levels by ignoring the combined effect of multiple stressors (Duinker and Greig, 2006). The approach used in this analysis makes it possible to include a range of disturbances in the evaluation of multiple stressors across a region. Combined with data on proposed developments, this approach may be particularly useful in identifying when additional impacts will exceed thresholds for acceptable disturbance levels.

Future Disturbance Scenarios

Our analysis based on future disturbance scenarios showed that additional perturbations reduce the potential to conserve undisturbed harvesting areas in the ISR. Scenarios 2 to 6 maintain the same 82% failure threshold that exists under current disturbance levels, while scenarios with large increases in fire frequency (7 to 10) have a higher failure rate at all targets and a lower failure threshold of 76%. This result emphasizes that predicted increases in natural disturbance frequency and intensity (ACIA, 2005; Jandt et al., 2008; de Groot et al., 2013) are likely to limit flexibility in meeting conservation targets and alter the potential to maintain undisturbed harvesting areas in the ISR. Global climate change and increasing pressure from human activity require conservation strategies that anticipate these types of change (Pressey et al., 2007; Trombulak and Baldwin, 2010; Groves et al., 2012; Brodie et al., 2013). Cumulative effects management has proven effective when it considers reasonably foreseeable impacts in addition to those that are most likely to occur (Ehrlich, 2010). Our Marxan simulations of future disturbance scenarios

