



Shrubification along Pipeline Corridors in Permafrost Regions

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Abstract: Pipeline corridors have been rapidly increasing in length and density because of the ever growing demand for crude oil and natural gas resources in hydrocarbon-rich permafrost regions. Pipeline engineering activities have significant implications for the permafrost environment in cold regions. Along these pipeline corridors, the shrubification in the right-of-way (ROW) has been extensively observed during vegetation recovery. However, the hydrothermal mechanisms of this ROW shrubification have seldom been studied and thus remain poorly understood. This paper reviews more than 112 articles mainly published from 2000 to 2022 and focuses on the hydrothermal mechanisms of shrubification associated with environmental changes induced by the rapidly degrading permafrost from pipeline construction and around the operating pipelines under a warming climate. First, the shrubification from pipeline construction and operation and the ensuing vegetation clearance are featured. Then, key permafrost-related ROW shrubification mechanisms (e.g., from the perspectives of warmer soil, soil moisture, soil type, soil nutrients, topography and landscapes, and snow cover) are discussed. Other key influencing factors on these hydrothermal and other mechanisms are hierarchically documented as well. In the end, future research priorities are identified and proposed. We call for prioritizing more systematic and in-depth investigations and surveys, laboratory testing, long-term field monitoring, and numerical modeling studies of the ROW shrubification along oil and gas pipelines in permafrost regions, such as in boreal and arctic zones, as well as in alpine and high-plateau regions. This review can improve our understanding of shrubification mechanisms under pipeline disturbances and climate changes and help to better manage the ecological environment along pipeline corridors in permafrost regions.

Keywords: shrubification; engineering disturbances; climate change; permafrost thaw; soil drainage

1. Introduction

Pipeline corridors, as one representative type of linear engineering infrastructures and environmental disturbances, are widespread owing to the growing demand for natural resources [1,2]. Pipeline corridors are created for oil and gas exploration and transportation in hydrocarbon-rich boreal and tundra ecosystems in North America [3] and northern Eurasia [4], and in other alpine and high-plateau permafrost regions at mid- to low latitudes, e.g., [5–7]. There are more than 2485 km of pipelines in Alaska, 2031 km in China [8], and



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Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). hundreds of potential routes and tens of thousands of kilometers for pipelines in northern Canada and Russia [9].

Pipeline systems built in permafrost regions are represented by the Alyeska (Trans-Alaska) pipeline system in Alaska, USA, the Norman Wells Oil Pipeline in western Canada, the Eastern Siberia to Pacific Ocean Oil and Gas Pipelines Systems (ESPO) in Russia and its spur line, the China-Russia Crude Oil Pipelines (CRCOP) in northeast China, and the Golmud-Lhasa Products Oil Pipeline (GLPOP) on the interior Qinghai-Tibet Plateau in southwest China [5,10]. Construction of pipeline corridors generally necessitates the partial (elevated construction mode) or complete (burial construction mode) clearance of surface vegetation (except arctic tundra due to low vegetation height) along a belt transect 5–20 m in width (also named the pipeline right-of-way (ROW)) [11,12]. Furthermore, roots of trees and other vegetation and surface organic soil are removed for machine and vehicle movement. For buried pipelines, a trench about 1.5–2.0 m in width or wider and 1.5–3.0 m in depth (depending on the depth of the permafrost table, pipe diameter, and the associated pipe-wall configurations) is excavated [13]. Soil is backfilled after installation of pipelines [14]. These construction processes have substantial ecological impacts, altering the abiotic and biological environments, usually extending far beyond the pipeline corridor widths [15].

Pipeline construction and operation, as well as maintenance (e.g., by adding more readily available gravelly soils above or near pipelines to mitigate water and wind erosion and filling up the thermokarst lakes and depressions with soils) and emergency responses, may generally result in permafrost degradation, as evidenced by a warmer soil/ground, lowering the permafrost table and/or thickening the active layer, ground surface subsidence and thermokarsting, and formation of the supra-permafrost subaerial talik; consequently, they modify or alter the physical, biophysical, chemical and biological properties of foundation soils [1,16].

Pipeline disturbances may have profound implications for boreal forest, wetlands and peatlands, and arctic/alpine tundra ecosystems, where, because of low temperatures, vegetation recovery rate is slow, if ever possible, to return to the pre-disturbance state under severe disturbances [11,17]. Shrub invasion, colonization, establishment, and expansion in the ROW, as characterized by increases in abundance, coverage, and phytomass, also known as shrubification, have been reported in many permafrost regions during vegetation recovery e.g., [14,18–20]. Shrubification in the ROW has been linked to permafrost thaw and soil disturbances resulting from pipeline construction and operation [11,12,18]. However, how permafrost thaw influences shrubification in the ROW along pipeline corridors remains evasive [21].

This shrubification, in turn, suppresses the growth and development of herbaceous plants [15] that could effectively mitigate soil erosion and help water and soil conservation in the ROW [22]. In addition, shrubification in the ROW may destabilize the foundation soils of pipeline systems by accelerating permafrost thaw, trapping more snow and anchoring more deep roots, and changing the hydrothermal environment of pipeline foundation soils; these changes may incur other damages that impair the integrity and safety of pipeline systems [23]. However, hydrothermal/abiotic and nutrient/biotic mechanisms of ROW shrubification have been seldom studied and thus remain poorly understood [18,21].

