

The Trans-Alaska Pipeline System Facilitates Shrub Establishment in Northern Alaska

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ABSTRACT. The Arctic tundra is undergoing many environmental changes in addition to increasing temperatures: these changes include permafrost degradation and increased shrubification. Disturbances related to infrastructure can also lead to similar environmental changes. The Trans-Alaska Pipeline System (TAPS) is an example of infrastructure that has made a major imprint on the Alaskan landscape. This paper assesses changes in shrub presence along the northernmost 255 km of the TAPS. We used historical satellite imagery from before construction of the TAPS in 1974 and contemporary satellite imagery from 2010 to 2016 to examine changes in shrub presence over time. We found a 51.8% increase in shrub presence adjacent to the pipeline compared to 2.6% in control areas. Additionally, shrub presence has increased significantly more in areas where the pipeline is buried, indicating that the disturbances linked to pipeline burial have likely created favorable conditions for shrub colonization. These results are important for predicting potential responses of tundra vegetation to disturbance, which will be crucial to forecasting the future of Arctic tundra vegetation.

Key words: shrub expansion; Arctic change; tundra; Trans-Alaska Pipeline System; permafrost; disturbance

RÉSUMÉ. La toundra de l'Arctique fait l'objet de nombreux changements environnementaux, sans compter que les températures augmentent. Ces changements touchent notamment la dégradation du pergélisol et l'intensification des arbustives. Les perturbations découlant des infrastructures peuvent également entraîner des changements environnementaux semblables. Le réseau pipelinier transalaskien (TAPS) est un exemple d'infrastructure qui a laissé d'importantes traces sur le paysage de l'Alaska. Dans cet article, nous abordons les changements concernant les arbustes sur le tronçon de 255 km le plus au nord du TAPS. Nous nous sommes servis d'images satellitaires historiques datant d'avant la construction du TAPS en 1974 ainsi que d'images satellitaires contemporaines pour la période allant de 2010 à 2016 pour examiner les changements caractérisant les arbustes au fil des ans. Nous avons constaté une augmentation de 51,8 % pour ce qui est de la présence d'arbustes adjacents au pipeline, comparativement à 2,6 % dans les aires de contrôle. De plus, la présence d'arbustes a augmenté beaucoup plus là où le pipeline est enfoui sous la terre, ce qui indique que les perturbations liées à l'enfouissement du pipeline ont vraisemblablement créé des conditions favorables à l'établissement d'arbustes. Ces résultats jouent un grand rôle dans la prévision des réactions éventuelles de la végétation de la toundra aux perturbations, ce qui est crucial en matière de prévision de l'état futur de la végétation de la toundra de l'Arctique.

Mots clés : intensification des arbustives; changement de l'Arctique; toundra; réseau pipelinier transalaskien; pergélisol; perturbation

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INTRODUCTION

The Arctic is experiencing warming at more than two times the mean global rate (IPCC, 2007), a process known as “Arctic Amplification.” Increases in regional temperatures are expected to result in widespread permafrost degradation (thermokarst), especially in areas where ground temperatures are close to freezing (Jorgenson et al., 2006; Shur and Jorgenson, 2007; Grosse et al., 2011). Ice-rich permafrost is an important factor that controls the responses of Arctic systems to disturbance (Walker and Walker, 1991). If thermokarst is initiated on a large

scale, it can take up to 30 years after the disturbance for stabilization to occur in ice-rich, unstable thaw areas (Lawson, 1986; Walker and Walker, 1991).

Disturbance to the surface in permafrost terrain results in a disruption of the thermal equilibrium, which can lead to increased thaw (Brown, 1997). Since the base of the active layer is impermeable to water and impenetrable to roots (NRC, 2003), permafrost warming and degradation changes the hydrological and nutritional characteristics of soils, which affect vegetation distribution, plant community structure, and productivity in Arctic and Subarctic regions (Reynolds and Tenhunen, 1996; Lloyd et al., 2003;

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Christensen, 2004). Thus, temperature changes affect both permafrost regimes and the related changes in hydrology and vegetation (Christensen, 2004).