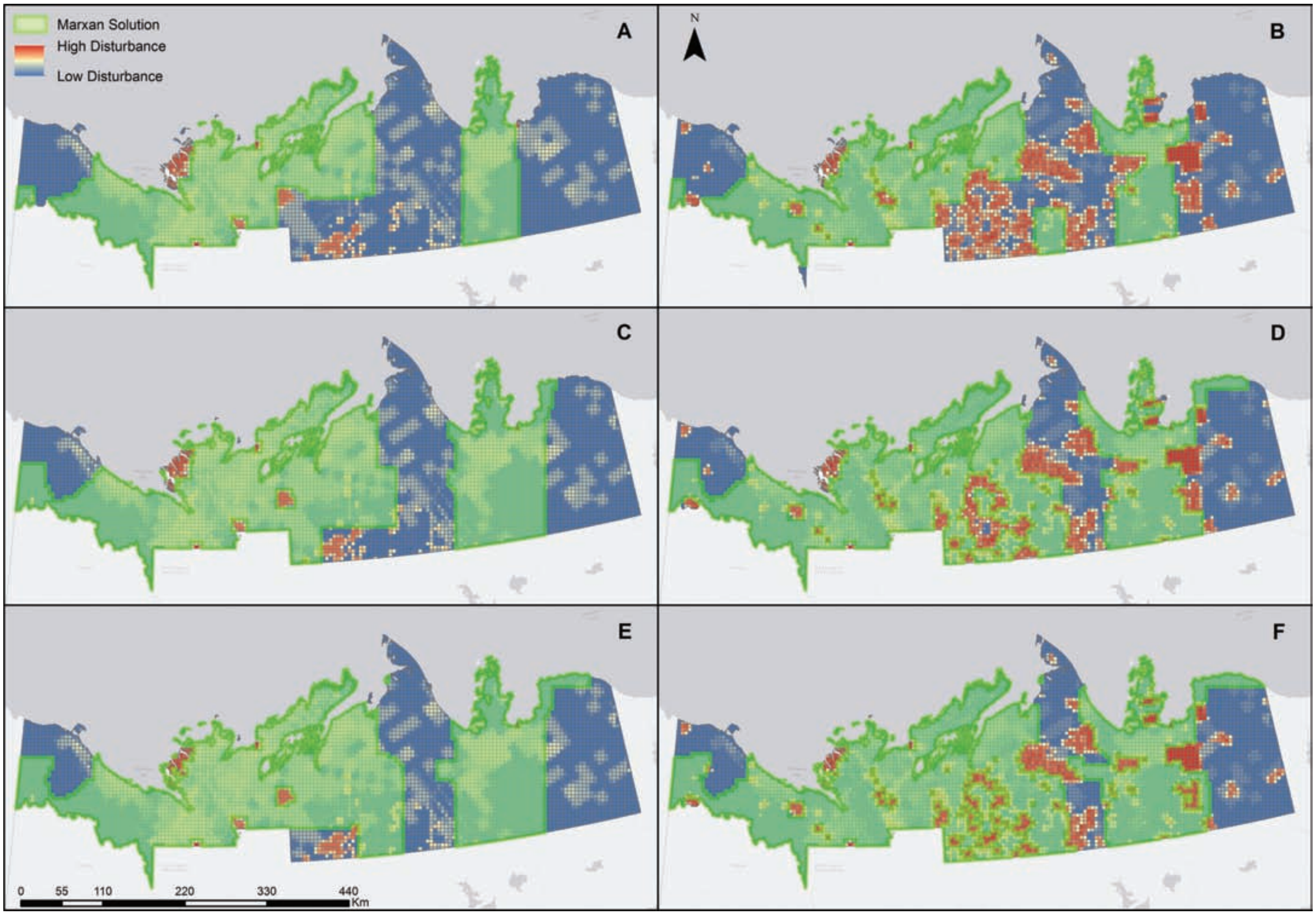

FIG. 6. Maps showing the "best output" from Marxan runs, using (A) disturbance scenario 1, 50% conserved; (B) scenario 10, 50% conserved; (C) scenario 1, 75% conserved; (D) scenario 10, 75% conserved; (E) scenario 1, 82% conserved; and (F) scenario 10, 90% conserved. The shading on the base maps represents disturbance intensity from low (blue) to high (red). Areas selected are shown in green. As disturbance levels and conservation targets increase, the contiguity of Marxan outputs decreases.

demonstrate that climate change will reduce the availability of high-quality harvesting areas in the ISR. They also highlight the importance of conservation planning efforts that limit direct human disturbance in order to allow ecosystems to absorb the impacts of climate change (Doak et al., 2013).

Our results indicate that an increase in disturbance will reduce the quality of conservation outcomes by increasing fragmentation. Even if optimizations are able to meet conservation targets, increased disturbance levels in our scenarios limit the potential for large configurations of contiguous harvesting areas. This result is concerning because habitat fragmentation is directly correlated with species decline (Lindenmayer and Fischer, 2006; Collinge, 2009). Even large protected areas have struggled to meet conservation goals as surrounding landscapes become increasingly disturbed (Trombulak and Baldwin, 2010), which raises the possibility that the conservation solutions in our scenarios may not represent adequate protection of harvesting areas if they are highly fragmented or surrounded by significantly disturbed PUs.

Our scenarios coupled modest industrial development in a region with a range of natural disturbance intensities. These scenarios provided a simplified method for exploring the conservation implications of development in a future affected by climate change. These simulations were based on the likelihood that wildfire will become more common with increases in temperature (ACIA, 2005; Jandt et al., 2008; de Groot et al., 2013) and are used as estimations, not predictions. Given the likelihood of additional increases in permafrost degradation (Kokelj et al., 2015) and storm surges (Lantz et al., 2015), our future scenarios are conservative generalizations of potential impacts.

The large range of variation in fire frequency and narrow range in human disturbance used in our simulations do not represent the relative significance of human impacts in the region. Human disturbance modeling was restricted to potential development that is either in progress (Kiggiak – EBA Consulting Ltd., 2011) or has publicly available plans (WWF, 2002), which limited the spatial extent of human disturbances relative to simulated wildfire. Roads, pipelines, and infrastructure all significantly affect Arctic wildlife (Nellemann and Cameron, 1998; Johnson et al., 2005;

Gunn et al., 2011), ecological processes (Myers-Smith et al., 2006; Kokelj et al., 2010; Gill et al., 2014; Raynolds et al., 2014), and land users' ability to hunt and trap (Tyson, 2015). Their impacts should not be discounted because of their relatively small footprint in this analysis. Even development projects with a small spatial footprint may be undesirable in particularly sensitive or culturally important ecosystems (Ehrlich, 2010). To assess the full range of potential human disturbance, future research should simulate human disturbance in the region by projecting a number of scenarios that represent more widespread potential resource extraction (Holroyd and Retzer, 2005).

CONCLUSION

The results of this analysis emphasize three main points: 1) the ISR is already widely affected by environmental disturbance; 2) the potential to conserve large contiguous areas of habitat is limited by existing disturbances; and 3) future environmental disturbances, particularly those associated with climate change, will further reduce the potential to conserve large, contiguous undisturbed harvesting areas. These findings indicate that land-use planning in the ISR needs to account for increasing environmental change in order to achieve conservation objectives in culturally important ecosystems. The mapping and weighting approach described in this paper can be used to quantify the impacts of environmental change on subsistence land use, particularly where local communities are concerned about changes across a large landscape (Ehrlich, 2010). This approach creates tractable representations of the impacts to culturally significant ecosystems and encourages greater consideration of local land users in cumulative effects analysis.

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APPENDICES

The following appendices are available in a supplementary file to the online version of this article at:
http://arctic.journal.hosting.ucalgary.ca/arctic/index.php/arctic/rt/suppFiles/4607/0

APPENDIX 1: TABLE S1. Parameters for fire scenario generation Geospatial Modeling Environment (GME) software (Beyer, 2014).
TABLE S2. Parameters used in this Marxan analysis and their treatment across all simulations.
APPENDIX 2: Parameters imported from Marxan input file (input.dat).
APPENDIX 3: Wildlife harvesting areas included in Marxan analysis (imported from Marxan spec.dat file).

REFERENCES

ACIA. 2005. Arctic climate impact assessment: Scientific report. New York: Cambridge University Press.