This review adopted the Systematic Review and Meta-analysis Protocols (PRISMA-P) 2015 to guide the systematic reviews [24] in searching the publications relevant to land shrubification in the ROW along the pipeline corridors, particularly in permafrost regions. The Web of Science Core Collection database was also used to search for the relevant peer-reviewed articles published in English between 2000 and 2022 through keyword search [25]. All subject categories were included in the search terms (Table 1).

| Category | Specific Standard Requirements | | | |
|--------------------|--|--|--|--|
| Research database | Web of Science Core Collection and Google Scholar | | | |
| Citation indexes | SCI-Expanded and SSCI | | | |
| Searching period | January 2000 to April 2022 | | | |
| Language | English | | | |
| Searching keywords | TS = ((pipeline vegetation AND permafrost) OR (pipeline shu OR pipeline shrubification) OR ("seismic lines")) | | | |
| Subject categories | All | | | |
| Document types | Articles and review articles | | | |
| Data extraction | Export with full records and cited references in plain test format | | | |
| Sample size | 112 | | | |

Table 1. Summary of data sources and selection methods in this paper.

The search strategy selected was TS= (("pipeline vegetation" AND "permafrost") OR ("pipeline shrub" OR "pipeline shrubification") OR ("seismic lines" OR "tundra road")). Furthermore, some articles that were inconsistent with the targeted topics were removed from the records, while other articles that were relevant to the topics from Google Scholar were included in the proper citations, critical reviewing, and integral analysis of this paper. Finally, 112 articles were obtained.

This review focuses on permafrost-related mechanisms of ROW shrubification along pipeline corridors. ROW shrubification along pipeline corridors is defined and documented first. Then, key permafrost-related environmental variables and other factors associated with ROW shrubification are hierarchically analyzed. Finally, future research priorities for ROW shrubification are identified and proposed. This study can improve our understanding of ROW shrubification after engineering disturbances under a warming climate. The review will help better design, construct, and operate the oil and gas pipelines in permafrost regions, and it will also help manage cold region environments along engineered pipelines in a sustainable manner.

2. Shrubification along Pipeline Corridors in Permafrost Regions

Vegetation is greatly disturbed by pipeline construction since plants are removed in the ROW along the corridor at the initial stage of pipeline engineering (Figure 1a,b) [12,14]. In this section, we discuss the observed shrubification along pipeline corridors in permafrost regions and some seismic lines created for resource exploration [11,12,21]. Pipeline corridors and seismic lines have similar characteristics from removal of the surface vegetation in boreal forests, and shrubification is also extensively observed in seismic lines in boreal forests and arctic tundra ecosystems (Table 2). Moreover, there are fewer studies engaged in documenting vegetational changes in the pipeline ROW in permafrost regions.

The impacts of pipeline corridors can reach far into the adjacent ecosystems [15,26]. For example, Abib et al. [3] found that the impacts of seismic lines on the adjacent ecosystems extended laterally to 55 m, and the vegetation height varied greatly within 5 m of the pipeline axis in a proximal boreal forest and wetland environment. Li et al. [14] found that the hydrothermal impacts of buried CRCOPs I and II extended laterally to about 60 m in the undisturbed hemiboreal forest in the northern Da Xing'anling Mountains in northeast China.

| Shrubification Features Shrubification Indices | Trajectory | Geographic Location | Study Method | Environmental Attribute | Disturbance Type | Selected References |
|---|--|-----------------------------|-------------------------------|--|-----------------------------------|------------------------|
| Shrub cover | Increase/ abundant | Alberta, Canada | Field survey | Soil moisture | Seismic line/forest | [2,17,19,26] |
| Cover of evergreen shrub/deciduous shrub | Decrease/ Increase | Northeastern Alaska, USA | Field survey | Soil moisture | Seismic line/tundra | [11,27] |
| Shrub cover | Increase | Northeastern China | Field survey | Permafrost table | Pipeline disturbance | [14] |
| Shrub presence | Increase | Northern Alaska | Remote Sensing | Active layer thickness and soil moisture | Pipeline disturbance | [18] |
| Shrub area | Increase in bog, while vary in fen | Alberta, Canada | Bi-temporal airborne lidar | Soil moisture | Seismic line/boreal wetland | [20] |
| Shrub cover | Increase | Alaska | Field survey | Soil properties | Pipeline disturbance | [28] |
| Shrub diversity | Decrease | Northeastern China | Field survey | Soil nutrient | Pipeline disturbance | [29] |

 Table 2. Shrubification along pipeline corridors/seismic lines based on selected references published since 2000.

In a spatial pattern, with the increasing perpendicular distance from the ROW, plant species diversity and recovery rates increase in the engineering construction- and maintenancedisturbed area of the ROW, and plant community structure and dominant species differ greatly from those in the increasingly undisturbed area going laterally away from the pipelines [3,30]. In boreal forest and arctic tundra ecosystems, vegetation may not recover to its pre-pipeline construction state [11,28]. This is because of the competitive advantages of non-native and invasive species, which are disturbance-tolerant, aggressive, and fast-growing [19]. Furthermore, tree seedlings grow much slower in the ROW compared to those in the adjacent forest, since the abundant 1-m-tall invasive graminoids are shading and smothering small conifer seedlings [12]. In the arctic tundra, compared to those at the undisturbed sites, the patterns of vegetation recovery at the disturbed sites are characterized by increases in coverage of graminoids, forbs, and deciduous shrubs and a decrease in coverage of evergreen shrubs [11].