Increasing productivity of Arctic vegetation in response to recent climate warming has been well documented (Goetz et al., 2005; Jia et al., 2006; Stow et al., 2007). A major component of these increases can be attributed to increases in deciduous shrub cover (shrubification), mostly *Betula*, *Salix*, and *Alnus* species (Myers-Smith et al., 2011a; Naito and Cairns, 2015), which may also be influenced by the permafrost regime. In turn, shrubification has the potential to affect many components of tundra ecosystems, such as the surface energy balance, hydrology, nutrient cycling, snow depth, and albedo (Swann et al., 2010; Naito and Cairns, 2011b; Pearson et al., 2013; Myers-Smith et al., 2015). Permafrost is not directly connected to the atmosphere because the influences of topography, groundwater, soil properties, vegetation, snow, and the interactions of these factors can result in positive or negative feedbacks to permafrost stability (Jorgenson et al., 2010). While permafrost plays an important role in shaping vegetation patterns, vegetation cover also has the potential to reduce permafrost degradation (Yi et al., 2007). However, there is still uncertainty regarding the relationship between shrub expansion and active-layer dynamics (Frost et al., 2018).

In Alaska, the discovery of oil at Prudhoe Bay in 1968 initiated the start of major industrial activity and environmental research in the Arctic (Walker and Walker, 1991). The Trans-Alaska Pipeline System (TAPS) was constructed over a period of three years, concluding in 1977, to move oil over 1287 km from Prudhoe Bay to the port of Valdez in a 1219 mm diameter pipeline (Brown and Kreig, 1983; Hall et al., 2003). The TAPS has made a significant imprint on the landscape: oilfield infrastructure on the North Slope of Alaska covers an area of 7429 ha (Walker et al., 1987a; Walker and Walker, 1991; Reynolds et al., 2014).

Infrastructure in permafrost terrain can cause ground-ice degradation by the structure itself or by modifying the subsurface conditions during the construction process (Bommer et al., 2010). Lawson (1986) found that ice-rich areas disturbed by exploratory drilling activities in the National Petroleum Reserve-Alaska took more than 30 years to stabilize to a point that would allow for vegetation growth and thermal equilibrium, whereas areas with ice-poor materials stabilized within 5 to 10 years. Although pipeline burial is the preferred method of construction for such infrastructure in nonpolar environments, this method can cause problems in permafrost regions because the subsurface heat from the transmission of the warm fluids results in permafrost thaw in the soils surrounding the pipeline and differential settlement (NRC, 2003). The Arctic Foothills and Arctic Coastal Plain are mostly underlain by deep continuous permafrost, with unfrozen areas mostly limited to deep river channels and deep lake basins (Brown and Berg, 1980). Since pipeline burial

requires thaw-stable conditions, 57% of the pipeline north of the Yukon River was constructed aboveground (Brown and Berg, 1980; Brown and Kreig, 1983). Following disturbance from the pipeline construction, thaw depths increased for at least the subsequent three years, reaching depths 28 cm greater along the oil pipeline than at control sites (Reynolds and Tenhunen, 1996).

The thermal stability of a disturbed area determines the timeframe for vegetation recovery, as well as the type of vegetation that is able to colonize a site (Walker and Walker, 1991). Most studies have emphasized the environmental impacts of roads, gravel sites, and the Prudhoe Bay Oil Field (e.g., Johnson, 1987; Walker et al., 1987a); however, a survey of published literature reveals that little is known about the current response of vegetation to the disturbance of the pipeline across the wide range of environments it traverses. Following construction of the TAPS, the Alyeska Pipeline Service Company attempted revegetation using a seed mix of grasses (Johnson, 1981). Initially, the revegetation process along the TAPS was found to be very slow (Walker et al., 1987b). At the time of the study by Johnson (1981), revegetation on disturbed areas by native species was limited, and establishment of *Salix pulchra* and *Betula nana* cuttings also had limited success. Some revegetated areas were dominated by grass cover from the seed mix of exotic species; the potential impact of their effects on native species revegetation was not known at the time (Johnson, 1981). The restoration of disturbed sites is often slow; however, even so, it has been found that revegetation can occur naturally (Forbes and Jefferies, 1999). Since gravel pads are akin to riparian gravel bars, it is likely that riparian species will be more successful in colonizing gravel pads (Bishop and Chapin, 1989). At present, natural colonizers that are well adapted to well-drained, nutrient-poor soils have become the dominant species along the TAPS (Jorgenson, 1997). However, we still have much to learn regarding the impacts of energy development on the processes of tundra ecosystems and how best to rehabilitate these ecosystems (Reynolds and Tenhunen, 1996).