Adamczewski, J., Boulanger, J., Croft, B., Cluff, D., Elkin, B., Nishi, J., Kelly, A., D'Hont, A., and Nicolson, C. 2009. Decline in the Bathurst caribou herd 2006–2009: A technical evaluation of field data and modeling. Yellowknife: Department of Environment and Natural Resources, Government of the Northwest Territories.

Alunik, I., Kolausok, E.D., and Morrison, D. 2003. Across time and tundra: The Inuvialuit of the Western Arctic. Vancouver, British Columbia: Raincoast Books.

Ball, I.R., Possingham, H.P., and Watts, M. 2009. Marxan and relatives: Software for spatial conservation prioritization. In: Moilanen, A., Wilson, K.A., and Possingham, H.P., eds. Spatial conservation prioritization: Quantitative methods & computational tools. Oxford: Oxford University Press. 185–195.

Bennett, T.D., and Lantz, T.C. 2014. Participatory photomapping: A method for documenting, contextualizing, and sharing indigenous observations of environmental conditions. Polar Geography 37(1):28–47.
http://dx.doi.org/10.1080/1088937X.2013.873089

Berkes, F., and Jolly, D. 2001. Adapting to climate change: Social-ecological resilience in a Canadian Western Arctic community. Conservation Ecology 5(2): 18.
http://www.consecol.org/vol5/iss2/art18/

Beyer, H.L. 2014. Geospatial modelling environment. Brisbane, Australia: Spatial Ecology LLC.
http://www.spatialecology.com/gme/

Bret-Harte, M.S., Mack, M.C., Shaver, G.R., Huebner, D.C., Johnston, M., Mojica, C.A., Pizano, C., and Reiskind, J.A. 2013. The response of Arctic vegetation and soils following an unusually severe tundra fire. Philosophical Transactions of the Royal Society B: Biological Sciences 368(1624): 20120490.
http://dx.doi.org/10.1098/rstb.2012.0490

Brodie, J.F., Post, E., and Doak, D.F., eds. 2013. Wildlife conservation in a changing climate. Chicago: University of Chicago Press.

Brooke, B.W., Sodhi, N.S., and Bradshaw, C.J.A. 2008. Synergies among extinction drivers under global change. Trends in Ecology & Evolution 23(8):453–460.
http://dx.doi.org/10.1016/j.tree.2008.03.011

Burn, C.R., and Kokelj, S.V, 2009. The environment and permafrost of the Mackenzie Delta area. Permafrost and Periglacial Processes 20(2):83 – 105.
http://dx.doi.org/10.1002/ppp.655

Collinge, S.K. 2009. Ecology of fragmented landscapes. Baltimore, Maryland: Johns Hopkins University Press.

Corell, R.W. 2006. Challenges of climate change: An Arctic perspective. AMBIO 35(4):148 – 152.
http://dx.doi.org/10.1579/0044-7447(2006)35[148:COCCAA]2.0.CO;2

Debinski, D.M., and Holt, R.D. 2000. A survey and overview of habitat fragmentation experiments. Conservation Biology 14(2):342 – 355.
http://dx.doi.org/10.1046/j.1523-1739.2000.98081.x

de Groot, W.J., Flannigan, M.D., and Cantin, A.S. 2013. Climate change impacts on future boreal fire regimes. Forest Ecology and Management 294:35 – 44.
http://dx.doi.org/10.1016/j.foreco.2012.09.027

Department of Community Services. 2014. Wildlife fire management data, maps, and bulletins archive. Whitehorse: Yukon Government.
www.community.gov.yk.ca/firemanagement/wfarchives.html

Doak, D.F., Brodie, J.F., and Post, E. 2013. What to expect and how to plan for wildlife conservation in the face of climate change. In: Brodie, J.F., Post, E., and Doak, D.F., eds. Wildlife conservation in a changing climate. Chicago: University of Chicago Press. 387 – 396.

Duinker, P.N., and Greig, L.A. 2006. The impotence of cumulative effects assessment in Canada: Ailments and ideas for redeployment. Environmental Management 37(2):153 – 161.
http://dx.doi.org/10.1007/s00267-004-0240-5

Duinker, P.N., Burbidge, E.L., Boardley, S.R., and Greig, L.A. 2013. Scientific dimensions of cumulative effects assessment: Toward improvements in guidance for practice. Environmental Reviews 21(1):40 – 52.
http://dx.doi.org/10.1139/er-2012-0035

Ecosystem Classification Group. 2009. Ecological regions of the Northwest Territories – Taiga Plains, rev. ed. Yellowknife: Department of Environment and Natural Resources, Government of the Northwest Territories.

———. 2012. Ecological regions of the Northwest Territories – Southern Arctic. Yellowknife: Department of Environment and Natural Resources, Government of the Northwest Territories.