During the period of vegetation recovery after pipeline construction, herbs and shrubs jointly develop in the disturbed areas, but the shrubs, the *Salix* spp. in particular, are more competitive in gaining the average coverage and the amount of space in the newly available habitats (Figure 1c) [27]. A survey along the Alyeska pipeline route in Alaska, USA, showed that the pipeline construction area was fully covered by shrubs in 5 years without artificial intervention [28]. In addition, remote sensing results indicated a 51% increase in shrub cover in the areas adjacent to the pipeline from 2010 to 2016, but only a 2.6% increase in the natural/undisturbed areas in the same period [18]. Although shrub cover increases during recovery, shrub diversity may decrease after pipeline disturbance (Table 2). In the ROW of CRCOP I, which was built during 2009–2010 and began operation in 2011, shrub diversity declined in the pipeline construction area, while the shrub phytomass increased in the undisturbed Rhododendrom dauricum-Betula platyphylla forest in 2014 [29]. After disturbance, the evergreen shrub cover decreases, while that of deciduous shrub increases [11]. Finnegan et al. [17] found that large shrubs, such as alder (*Alnus* spp.), birch (Betula spp.), and willow (Salix spp.), were more likely to present and more abundant in wet soils with poor or medium nutrients, while dwarf (low-statured) shrubs, such as Vaccinium spp. and *Rhododendron* spp., were associated with dry soils in the ROW along the pipelines with medium or rich nutrients. Generally, shrub growth is light-preferred, and the cover is



greater and more abundant in the ROW along the pipelines, on edges of forest stands, and in open and young forests [31].

Figure 1. Construction and shrubification of the China-Russia Crude Oil Pipelines (CRCOP) I and II at the eastern flank of the northern Da Xing'anling Mountains in the northern part of northeast China. (a) Removal of surface vegetation in winter 2009 prior to the ditching for pipeline laying; (b) soil disturbances increased the presence of gravels on the ground surface immediately above the CRCOP II (photo taken in September 2020); (c) shrubification in the pipe ROW (photo taken in September 2020), and (d) thermokarst ponds in construction-disturbed area alongside the access road to the pipelines (photo taken in September 2020). Notes: The CRCOP I was built in the period from May 2009 to October 2010, and it was put into operation in January 2011; the CRCOP II was built from August 2016 to December 2017 and it was put into operation in January 2018.

In the ROW in permafrost regions, the impacts of pipeline disturbances on local vegetation are determined by pipeline corridor/ROW widths and depths of soil disturbances, corridor orientation/directions and complexity, ecosystem types, substrates, and postconstruction stage (time) of vegetation recovery [32,33]. Meanwhile, ground ice content plays an important role in permafrost regions, and the melting of ground ice caused by the warming ground and ensued thermokarsting processes dramatically alter the permafrost landscapes, creating new and exposed soils/niches for plant species invasion and colonization. Thus, we need to better understand the impacts of rapid permafrost degradation on shrubification along the pipeline corridors under a rapidly changing hydroclimate [34].

3. Hydrothermal and Biophysical Mechanisms of Pipeline ROW Shrubification

3.1. Permafrost Thaw along the Pipeline Corridor

Despite the different characteristics of the permafrost environment, such as climate, vegetation types (e.g., boreal forest or tussock tundra), ground ice content, topography (upland, slopes, or lowland) and soil types, permafrost thaw has been extensively observed

along pipeline corridors [16,35–37]. Permafrost thaw induced by pipeline construction and operation is mainly attributed to vegetation and soil disturbances during the pipeline construction [38] and the heating from the operating pipeline buried in the near-surface permafrost and active layer. During the period of pipeline construction, vegetation is removed, which could increase the incoming short radiation, reduce the surface albedo, and control the surface conductance and surface temperature; these processes increase the incoming energy into the ground, resulting in a warmer surface soil, a thicker active layer, melting of ground ice, ground surface subsidence, and formation of supra-permafrost subaerial taliks (Figure 2) [1,6,14,16,36].



Figure 2. Schematic diagram of key permafrost-related factors associated with shrubification along a buried pipeline corridor. The symbol "+" means enhanced environmental variables and facilitated shrubification. Notes: Figure 2 shows that surface vegetation removal would result in more light shed on the ground surface. This warms the surface soil, increases soil moisture and nutrient availability, melts the ground ice, thickens the active layer, and leads to thermokarsting in the ROW. Soil disturbances, water erosion, and frost sorting increase the content of surface gravels, further improve the soil drainage and preferential flow along the supra-permafrost subaerial talik under the ROW. These collectively favor the shrubification. In addition, ground heating from pipeline engineering and snow accumulation/redistribution from increasing shrub presence and height may accelerate permafrost thaw, positively feeding back to the ROW shrubification.

Pipeline disturbance generally results in rapid permafrost degradation by increasing soil temperature in the ROW compared to the adjacent undisturbed areas off the ROW [37,39,40]. Monitoring of ground temperature in a borehole at the kilometer post 304 site showed that soils at shallow depths in the ROW 1.2 to 2.1 m away from the CRCOP pipeline axis were warmed by 1 °C and permafrost (as indicated by the mean annual ground temperature (MAGT) at the depth of zero annual amplitude of ground temperature, 15 m) were warmed by 0.16 °C from 2012 to 2014 in an intermontane boreal wetland [39]; under a warming climate, MAGT increased by 0.3 °C under the ROW, while that off the ROW increased by only 0.1 °C from 2014 to 2018 [36].