Here, we aimed to assess the state of shrub presence along the TAPS north of the Brooks Range, Alaska. Our objectives were to determine (1) whether shrub presence has increased more near the pipeline than in adjacent undisturbed areas, and (2) whether the placement of the pipeline (aboveground or buried) has an impact on shrub presence.

METHODS

Study Area

The North Slope of Alaska is the 230 000 km² area north of the crest of the Brooks Range. This area is divided into three regions: the Arctic Coastal Plain, the Arctic Foothills, and the Brooks Range. The North Slope is underlain

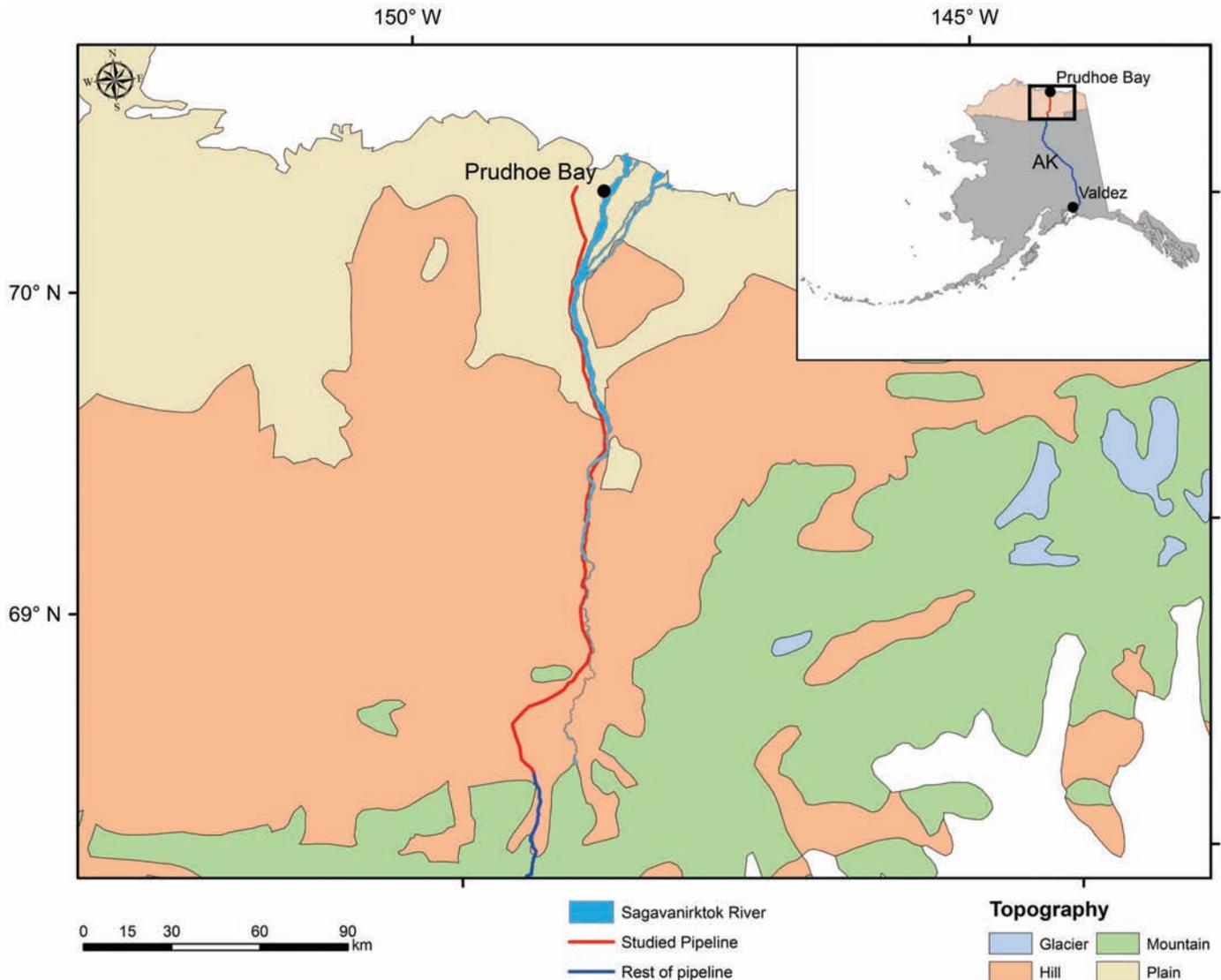


FIG. 1. Path of the section of the pipeline studied, including topography and the Sagavanirktok River. Topographical data from Reynolds and Cooper (2016).