Ehrlich, A. 2010. Cumulative cultural effects and reasonably foreseeable future developments in the Upper Thelon Basin, Canada. Impact Assessment and Project Appraisal 28(4):279 – 286.
http://dx.doi.org/10.3152/146155110X12838715793084

Ehrlich, A.J., and Sian, S. 2004. Cultural cumulative impact assessment in Canada's Far North. In: Proceedings of the 24th Annual Conference, International Association for Impact Assessment, 24 April – 1 May 2004, Vancouver, British Columbia.

Environment and Natural Resources. 2011. Caribou forever – our heritage, our responsibility: A barren-ground caribou management strategy for the Northwest Territories 2011 – 1015. Yellowknife: Department of Environment and Natural Resources, Government of the Northwest Territories.

Fraser, R.H., Lantz, T.C., Olthof, I., Kokelj, S.V., and Sims, R.A. 2014. Warming-induced shrub expansion and lichen decline in the western Canadian Arctic. Ecosystems 17(7):1151 – 1168.
http://dx.doi.org/10.1007/s10021-014-9783-3

Fuller, T., Morton, D.P., and Sarkar, S. 2008. Incorporating uncertainty about species' potential distributions under climate change into the selection of conservation areas with a case study from the Arctic Coastal Plain of Alaska. Biological Conservation 141(6):1547 – 1559.
http://dx.doi.org/10.1016/j.biocon.2008.03.021

Furgal, C., and Seguin, J. 2006. Climate change, health and vulnerability in Canadian northern Aboriginal communities. Environmental Health Perspectives 114(12):1964 – 1970.
http://dx.doi.org/10.1289/ehp.8433

Garcia, R.A., Cabeza, M., Rahbek, C., and Araújo, M.B. 2014. Multiple dimensions of climate change and their implications for biodiversity. Science 344(6183).
http://dx.doi.org/10.1126/science.1247579

Gill, H.K., Lantz, T.C., O'Neill, B., and Kokelj, S.V. 2014. Cumulative impacts and feedbacks of a gravel road on shrub tundra ecosystems in the Peel Plateau, Northwest Territories, Canada. Arctic, Antarctic, and Alpine Research 46(4):947 – 961.
http://dx.doi.org/10.1657/1938-4246-46.4.947

Government of Canada. 1998. Mackenzie Valley Resource Management Act. S.C. 1998, c. 25.
http://laws-lois.justice.gc.ca/eng/acts/m-0.2/page-1.html

———. 2010. GeoBase - Municipal Boundaries - NT – Northwest Territories. Ottawa: Natural Resources Canada, Earth Sciences Sector, Canada Centre for Mapping and Earth Observation.
http://geogratis.gc.ca/api/en/nrcan-rncan/ess-sst/3e22920a-7470-4c13-98a7-77a7122fc6c2.html

Groves, C.R., Game, E.T., Anderson, M.G., Cross, M., Enquist, C., Ferdaña, Z., Gondor, A., et al. 2012. Incorporating climate change into systematic conservation planning. Biodiversity and Conservation 21(7):1651 – 1671.
http://dx.doi.org/10.1007/s10531-012-0269-3

Gunn, A., Johnson, C.J., Nishi, J.S., Daniel, C.J., Russell, D.E., Carlson, M., and Adamczewski, J.Z. 2011. Understanding the cumulative effects of human activities on barren-ground caribou. In: Krausman, P.R., and Harris, L.K., eds. Cumulative effects in wildlife management: Impact mitigation. Boca Raton, Florida: CRC Press.

Hegmann, G., Cocklin, C., Creasey, R., Dupuis, S., Kennedy, A., Kingsley, L., Ross, W., Spaling, H., and Stalker, D. 1999. Cumulative effects assessment practitioners' guide. Prepared by AXYS Environmental Consulting Ltd. and the CEA Working Group for the Canadian Environmental Assessment Agency, Hull, Quebec.
http://www.ceaa.gc.ca/default.asp?lang=En&n=43952694-1

Holroyd, P., and Retzer, H. 2005. A peak into the future: Potential landscape impacts of gas development in northern Canada. Vancouver, British Columbia: Pembina Institute.

INAC (Indian and Northern Affairs Canada). 1984. The Western Arctic Claim: The Inuvialuit Final Agreement. Ottawa: INAC.

———. 2005. ESRF online sumps database. Yellowknife: INAC.

IJS (Inuvialuit Joint Secretariat). 2008a. Aklavik Inuvialuit community conservation plan. Inuvik: IJS.

———. 2008b. Inuvik Inuvialuit community conservation plan. Inuvik: IJS.

———. 2008c. Paulatuk community conservation plan. Inuvik: IJS.

———. 2008d. Tuktoyaktuk community conservation plan. Inuvik: IJS.