Rising soil temperature results in an enlarged active layer thickness (ALT), lowered burial depth of the permafrost table, and the formation of thaw bulbs/cylinders (suprapermafrost subaerial talik) around the buried pipeline in permafrost regions [13,14,41]. In alpine meadows in the Laji Mountains on the northeastern QTP, the greatest burial depth of the alpine permafrost table was 7.0 m observed from August 2016 to July 2017 under the disturbances of two gas pipelines, while the ALT was about 1.5 m under the nearby natural/undisturbed alpine meadows or wetlands/bogs underlain by attached permafrost [42]. Substantial permafrost changes in the ROW were found in the pipeline foundation soils in wetland and forest areas along the CRCOPs [13,16,36,39]. Borehole monitoring data of the CRCOP I in a wetland revealed a thaw depth (permafrost table) of about 6.0 m in the ROW, while only 2.0 m off the ROW in October 2014, and the permafrost table lowered to 8.0 m in depth in October 2017 [37]. At the same time, the thaw bulb was detected by ground penetration radar (GPR) surveys in the same location. According to GPR results, the thaw bulb was 0.5 m above the CRCOP I (initial burial depth was 1.6 m), 2.0 m under the CRCOP I, and 3.5 m laterally from CRCOP I in March 2014 (3 years after operation) in a wetland [39]. For the CRCOP II, the base of the thaw bulb lowered from 4.9 m in depth in 2014 to 9.7 m in 2018 [36], indicating a rapid permafrost table was about 10.0 m in the ROW, while that off the ROW was 2.0 m in October 2017 [43]. Recent surveys and monitoring by electrical resistivity tomography (ERT) along the CRCOPs showed that the burial depth of the permafrost table in the ROW was 1.7-6.7 m lower than that in the undisturbed forest areas, and the rate of thaw bulb development was 1.0 m/a in zones of discontinuous permafrost in the northern part of CRCOPs [14,16].

Increases in soil temperature from pipeline disturbances lead to melting of ground ice and ensuing ground surface subsidence and the development of ponding/thermokarst in the ROW [14,44]. Thaw settlement was detected or observed immediately following pipeline operation, and progress in the ground settlement depends on soil types, vegetation cover, ground ice content, landforms, and elapsed time after pipeline operation [38,39,44,45]. For example, thaw settlement in the ROW continued to develop after 17 years of operation of the Norman Wells pipeline, and the amounts of ground surface settlement differed among sites, with fine-grained lacustrine soils (0.4–0.7 m), coarse-grained tills (0.1–0.35 m), and organic soils (0.7 m) [45]. Field observations combined with remote sensing data along a 400 km section of the CRCOPs in 2018 indicated that there were 264 ponds/thermokarst, of which about 47% were larger than 500 m², and most of these ponds/thermokarst were distributed in areas underlain by ice-rich permafrost [44].

Although rapid and persistent permafrost thaw resulting from pipeline construction, operation, and associated heat accumulation was observed by site surveys, field monitoring, and remote sensing, the rate of permafrost thaw could be effectively reduced by proper pipeline insulation, air-cooled embankment, and some other mitigative measures as evidenced by site and laboratory experiments and numerical model simulations under a warming climate [13,40,42,44,46]. However, most of the abovementioned engineering studies focused on the relationships between the pipelines and pipeline foundation soils. Thus, understanding the responses of current and future permafrost to pipeline disturbances and changes in ecosystem variables, especially vegetation composition and cover, should be taken into account. Because permafrost in these boreal and arctic regions is ecosystem-dominated (driven, modified or protected), it is fragile and sensitive to disturbances, e.g., [47,48].

3.2. Soil Moisture, Topography, and Soil Drainage

The movement of heavy/crawler machines and vehicles during pipeline construction and operation increases soil compaction and bulk density, and therefore, it decreases soil water holding and retention capacities [1]. The melting of ground ice resulting from pipeline construction and operation increases ALT and soil moisture contents in the ROW, which increases the depth of root spreading for deeper-rooted shrubs, favoring shrub expansion in the flat, open areas and lowlands [49]. Boulanger-Lapointe et al. [50] found greater shrub colonization at the sites with a higher soil moisture content compared with those sites with limited water availability in the High Arctic of Greenland and Canada. Remote sensing and field investigations showed the close association of higher soil moisture and thicker organic soils with tall shrub expansion adjacent to the Dempster Highway, Northwest Territories, Canada [51].

The melting of ground ice may also result in thaw subsidence of the ground surface and (differential) thaw settlement of foundation soils and underlying permafrost; snow and ice melt-water, and precipitation bring more water to fill these depressions, forming positive feedbacks to ground thaw settlement and ground surface subsidence [34,52]. These shallow thaw depressions could further develop into thermokarst lakes and ponds and thaw slumps and wetland environment, which may enhance the hydraulic connectivity via deepened, elongated, and/or new surface and subsurface flow paths [53,54]. These processes result in changes in microtopography and landscapes, creating drier areas adjacent to thermokarst depressions and lakes/ponds and improved soil drainage, thereby favoring the shrub establishment and growth [55,56]. Field surveys found that tall shrubs (e.g., *Betula nana* and *Salix glauca*) were more dominant on thaw pond banks, where the soil drainage was improved and there was lower soil moisture content in comparison with those in the tundra and thaw pond channels on the Seward Peninsula, Alaska [57]. However, excess soil moisture may limit shrub growth [58], and sedges dominate in wetlands in the ROW [16,36].