by continuous permafrost (> 90% coverage), and sedge tussocks and shrubs characterize the tundra vegetation. The most common shrub species are birch (*Betula nana* and *B. glandulosa*), willow (*Salix alaxensis*, *S. pulchra*, and *S. glauca*), and alder (*Alnus crispa*) (Tape et al., 2006). Most of the oil activities are constrained to the Arctic Coastal Plain; however, the TAPS corridor stretches 1287 km from Prudhoe Bay in the north to Valdez in the south (Fig. 1).

Satellite Image Acquisition and Analysis

Digital scans of historical black-and-white images from 21 June 1974, captured by the Keyhole satellite system (KH-9) with a high spatial resolution of 2–4 feet, were acquired from the U.S. Geological Survey Earth Resources Observation and Science Center. The historical images were co-registered to the contemporary images using ArcMap 10.5. The contemporary panchromatic images for the entire 255 km section were sourced from

the DigitalGlobe archives (DigitalGlobe, Inc., USA). The contemporary images were captured in June to September of 2010–16 by the Worldview-1 (0.5 m), Worldview-2 (0.46 m), Worldview-3 (0.31 m), and GeoEye-1 (0.41 m) satellites (DigitalGlobe, Inc., USA). Images were selected for lack of cloudiness and snow. The pipeline was classified as either “aboveground” or “buried,” with a total of 110 km of pipeline aboveground and 115 km of buried pipeline. Transects that were located over gravel pads or rivers were marked as “obstructed” and excluded from analysis.

To address the first objective, five control lines not affected by the TAPS were used to determine whether the increase in shrub presence over time was greater along the pipeline than in the adjacent tundra (Fig. 2). Control lines were placed parallel to the pipeline; every effort was made to put the control lines in settings similar to those of the adjacent pipeline. Where possible, this was done by placing the control lines on the opposite side of the Sagavanirktok River and at a similar distance from the river as the