Jandt, R., Joly, K., Randy Meyers, C., and Racine, C. 2008. Slow recovery of lichen on burned caribou winter range in Alaska tundra: Potential influences of climate warming and other disturbance factors. Arctic, Antarctic, and Alpine Research 40(1):89–95. http://dx.doi.org/10.1657/1523-0430(06-122)[JANDT]2.0.CO;2

Johnson, C.J., Boyce, M.S., Case, R.L., Cluff, H.D., Gau, R.J., Gunn, A., and Mulders, R. 2005. Cumulative effects of human development on Arctic wildlife. Wildlife Monographs 160. 36 p.

Johnstone, J.F., and Kokelj, S.V. 2008. Environmental conditions and vegetation recovery at abandoned drilling mud sumps in the Mackenzie Delta region, Northwest Territories, Canada. Arctic 61(2):199–211. http://dx.doi.org/10.14430/arctic35

Joint Review Panel. 2010. Foundations for a sustainable northern future: Report of the Joint Review Panel for the Mackenzie Gas Project. Inuvik, Northwest Territories: Joint Review Panel. http://www.reviewboard.ca/upload/project_document/EIR0405-001_JRP_Report_of_Environmental_Review_Executive_Volume_I.PDF

Joint Secretariat. 2003. Inuvialuit harvest study: Data and methods report 1988–1997. Inuvik: The Joint Secretariat.

Joly, K., Chapin, F.S., III, and Klein, D.R. 2010. Winter habitat selection by caribou in relation to lichen abundance, wildfires, grazing, and landscape characteristics in Northwest Alaska. Ecoscience 17(3):321–333. http://dx.doi.org/10.2980/17-3-3337

Kemper, J.T., and Macdonald, S.E. 2009. Directional change in upland tundra plant communities 20–30 years after seismic exploration in the Canadian low-Arctic. Journal of Vegetation Science 20(3):557–567. http://dx.doi.org/10.1111/j.1654-1103.2009.01069.x

Kiggiak - EBA Consulting Ltd. 2011. Environmental impact statement for construction of the Inuvik to Tuktoyaktuk Highway, NWT. EIRB File No.: 02/10-05. Inuvik: Kiggiak - EBA Consulting Ltd.

Kokelj, S.V., Riseborough, D., Coutts, R., and Kanigan, J.C.N. 2010. Permafrost and terrain conditions at northern drilling-mud sumps: Impacts of vegetation and climate change and the management implications. Cold Regions Science and Technology 64(1):46–56. http://dx.doi.org/10.1016/j.coldregions.2010.04.009

Kokelj, S.V., Lantz, T.C., Solomon, S., Pisaric, M.F.J., Keith, D., Morse, P., Thienpont, J.R., Smol, J.P., and Esagok, D. 2012. Using multiple sources of knowledge to investigate northern environmental change: Regional ecological impacts of a storm surge in the outer Mackenzie Delta, N.W.T. Arctic 65(3):257–272. http://dx.doi.org/10.14430/arctic4214

Kokelj, S.V., Lacelle, D., Lantz, T.C., Tunnicliffe, J., Malone, L., Clark, I.D., and Chin, K.S. 2013. Thawing of massive ground ice in mega slumps drives increases in stream sediment and solute flux across a range of watershed scales. Journal of Geophysical Research: Earth Surface 118(2):681–692. http://dx.doi.org/10.1002/jgrf.20063

Kokelj, S.V., Tunnicliffe, J., Lacelle, D., Lantz, T.C., Chin, K.S., and Fraser, R. 2015. Increased precipitation drives mega slump development and destabilization of ice-rich permafrost terrain, northwestern Canada. Global and Planetary Change 129:56–68. http://dx.doi.org/10.1016/j.gloplacha.2015.02.008

Lantz, T.C., and Kokelj, S.V. 2008. Increasing rates of retrogressive thaw slump activity in the Mackenzie Delta Region, N.W.T., Canada. Geophysical Research Letters 35, L06502. http://dx.doi.org/10.1029/2007GL032433

Lantz, T.C., Marsh, P., and Kokelj, S.V. 2013. Recent shrub proliferation in the Mackenzie Delta Uplands and microclimatic implications. Ecosystems 16(1):47–59. http://dx.doi.org/10.1007/s10021-012-9595-2

Lantz, T.C., Gergel, S.E., and Henry, G.H.R. 2010. Response of green alder (*Alnus viridis* subsp. *fruticosa*) patch dynamics and plant community composition to fire and regional temperature in north-western Canada. Journal of Biogeography 37(8):1597–1610. http://dx.doi.org/10.1111/j.1365-2699.2010.02317.x

Lantz, T.C., Kokelj, S.V., and Fraser, R.H. 2015. Ecological recovery in an Arctic delta following widespread saline incursion. Ecological Applications 25(1):172–185. http://dx.doi.org/10.1890/14-0239.1

Lindenmayer, D.B., and Fischer, J. 2006. Habitat fragmentation and landscape change: An ecological and conservation synthesis. Washington, D.C.: Island Press.