In addition, pipeline foundations (backfilled into pipe trenches) and periodical maintenance on flat or concave ground could also intercept or alter shallow groundwater paths, generate preferential flows in taliks, change the timing and routing of surface and groundwater runoffs, and create riparian habitats, which benefit the aquatic vegetation and shrub growth [55,59]. On slopes, disturbances from pipeline construction and the ensuing heating delay ground freezing in the ROW and may create preferential flow paths in the supra-permafrost subaerial talik under the ROW, because the ground has already re-frozen outside the ROW while inside the ROW, the ground maintains a perennially thawed cylinder (linear supra-permafrost subaerial talik) [60]. This, therefore, accelerates surface water or groundwater flows, resulting in enhanced water erosion on slopes and accumulating water and high nutrients at the slope toes and eventually on the valley bottoms, favoring the shrubification on the valley bottoms [44].

Numerous studies have demonstrated that shrub expansion is substantially influenced by topography [49,61–64]. Wetlands or peatlands are generally topographically lower than upland forest and are less resilient than uplands after disturbances since vegetation, especially tree seedlings, fails to recover in very wet areas [3,12]. In addition, thawed pipeline trenches/cylinders can form a hydraulic connection among peat plateaus, bogs, and fens, resulting in forest fragmentation and tree losses [1].

Changes in microtopography resulting from pipeline construction and operation, together with the rutting from large machines and vehicle movement, are related to vegetation and organic damage or removal and, subsequently, a warmer soil and rapid permafrost thaw [14,34]. Williams and Quinton [65] found that removal of surface vegetation for pipelines increased incoming solar radiation by 11% on a boreal peatland in Northwest Territories, Canada. This modifies the microtopography along the pipeline corridor by warming the soil and melting the ground ice, leading to the ground surface subsidence and settlement of foundation soils and near-surface permafrost, as well as thermokarst, in the landscapes; these processes could further modify or change nutrient availability, soil moisture contents, soil hydrology, rooting depths, and surface soil cryoturbation, influencing shrub colonization and coverage [66].

Soil moisture and drainage and local topography have been highlighted as key factors related to shrub establishment in the ROW in boreal forest and arctic tundra. Permafrost thaw resulting from pipeline construction and heat dissipation from oil flows increases soil moisture content and results in ground surface subsidence and thermokarst, creating waterlogged lowlands and relatively drier uplands with improved soil drainage in the ROW. These can contribute to shrubification in the ROW.

3.3. Soil Types and Nutrient

Buried pipelines disturb the soil's biophysical and biochemical properties since trenches about 1.5–2.0 m in width and 2.0–3.0 m in depth are excavated and backfilled, generally not in the original order of the layered structure, after installing pipelines [6]. Therefore, the backfilled soil layers are disordered around and above the pipelines. This results in the

replacement of organic soils by mineral soils, often gravelly and sandy soils, at shallow depths (Figure 1b), which often are also the seedbeds favorable for tall shrub recruitment, growth, and seed production [67]. For example, Frost et al. [61] found the expansion of tall shrubs on patterned ground in the Northwest Siberian Low Arctic, which resulted from frost heave sorting and promoting of mineral-rich substrates with good drainage; these conditions may have favored and facilitated the shrub recruitment.

Thaw settlement resulting from melting ground ice is also affected by soil types. After long-term studies and monitoring along the Norman Wells pipeline, Northwest Territories, Canada, Burgess and Smith [45] found thaw settlement of 0.4–0.7 m for sites with finegrained lacustrine soil and of 0.7 m for organic terrains in the ROW, which were deeper than those in the undisturbed areas off the ROW in permafrost terrains. Furthermore, Schuur et al. [55] documented that the oldest, most subsided sites were dominated by shrubs, implying that shrubs indeed prefer warm and moist habitats.

Increased nutrient concentrations from a higher decomposition rate in the ROW along the pipelines resulted from the warmer soil directly caused by soil disturbances and indirectly by the ensued permafrost thaw [12]. During the construction of buried pipeline, the extensive and massive ditching greatly disturbed or completely altered the soil/cryosol pedons and profiles, drastically reducing organic carbon content and increasing the content of gravels in the near-surface soil layers [18]. This disturbance resulted in a warmer soil, a high decomposition rate and heterogeneity of nutrient distribution in the ROW [68]. In the ROW, soil is alkaline or acidic and has lower organic carbon and nitrogen contents, but a higher carbon-to-nitrogen ratio and higher contents of available phosphorous and total potassium compared to that in the undisturbed areas [68,69].

The construction of pipeline, particularly the improper backfilling of pipeline ditches, disrupts the long-established soil structures; this does not favor permafrost preservation owing to the impaired or removed thermal semi-conductor effect of layered surface organic-rich soils [70]. Increases in the contents of mineral soil and gravels on the ground surface coupled with soil compaction by machine result in decreased latent heat loss, increased soil heat flux and soil temperature, and accelerated permafrost thaw [12]. Thaw of this deep permafrost releases new soil nutrients, such as nitrogen, phosphorous and potassium, enhancing nutrient availability and shrub growth [71].