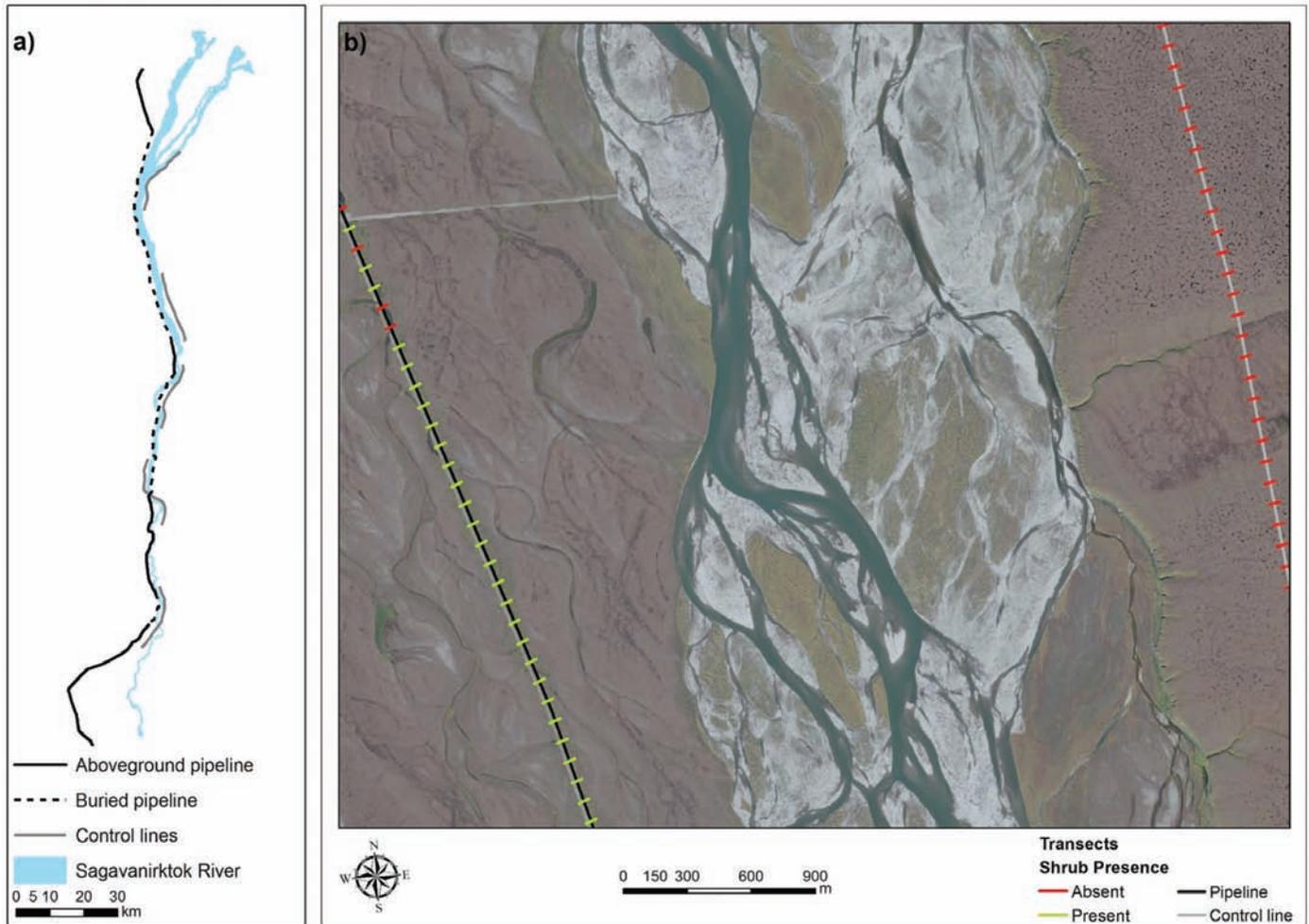


FIG. 2. a) The path of the pipeline and control lines in relation to the Sagavanirktok River. b) Example of the pipeline and a control line with sample transects from WorldView-2 imagery (© 2016 Digital Globe, Inc.).

pipeline was at that point (Fig. 2). Transects 50 m wide and perpendicular to the line were created at 100 m intervals along the pipeline and control lines, using ArcMap 10.5. The transects were manually classified according to whether they intersected shrub cover or not, limiting classification to the presence or absence of tall shrubs. We recorded shrub presence (“1”) or absence (“0”) along 1090 transects on the control lines of both the historical and contemporary imagery. We then repeated this process using 1037 transects at parallel points along the pipeline to assess change in shrub presence over time (e.g., Fig. 3). To quantify the contemporary association between the pipeline burial status and shrub presence for objective two, we classified a total of 2155 transects along the 255 km of studied pipeline for shrub presence (“1”) or absence (“0”). Any transects intersecting a gravel pad, river or lake were omitted from the analysis.

Statistical Analysis

Change detection was conducted by subtracting the historical classification values from the contemporary

classification values. Values of “-1” represented a loss in shrub presence, “0” indicated no change, and “+1” indicated shrub presence along a transect where there was none previously. Pearson’s chi-squared test with Yate’s continuity correction was used to test for the association between shrub presence and pipeline burial status.

RESULTS

Changes in Shrub Presence over Time

In the control areas, a total of 67 of the 1090 transects (6.1%) intersected shrubs in the historical imagery. Of the 1090 transects, only 29 (2.6%) transitioned from “no shrub” in the historical imagery to “shrub” in the contemporary imagery (Fig. 4). Along the pipeline, 95 of the 1037 (9.2%) transects intersected shrubs in the historical imagery. A greater increase in shrub presence was found in the vicinity of the pipeline; of the 1037 transects, 602 (58.1%) transitioned from “no shrub” to “shrub” in the contemporary imagery. A total of 29.6% of the sampled