Mitchell, R.E., and Parkins, J.R. 2011. The challenge of developing social indicators for cumulative effects assessment and land use planning. Ecology and Society 16(2): 29. http://www.ecologyandsociety.org/vol16/iss2/art29/

Moilanen, A., Wilson, K.A., and Possingham, H., eds. 2009. Spatial conservation prioritization: Quantitative methods & computational tools. Oxford: Oxford University Press.

Moilanen, A., Leathwick, J.R., and Quinn, J.M. 2011. Spatial prioritization of conservation management. Conservation Letters 4(5):383–393. http://dx.doi.org/10.1111/j.1755-263X.2011.00190.x

MVEIRB (Mackenzie Valley Environmental Impact Review Board). 2004. Environmental impact assessment guidelines. Yellowknife: MVEIRB.

Myers-Smith, I.H., Arnesen, B.K., Thompson, R.M., and Chapin, F.S., III. 2006. Cumulative impacts on Alaskan Arctic tundra of a quarter century of road dust. Ecoscience 13(4):503–510. http://dx.doi.org/10.2980/1195-6860(2006)13[503:CIOAAT]2.0.CO;2

Nellemann, C., and Cameron, R.D. 1998. Cumulative impacts of an evolving oil-field complex on the distribution of calving caribou. Canadian Journal of Zoology 76(8):1425–1430. http://dx.doi.org/10.1139/z98-078

Noss, R.F., Quigley, H.B., Hornocker, M.G., Merrill, T., and Paquet, P.C. 1996. Conservation biology and carnivore conservation in the Rocky Mountains. Conservation Biology 10(4):949–963.
http://dx.doi.org/10.1046/j.1523-1739.1996.10040949.x

NWT Geomatics. 2004. Mackenzie Valley Air Photo Project. Yellowknife: Indian and Northern Affairs Canada, Natural Resources Canada, and Environment Canada.

Parlee, B.L., Geertsema, K., and Willier, A. 2012. Social-ecological thresholds in a changing boreal landscape: Insights from Cree knowledge of the Lesser Slave Lake region of Alberta, Canada. Ecology and Society 17(2): 20.
http://dx.doi.org/10.5751/es-04410-170220

Pearce, T., Ford, J.D., Duerden, F., Smit, B., Andrachuk, M., Berrang-Ford, L., and Smith, T. 2011. Advancing adaptation planning for climate change in the Inuvialuit Settlement Region (ISR): A review and critique. Regional Environmental Change 11(1):1–17.
http://dx.doi.org/10.1007/s10113-010-0126-4

Pisaric, M.F.J., Thienpont, J.R., Kokelj, S.V., Nesbitt, H., Lantz, T.C., Solomon, S., and Smol, J.P. 2011. Impacts of a recent storm surge on an Arctic delta ecosystem examined in the context of the last millennium. Proceedings of the National Academy of Sciences 108(22):8960–8965.
http://dx.doi.org/10.1073/pnas.1018527108

Pressey, R.L., Cabeza, M., Watts, M.E., Cowling, R.M., and Wilson, K.A. 2007. Conservation planning in a changing world. Trends in Ecology & Evolution 22(11):583–592.
http://dx.doi.org/10.1016/j.tree.2007.10.001

Racine, C., Jandt, R., Meyers, C., and Dennis, J. 2004. Tundra fire and vegetation change along a hillslope on the Seward Peninsula, Alaska, U.S.A. Arctic, Antarctic, and Alpine Research 36(1):1–10.
http://dx.doi.org/10.1657/1523-0430(2004)036[0001:TFAVCA]2.0.CO;2

Raynolds, M.K., Walker, D.A., Ambrosius, K.J., Brown, J., Everett, K.R., Kanevskiy, M., Kofinas, G.P., Romanovsky, V.E., Shur, Y., and Webber, P.J. 2014. Cumulative geoecological effects of 62 years of infrastructure and climate change in ice-rich permafrost landscapes, Prudhoe Bay Oilfield, Alaska. Global Change Biology 20(4):1211–1224.
http://dx.doi.org/10.1111/gcb.12500

Segal, R.A., Kokelj, S.V., Lantz, T.C., Durkee, K., Gervais, S., Mahon, E., Snijders, M., Buysse, J., and Schwarz, S. 2016. Broad-scale mapping of terrain impacted by retrogressive thaw slumping in northwestern Canada. NWT Open Report 2016-008. Yellowknife: Northwest Territories Geoscience Office.