Manipulation experiments and field observations have demonstrated that shrubs are generally nutrient-limited in cold regions [49,72]. During vegetation recovery in the ROW, wet species with deep roots, such as sedges and graminoids, dominate [16,36,37]. Field experiments have indicated that deep-rooted herbs are able to immediately take up newly available nitrogen in deep soils released from thawing permafrost soils [73]. However, shrubs acquire nutrients and light by growing faster and taller with dense canopies and leaves to compete with graminoids [74]. Iturrate-Garcia et al. [75] found that the heights of *Betula nana, Salix pulchra, Ledum palustre,* and *Vaccinium vitis-idaea* are sensitive to the addition of nutrients (e.g., nitrogen, phosphorous, and potassium). Similarly, a 6-yearlong manipulation experiment found that high level nitrogen and phosphorous addition substantially enhanced the growth of birch apical stem over other factors (e.g., summer temperature, snow depth, and caribou exclusion) in Northwest Territories, Canada [71].

Overall, pipeline construction and operation increase nutrient concentration resulting from the warmer soil and higher decomposition rate, alter soil types, and disturb nutrient conditions, resulting in permafrost thaw and soil nutrient enrichment. This favors shrub colonization and growth in the ROW in permafrost regions.

3.4. Snow Cover

To lower disturbances to vegetation and permafrost along the engineering corridors, oil and gas exploration, construction and operational maintenance are mainly conducted in winter when the ground is frozen, with an adequately thick snow cover on the ground surface [1,76]. Vegetation clearance in boreal forest affects snowpacks by reducing canopy interception and snow redistribution [12]. This results in deeper snow, greater snow com-

paction by wind, and changed snowmelt time and snow depth and density in open areas compared to forests [77,78]. Earlier snowmelt time due to the increased incoming radiation caused by vegetation removal and pipeline heating in the ROW leads to a longer growing season and earlier snowmelt water into the soil, promoting the nutrient cycling and possibly shrub growth, as well [78,79]. In turn, dense shrub canopies trap more snow, leading to a greater snow depth and higher soil temperature in winter; they might promote shrub growth and create positive feedback between snow cover and shrubification [49,71]. In addition, changes in microtopography caused by ground surface subsidence, thermokarst, and vehicle movement result in the heterogeneity of snow cover. This may also be associated with shrubification in the ROW. However, their feedback mechanisms remain poorly understood.

4. Other Disturbances Associated with Shrubification

In addition to pipeline engineering activities, other geo-environmental factors contribute to increases in shrub abundance, coverage, and biomass [80]. Numerous studies have shown that shrubs have expanded and are expanding in arctic, subarctic, boreal, and alpine and high-plateau regions because of climate warming, forest and tundra fire disturbances, herbivories, and other non-pipeline-related anthropogenic activities [49,72,81,82].

4.1. Climate Warming

Climate warming has directly and indirectly led to recruitment and expansion of shrubs in the Circumpolar Arctic [83], the Third Pole (the Qinghai-Tibet Plateau and adjacent high mountains) [84], Arctic Alaska [85], Arctic Canada [86], Arctic Russia [87], Greenland [88], and Norway and Svalbard [49]. Field surveys, warming experiments, and remote sensing studies have documented the direct associations of increases in shrub coverage and biomass with a warmer and longer growing season e.g., [72,89–92]. In addition, shrub expansion is also related to climate-induced permafrost degradation, since warmer soil in the thicker active layer creates more space and releases more available nutrients for root development [93]. Melting of ground ice helps enrich soil moisture for promoting shrub expansion [94]. Development of thermokarst increases the bare ground that favors shrub germination [20]. Furthermore, under a warming climate, warmer soils underneath thicker winter snowpacks and in the supra-permafrost subaerial taliks boost soil nutrient availability, favor the growth of shrub-associated fungi in winter, and bring more water into the soil, thus increasing shrub productivity, phytomass, and coverage [49,77]. However, the response of shrubification to climate warming is inconsistent owing to other factors (e.g., site location, soil moisture and nutrients, and specific plant species) [49]. Responses of pipeline-disturbed environments to climate warming range from negligible to considerable, depending on surface soil conditions and current permafrost temperature [95], and more studies are needed.

4.2. Widlfires

In addition to the well-documented climate warming that may have greatly affected shrub expansion, observations suggest that wildfire disturbances may also significantly affect shrub dynamics [49,72]. Wildfire frequency and burned-over area have been increasing in the boreal forest and circumpolar tundra [96,97]. Studies have shown that the average extent of annual fire burned-over area increased by 96% from 2010 to 2019 in the Alaskan tundra [98], and 22,091 fires burned a total areal extent of 1.52 million km² from 2001 to 2020 in the Siberian taiga and tundra [99]. Wildfires burn shrubs and herbs, resulting in decreases in shrub abundance and coverage shortly afterward [100]. Burning and removal of vegetation increase surface soil temperature and result in permafrost thaw; they increase ALT, soil moisture content, and nutrient availability; these activities would result in thermokarst, redistribution of snow cover, and concurrent increases in shrub growth for several decades after a fire [101]. A study from the Seward Peninsula, Alaska, showed a lowered cover of evergreen shrubs after a fire, which had not recovered 10 years

later [102]. However, other studies in this same region also documented long-term increases in shrubs [100,103].