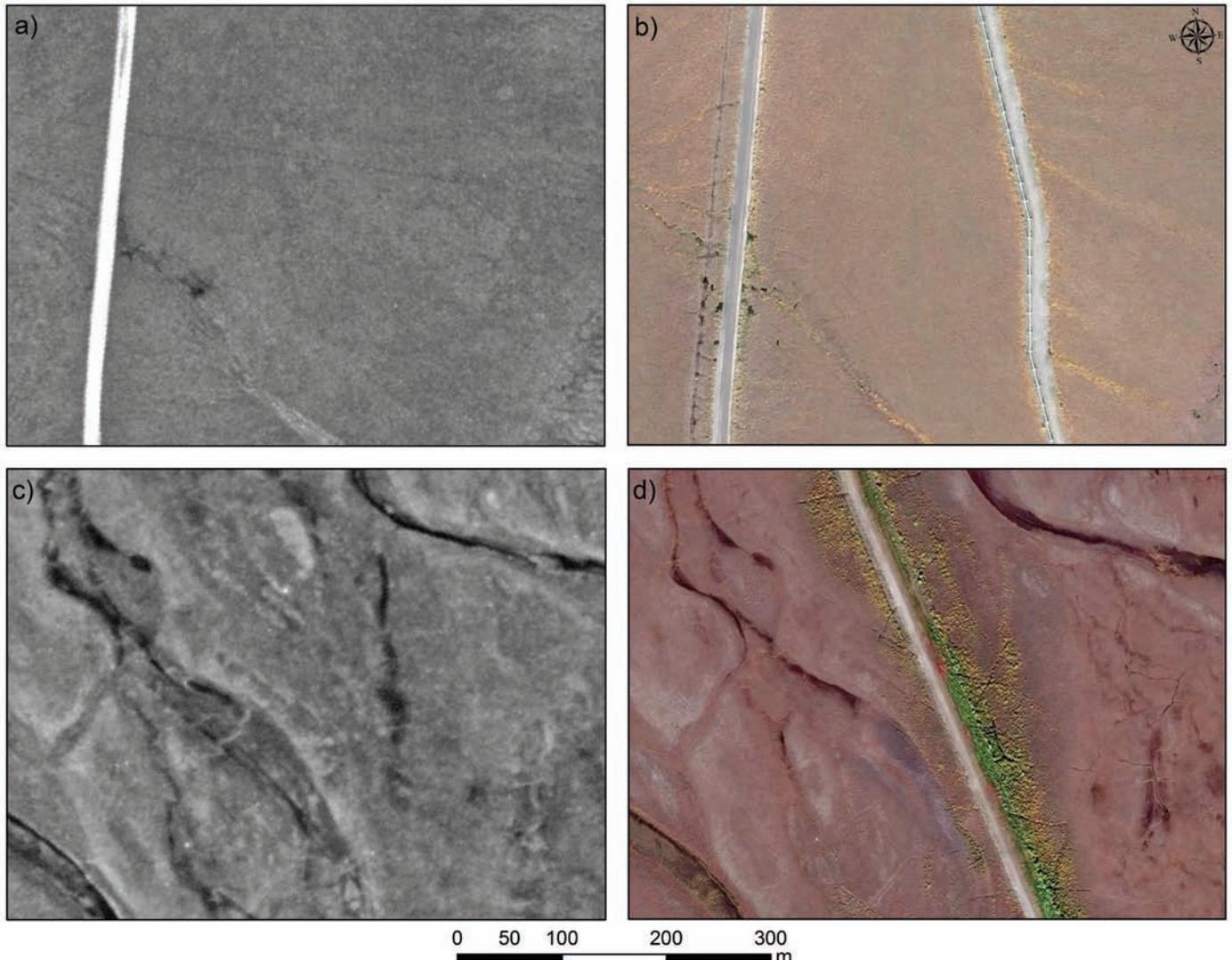


FIG. 3. a) Historical image of a location where a pipeline was later constructed aboveground. b) Contemporary image of that aboveground pipeline, from WorldView-2 imagery (© 2016 Digital Globe, Inc.). The straight line at the left of both images is the Dalton Highway. c) Historical image of a location where a pipeline was later buried. d) Contemporary image of that same location with buried pipeline, from WorldView-2 (© 2016 Digital Globe, Inc.).

transects transitioned from “no shrub” to “shrub” (Fig. 4). None of the sampled transects lost the presence of shrub cover along the control transects over time; however, one pipeline transect transitioned from having shrub cover in the historical imagery to not having shrubs in the contemporary imagery.