Serreze, M.C., Walsh, J.E., Chapin F.S., III, Osterkamp, T., Dyurgerov, M., Romanovsky, V., Oechel, W.C., Morison, J., Zhang, T., and Barry, R.G. 2000. Observational evidence of recent change in the northern high-latitude environment. Climatic Change 46(1):159–207.
http://dx.doi.org/10.1023/A:1005504031923

Shanley, C.S., Kofinas, G.P., and Pyare, S. 2013. Balancing the conservation of wildlife habitat with subsistence hunting access: A geospatial-scenario planning framework. Landscape and Urban Planning 115:10–17.
http://dx.doi.org/10.1016/j.landurbplan.2013.03.006

Spaling, H. 1994. Cumulative effects assessment: Concepts and principles. Impact Assessment 12(3):231–251.
http://dx.doi.org/10.1080/07349165.1994.9725865

Spyce, A., Weber, M., and Adamowicz, W. 2012. Cumulative effects planning: Finding the balance using choice experiments. Ecology and Society 17(1): 22.
http://dx.doi.org/10.5751/es-04491-170122

Statistics Canada. 2011. Census profile.
http://www12.statcan.gc.ca/census-recensement/2011/dp-pd/prof/index.cfm?Lang=E

Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., et al. 2015. Planetary boundaries: Guiding human development on a changing planet. Science 347(6223): 1259855.
http://dx.doi.org/10.1126/science.1259855

Thienpont, J.R., Kokelj, S.V., Korosi, J.B., Cheng, E.S., Desjardins, C., Kimpe, L.E., Blais, J.M., Pisaric, M.F.J., and Smol, J.P. 2013. Exploratory hydrocarbon drilling impacts to Arctic lake ecosystems. PLoS ONE 8(11): e78875.
http://dx.doi.org/10.1371/journal.pone.0078875

Timoney, K.P., La Roi, G.H., Zoltai, S.C., and Robinson, A.L. 1992. The high subarctic forest tundra of northwestern Canada: Position, width, and vegetation gradients in relation to climate. Arctic 45(1):1–9.
http://dx.doi.org/10.14430/arctic1367

Trombulak, S.C., and Baldwin, R.F., eds. 2010. Landscape-scale conservation planning. Dordrecht: Springer Netherlands.

Tyson, W. 2015. Assessing the cumulative effects of environmental change on wildlife harvesting areas in the Inuvialuit Settlement Region through spatial analysis and community-based research. MSc thesis, School of Environmental Studies, University of Victoria, Victoria, British Columbia.

Usher, P.J. 2002. Inuvialuit use of the Beaufort Sea and its resources, 1960–2000. Arctic 55(Suppl. 1):18–28.
http://dx.doi.org/10.14430/arctic732

Walker, D.A., Webber, P.J., Binnian, E.F., Everett, K.R., Lederer, N.D., Nordstrand, E.A., and Walker, M.D. 1987. Cumulative impacts of oil fields on northern Alaskan landscapes. Science 238(4828):757–761.
http://dx.doi.org/10.1126/science.238.4828.757

Williams, T.J., Quinton, W.L., and Baltzer, J.L. 2013. Linear disturbances on discontinuous permafrost: Implications for thaw-induced changes to land cover and drainage patterns. Environmental Research Letters 8(2): 025006.
http://dx.doi.org/10.1088/1748-9326/8/2/025006

WWF (World Wildlife Fund). 2002. Northwest Territories digital atlas. Toronto, Ontario: WWF Canada.

Yukon Ecoregions Working Group. 2004. Yukon Coastal Plain. In: Smith, C.A.S., Meikle, J.C., and Roots, C.F., eds. Ecoregions of the Yukon Territory: Biophysical properties of Yukon landscapes. PARC Technical Bulletin No. 04-01. Summerland, British Columbia: Agriculture and Agri-Food Canada. 63–72.

Yukon Highways and Public Works. 2014. Oil and gas: Oil and gas seismic lines (1961–2014). Whitehorse: Yukon Government.

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Cumulative Effects of Environmental Change on Culturally Significant Ecosystems in the Inuvialuit Settlement Region

William Tyson,[1] Trevor C. Lantz,[1,2] and Natalie C. Ban[1]

APPENDIX 1

TABLE S1. Parameters for fire scenario generation with Geospatial Modeling Environment (GME) software (Beyer, 2014). Parameters were adjusted for fire simulation in each vegetation zone. Each simulation created a range of outputs based on the write frequency and the number of iterations. Outputs contained progressively more area disturbed by fire in later iterations and time steps. After simulations were run, three outputs were chosen for each vegetation zone to represent the scenarios of low, moderate, and high future fire occurrence shown in Table 2.

Vegetation Zone	Susceptibility	Spread	Event rate	Time steps	Iterations	Write frequency
Boreal Forest	0.2	0.25	0.3	50	5	25
Forest/Tundra Boundary	0.25	0.23	0.48	50	2	10
Tree Limit	0.26	0.23	0.49	50	10	10
Upper Tundra	0.25	0.23	0.48	50	2	10

TABLE S2. Parameters used in this Marxan analysis and their treatment across all simulations. For a full list of Marxan parameters, see Table S1.