4.3. Herbivory

Herbivories may affect shrub expansion by reducing shrub abundance. (Over)grazing of reindeers, caribou and muskoxen reduce the abundance of lichen and tall deciduous shrubs, while microtine rodents reduce mosses and dwarf (low-stature) shrubs [104]. In addition to herbivory types and their associated diet preferences, herbivory density also plays important roles in regulating the shrub expansion [105].

Herbivories were anticipated to slow, stop, or even reverse shrub expansion resulting from climate warming, e.g., [105,106]. Field exclusion experiments showed that releases from both small and large herbivories may change the plant species composition of tundra communities [104,107]. For instance, a 20-year exclosure experiment on tundra vegetation in Scandinavia and Alaska indicated that mammalian herbivories helped in reducing the leaf area index (LAI), NDVI, and abundance of vascular plants, and large herbivories aided in lowering plant statures, while small herbivories assisted in boosting plant species diversity [104]. A 3-year exclosure experiment documented that the phytomass of deciduous shrubs, forbs, and silica-poor grasses increased by 40–50% in the absence of ungulate (e.g., reindeer) and small rodent herbivores (e.g., voles and lemmings) [106]. The impacts of herbivory on tundra shrub may depend on experiment periods, landscapes, characteristics of herbivore species and herbivory density in the plant community [106,108].

4.4. Vehicular Access Roads

Roads in cold regions are widespread and expanding because of the ever increasing high demand for natural resources. Roads change the physical (e.g., topography, snowpack, plant community composition, soil bulk density, hydrological conditions, and dusts in air), biophysical (e.g., light, winds, moisture, and temperature), and chemical environment (e.g., soil nutrient content and availability, soil pH and Eh, water contamination and ozone in air), resulting in the spreading of invasive exotic plant species by vehicles moving and by removing the surface vegetation and disturbing the surface soil [53,76,109]. Field surveys found that *Salix lanata* was abundant next to roads with $pH \ge 5$ soil in the arctic tundra along the Dalton Highway in northern Alaska [110], while alder growth and recruitment were significantly promoted adjacent to the Dempster Highway in Northwest Territories, Canada [111] and along Richardson, Glenn and Parks highways in Alaska. In addition to gravel roads and pads, asphaltic and concrete-surfaced roads, as well as railways, may amplify changes to vegetation, soil, and permafrost under a warming climate [112].

5. Summary and Research Priorities

5.1. Summary

Studies from site surveys and monitoring, remote sensing, field experiments and model simulations suggest that the permafrost is degrading from the hydrothermal impacts of pipeline construction and operation in the boreal forest and wetlands and arctic tundra under a warming climate. A warmer soil, improved soil drainage, and preferential flows in the environments of degrading permafrost could be the possible drivers for shrubification in the ROW or similar disturbed environments in arctic, boreal, alpine, and high-plateau regions. Degrading permafrost generally results in gradual modification or abrupt changes in landscape evolution. These successions in microreliefs and landscapes modify or change the spatiotemporal distribution of soil moisture contents and, as a result, alter drainage patterns, flow paths, and hydraulic connectivity. Consequently, at positions, such as lake/river/brook banks or terrace steps, new biophysical environments favor shrub invasion and the sustained growth of shrubs under a warming and wetting climate and ensuing permafrost degradation.

Changes in soil type and nutrients could also favor shrubification in the ROW. Pipeline construction, especially buried pipelines, disorders the original soil layers, resulting in

changes in soil type and nutrients characterized by replacement of the surface organic layer with mineral soils, particularly gravels, and hence a warmer ground. This further melts ground ice, causing surface subsidence and permafrost thaw associated with surface ponding, and newly thaw-released nutrients in the deep soil layers may favor shrub colonization and enhance shrub growth. In addition, changes in snow cover resulting from vegetation removal have important implications for shrubification in the ROW mainly characterized by a thicker snow pack, greater snow density, and earlier snow melting compared to the undisturbed forest. These could warm the soil underneath the ROW, increase soil nutrient availability, and change soil moisture conditions, which are closely associated with shrubification in the ROW. Similar to shrubification in the pipeline ROW, climate warming, wildfires, herbivories, and vehicular roads in permafrost regions have been observed to affect shrubification, further complicating its mechanisms. Thus, more systematic, in-depth, and multidisciplinary integral studies are urgently needed for these complex disturbance factors.

5.2. Research Priorities

Many studies have documented the impacts of pipeline construction and operation on the induced permafrost degradation. However, fewer studies are focused on vegetation recovery, especially shrubification, in the pipeline ROW in the boreal forest and wetlands and tundra ecosystems underlain by permafrost.

Although field surveys and remote sensing have revealed shrub expansion caused by pipeline disturbances in the ROW in permafrost regions, such as those along the Alyeska pipeline systems [18] and numerous seismic lines in Canada [12], there are still large regional gaps in studies on pipeline shrubification in many other permafrost regions, such as the Qinghai-Tibet Plateau and northeast China and many sub-regions in Russia. Shrubification in boreal forests, wetlands, and peatlands in mountain and latitudinal permafrost regions in northeast China remains little studied, and its mechanisms are poorly understood. Generally, the ecosystem-protected (i.e., permafrost due to the thermal protection of vegetation and organic layer) mountain permafrost at mid-latitudes is relatively warm and fragile to external disturbances [47,48]. Disturbances from construction and the operation of pipelines in permafrost regions could have substantial effects on the adjacent permafrost ecological environment and need more systematic and in-depth studies. These disturbances include those from frequent trampling and crawling, extensive ditching and access road networks, continual operation and periodic maintenance of warm/normal oil and gas pipelines, and the hydrothermal erosion in the sloping thaw bulbs in the pipeline ROW and proximity at mid-latitudes [59].