Relationship between Shrub Presence and Pipeline Burial Status

In areas where the pipeline is aboveground, only 14.9% of the transects transitioned from “no shrub” to “shrub” (Fig. 4). In areas where the pipeline is buried, 70.2% of the transects transitioned from “no shrub” to “shrub” (Fig. 4).

Chi-squared analysis was conducted to test for an association between pipeline burial status and shrub presence along the entire 255 km of pipeline north of the Brooks Range. The associations, as seen in Table 1,

yielded a highly significant relationship ($\chi^2 = 1078.2$, $p < 0.01$) between shrub occurrence and pipeline burial status. This indicates that shrubs are more likely to establish in areas where the pipeline is buried than in cases where it is aboveground.

DISCUSSION

Change over Time

This study found that shrub presence increased by 58.1% in the vicinity of the pipeline, as opposed to 2.7% for the control transects, which suggests that the processes linked to the disturbance from the pipeline have facilitated shrub colonization. While shrub expansion in the Arctic has been widely reported, certain areas are more susceptible to shrub encroachment (Sturm et al., 2001; Tape et al.,

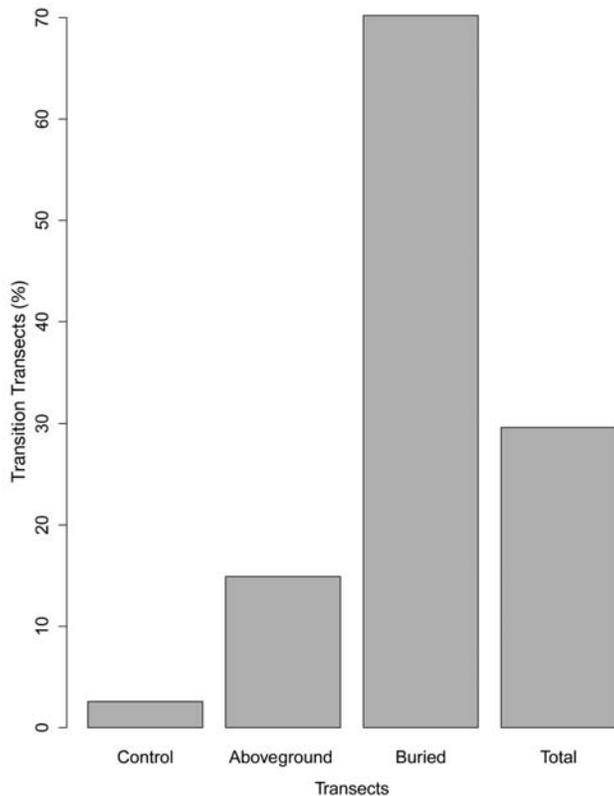


FIG. 4. Influence of pipeline burial on shrub presence. Graph shows the percentage of transects (control, aboveground pipeline, buried pipeline, and total) that transitioned from absence of shrubs in the historical imagery to shrub presence in the contemporary imagery.

TABLE 1. Associations between shrub presence and pipeline burial status, expressed in number of transects.

Pipeline burial status	No shrubs	Shrubs present	Total
Aboveground	958	132	1090
Buried	183	882	1065
Total	1141	1014	2155

2006; Hallinger et al., 2010; Myers-Smith et al., 2011b; Naito and Cairns, 2011a, 2015; Elmendorf et al., 2012b; Frost et al., 2013; Ackerman et al., 2017; Martin et al., 2017; Myers-Smith and Hik, 2017). The percent increase in shrub presence along the control transects is relatively low compared to some of the rates published in the studies listed above, which indicates that local conditions play a major role in facilitating shrub expansion (e.g., Tape et al., 2006; Myers-Smith et al., 2011b; Naito and Cairns, 2011b, 2015; Ackerman et al., 2017). Jorgenson et al. (2015) found that even though shrub expansion rates were relatively low for the region of northwest Alaska as a whole, they were highly variable according to ecotype and biophysical drivers. Favorable local conditions include floodplains, areas with higher topographic wetness index values (Naito and Cairns, 2011b), and frost-heaved soils (Frost et al., 2013). The disturbance of the ground from the TAPS

construction process, and the pipeline itself could create similar conditions to the favorable conditions that occur naturally, and hence, facilitate shrub colonization.