Parameter treatment	Importance
Value of 1 added to each planning unit (PU)	Cost scores of 0 represent "free" land. In order to avoid Marxan over-selecting land, all PUs were adjusted to reflect a base cost of 1.
Boundary length modifier (BLM) set to 1	The BLM is Marxan's prioritization of contiguity. In order to ensure that simulations responded most directly to changes in disturbance levels, the BLM was set to a low value of 1.
Species penalty factor (SPF) set to 1	The SPF reflects Marxan's prioritization of meeting targets for each use value. A high SPF results in a greater penalty for not meeting the targeted percentage of protected area for a certain use value. In order to ensure that simulations responded most directly to changes in disturbance levels, the SPF was set to a low value of 1 for all 40 use values.
PU disturbance score > 80 "locked out"	In order to emphasize the impact of increasing disturbance, any PU with a disturbance score greater than 80 was locked out of simulations and not included in output. A disturbance score of 80 represents the equivalent of 50% of a PU disturbed by wildfire, based on our disturbance weighting system.
Target features set to 50, 75, and 90%	Three sets of simulations were run for all disturbance scenarios in order to explore the feasibility of conserving a range of use values.

[1] School of Environmental Studies, University of Victoria, PO Box 1700 STN CSC, Victoria, British Columbia V8W 2Y2, Canada
[2] Corresponding author: tlantz@uvic. ca

APPENDIX 2

Parameters imported from Marxan input file (input.dat):

VERSION 0.1

BLM 0.1
PROP 0.5
RANDSEED -1
BESTSCORE 10
NUMREPS 10

Annealing Parameters:

NUMITNS 10000000
STARTTEMP -1.00000000000000E+0000
COOLFAC 6.00000000000000E+0000
NUMTEMP 10000

Cost Threshold:

COSTTHRESH 0.00000000000000E+0000
THRESHPEN1 1.40000000000000E+0001
THRESHPEN2 1.00000000000000E+0000

Input Files:

INPUTDIR input
SPECNAME spec.dat
PUNAME pu.dat
PUVSPRNAME puvspr2.dat
BOUNDNAME bound.dat

Save Files:

SCENNAME output
SAVERUN 2
SAVEBEST 2
SAVESUMMARY 2
SAVESCEN 2
SAVETARGMET 2
SAVESUMSOLN 2
SAVELOG 2
OUTPUTDIR output

Program control:

RUNMODE 1
MISSLEVEL 1
ITIMPTYPE 0
HEURTYPE -1
CLUMPTYPE 0
VERBOSITY 3

APPENDIX 3

Wildlife harvesting areas included in Marxan analysis (imported from Marxan spec.dat file). These 40 areas were selected because they were included in community conservation plans for Inuvik, Aklavik, Paulatuk, and Tuktoyaktuk (Inuvialuit Joint Secretariat, 2008a–d). Use areas were included in this analysis if wildlife harvesting was occurring within the area. In many instances, this fact was noted in the label of the area (i.e., Tuktoyaktuk Fall Caribou Harvesting). In other instances, the metadata for a particular area noted its importance for wildlife harvesting (e.g., Husky Lakes was noted as an important harvesting area for multiple communities).

1 Tuktoyaktuk Fall Caribou Harvesting
2 Tuktoyaktuk Fall Fishing
3 Tuktoyaktuk Fall Goose Harvesting
4 Tuktoyaktuk Fall Seal Harvesting
5 Tuktoyaktuk Spring Caribou Harvesting
6 Tuktoyaktuk Spring Fishing
7 Tuktoyaktuk Spring Goose Harvesting
8 Tuktoyaktuk Spring Moose Harvesting
9 Tuktoyaktuk Summer Caribou Harvesting
10 Tuktoyaktuk Summer Fishing
11 Tuktoyaktuk Summer Goose Harvesting
12 Tuktoyaktuk Winter Caribou Harvesting
13 Tuktoyaktuk Winter Fishing
14 Tuktoyaktuk Winter Wolverine Harvesting
15 Bluenose Caribou Winter Range
16 Caribou Hills
17 Eastern North Slope
18 First Creek Watershed
19 Firth Creek and Babbage Watersheds
20 Fish Hole, Cache Creek, and Big Fish River
21 Fish Lakes and Rivers
22 Husky Lakes
23 Inner Mackenzie Delta
24 Kugaluk River Estuary
25 Kugmallit Bay
26 Mackenzie Bay and Shallow Bay
27 Mackenzie River Delta Key Migratory Bird Habitat
28 Paulatuk Spring Caribou Harvest
29 Paulatuk Spring Fishing
30 Paulatuk Spring Grizzly Bear Harvesting
31 Paulatuk Spring Muskox Harvesting
32 Paulatuk Spring Wolf Harvesting
33 Paulatuk Summer/Fall Caribou Harvesting
34 Paulatuk Summer/Fall Fishing
35 Paulatuk Summer/Fall Grizzly Bear Harvesting
36 Paulatuk Winter Caribou Harvesting
37 Paulatuk Winter Fishing
38 Paulatuk Winter Muskox Harvesting
39 Paulatuk Winter Wolf Harvesting
40 Paulatuk Winter Wolverine Harvesting