Shrub expansion in the pipeline ROW in the mid-latitude mountain regions might be more extensive and rapid compared to that at high latitudes in boreal and arctic zones under a warming climate. Numerous studies have reported that rising temperature is associated with shrub expansion [49,72]. Pipeline disturbance is more intensive and rapid and may accelerate shrub expansion at mid-latitudes under a warming climate. Therefore, more studies are needed at mid-latitudes to assess the shrubification processes in the ROW, including which shrub species are more sensitive to pipeline engineering and other technogenic disturbances under a warming climate.

The impacts of pipeline disturbances on permafrost are well documented. The permafrost environment along pipeline corridors is threatened by the warming climate, increasing wildfires, and changing pedological, hydrological, and ecological environments. Because of the complicated interactions between buried warm oil pipelines and the harsh permafrost environment, geocryological and engineering geological conditions have been changing rapidly. However, it is still unclear how these permafrost degradation-related geo-environmental changes affect the shrub growth and expansion. Questions related to permafrost thaw include, but are not necessarily limited to, the following aspects: (1) How may ground/soil warming, active layer deepening and concordant changes in the groundwater table, thermokarsting, and subsequent supra-permafrost subaerial talik facilitate shrub recruitment and establishment? (2) How would changes in soil properties (e.g., soil types, drainage, and nutrients) in regional, local, and microtopography and in snow distribution and properties affect shrubification in the pipeline ROW? (3) What are the main controlling and/or impacting factors of hydrothermal states of the active layer and near-surface permafrost for the shrubification in the pipeline ROW? Studies on the mechanisms of ROW shrubification along oil and gas pipelines are thus badly needed under these circumstances [17]. A better and more accurate understanding of these factors and their controlling/impacting mechanisms could significantly benefit vegetation recovery programs after pipeline construction and help reduce the practical expenses of pipeline maintenance.

There are few investigations of the impacts of pipeline disturbance on snowpack in the ROW in permafrost regions. Shrubs cool the underlying ground in summer by shading the incoming radiation and substantially warm the ground by insulating the ground surface in winter through intercepting and re-distributing snowfall [23,71]. In addition, snow cover may have significant implications for surface runoff and subsurface water flows, which could strongly influence permafrost conditions or even facilitate the formation of new taliks and/or expansion or deepening of existing taliks under the shrublands, hence impacting the long-term hydrothermal and mechanical stability of the foundation soils of oil and gas pipelines [14,36,59]. Thick snowpacks are able to promote nutrient cycling by raising the temperatures of the underlying soils under a warming climate [77,78]. Feedbacks between shrubification in the ROW and the snow-related hydrothermal regimes of the underlying permafrost, active layer, and talik and the hydrothermal and mechanical stability of pipeline foundation soils need to be systematically discussed.

Future modeling of interactions between pipeline safety and the frozen and/or thawed foundation soils must take into account the processes and impacts of shrubification in the ROW. Systematic and periodical surveys, investigations, monitoring, and numerical modeling studies on the permafrost ecological environment along the pipeline and its changes are increasingly important and urgently needed for better understanding of shrubification processes and mechanisms in the pipeline ROW, as well as the mitigation of related geohazards.

6. Conclusions

Pipeline corridors for oil and gas exploration and transportation are rapidly increasing in the boreal and arctic permafrost regions, where huge amounts of oil and gas resources have been identified and developed. Results from field observations, remote sensing, and modeling have shown that shrub is rapidly expanding and will continue to expand along the pipeline corridors in the boreal forest, wetlands and peatlands, and arctic tundra ecosystem because of the tolerance of disturbance. Vegetation recovery trajectories after disturbances depend on permafrost thaw in the boreal forest and arctic tundra, which is generally underlain by continuous and/or discontinuous permafrost. This review highlights that pipeline construction and operation have led to and possibly enhanced the ROW shrubification along the pipeline corridors, mainly by a rapidly or accelerated thawing permafrost under a warming climate.

Disturbances from buried pipeline restructure the soil profiles, increase the contents of surface mineral soil, and decrease the organic matter content, favoring the shrub recruitment. Surface vegetation removal during the construction stage increases incoming radiation, coupled with heat loss from pipeline oil flows, warming the soil and thawing the underlying permafrost. This warmer soil and permafrost thaw increase soil moisture content and nutrient availability and change microtopography, leading to ground surface subsidence and thermokarst and subsequently creating new habitats for seed germination and seedling growth of shrubs. Changes in snow melting time, depth, and density resulting from vehicle movement also have substantial effects on ROW shrubification. In addition to pipeline disturbances, climate warming, wildfires, herbivory activities, and vehicular access roads also promote shrub encroachment. Processes and impacts of shrubification induced by pipeline construction and operation and other disturbances, such as wildfires, herbivories, and vehicle access roads under climate warming could become complicated when compounded by the ensuing permafrost degradation. To better understand the relationships among shrubification, permafrost degradation, snow cover redistribution, and pipeline safety, more research by field surveys, long-term monitoring, field experiments, laboratory testing, remote sensing, unmanned aerial vehicle technology, and numerical model simulations and predictions is needed to evaluate and estimate the interactions between pipeline foundation soils and the boreal and arctic ecosystems in the ROW.

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