Influence of the Pipeline

While we found that increases in shrub presence were greatest in the vicinity of the pipeline, these results were not uniform along its entire length. A significant relationship ($p < 0.01$) between shrub presence and pipeline burial status was found. This relationship is highly evident in Figure 5, with sharp changes even occurring where the pipeline transitions from being aboveground to buried. Processes linked to the disturbance from construction and the pipeline itself have likely created favorable conditions for recruitment. The buried pipeline increases the adjacent active layer thickness (Reynolds and Tenhunan, 1996), which will likely allow for greater moisture throughflow and rooting depths. Chapin and Shaver (1981) found that plants in areas affected by disturbance from vehicles had improved nutrient status (and therefore, high productivity); however, they concluded that this result could not be attributed solely to increases in soil temperature and thaw depth. Gill et al. (2014) found that the environmental changes associated with road construction facilitated alder growth and recruitment along the Dempster Highway in the Northwest Territories, Canada. Such changes can include altered surface energy balance, ground thermal properties, and the temperature regime of the underlying permafrost (Forbes and Jefferies, 1999; Forbes et al., 2001; Gill et al., 2014). A study by Ackerman and Breen (2016) notes four stands of *Populus tremuloides* on abandoned gravel roads and pads in the northern foothills of the Brooks Range, Alaska, which is north of the species' range. The authors attribute their presence to the favorable conditions created by the pads: increased rooting depth, well-drained microsites, an extended growing season, and acid-buffering capacity (Ackerman and Breen, 2016). Without ground observations it is beyond the scope of this study to posit the exact mechanism driving increased shrub growth along the pipeline (particularly where it is buried). However, like Gill et al. (2014) and Ackerman and Breen (2016), we suggest that the recruitment of new individuals along the pipeline is likely due to the creation of more favorable conditions, probably in the form of deeper rooting depths, well-drained microsites, and increased nutrient availability.

Implications

Shrub expansion is limited by local conditions. Disturbance is therefore an important factor influencing shrub presence and may even have a greater influence than climate warming in the recruitment of new individuals (Myers-Smith et al., 2011b). Shrub cover linked to disturbance can influence other parts of systems through feedbacks. Shrub proliferation along roads in the Canadian tundra resulted in a positive feedback cycle through



FIG. 5. Image from WorldView-3 (© 2016 Digital Globe, Inc.) showing the abrupt change in vegetation along the pipeline as it transitions from aboveground (red) to buried (black).

increased snow accumulation, altered ground temperatures, and soil chemistry (Gill et al., 2014). In areas where tall shrubs were not as established, not as much snow and dust accumulated; therefore, the feedbacks were not as pronounced (Gill et al., 2014). Positive feedbacks similar to those observed by Gill et al. (2014) could be expected along the pipeline in places where shrubs trap the snow, increasing snow depth. This positive feedback could have significant implications for the stability and integrity of infrastructure in tundra environments. It is essential to obtain better knowledge of how Arctic tundra vegetation recovers from disturbance to provide an idea of its potential responses to future disturbances, which are likely to become more frequent (Chapin et al., 2005; Cray and Pollard, 2015).

CONCLUSIONS

This study has shown that shrub colonization has been facilitated by processes linked to the disturbance of the TAPS. Identifying which factors are responsible for the recruitment of new individuals is imperative to quantify the impact of shrub expansion on the Arctic tundra ecosystems (Myers-Smith et al., 2011b). While this study cannot definitively identify the causes of shrubification, the correlation between shrub presence and the disturbance of the pipeline provides useful knowledge of how the vegetation has responded, with shrubs exploiting disturbed areas. Understanding the responses of tundra to disturbance and characterizing the vulnerability of the Low Arctic to tall shrub and tree expansion is critical for projecting possible feedbacks (Elmendorf et al., 2012a; Frost and Epstein, 2014). The findings of this study align with other Arctic studies (e.g., Gill et al., 2014; Ackerman and Breen, 2016); therefore, this study will contribute to

obtaining a better understanding of the cumulative effects of anthropogenic disturbances and how the Arctic tundra environment may respond to continued disturbances.

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