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Review

Terrestrial Ecosystem Impacts of Sulfide Mining: Scope of Issues for the Boundary Waters Canoe Area Wilderness, Minnesota, USA

Lee E. Frelich

Center for Forest Ecology, University of Minnesota, St.Paul, MN 55108, USA; freli001@umn.edu;
Tel.: +1-612-624-3671

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Abstract: Large-scale metal mining operations are planned or underway in many locations across the boreal forest biome in North America, Europe, and Asia. Although many published analyses of mining impacts on water quality in boreal landscapes are available, there is little guidance regarding terrestrial impacts. Scoping of potential impacts of Cu-Ni exploration and mining in sulfide ores are presented for the Boundary Waters Canoe Area Wilderness (BWCAW), Minnesota USA, an area of mostly boreal forest on thin soils and granitic bedrock. Although the primary footprint of the proposed mines would be outside the BWCAW, displacement and fragmentation of forest ecosystems would cause spatial propagation of effects into a secondary footprint within the wilderness. Potential negative impacts include disruption of population dynamics for wildlife species with migration routes, or metapopulations of plant species that span the wilderness boundary, and establishment of invasive species outside the wilderness that could invade the wilderness. Due to linkages between aquatic and terrestrial ecosystems, acid mine drainage can impact lowland forests, which are highly dependent on chemistry of water flowing through them. The expected extremes in precipitation and temperature due to warming climate can also interact with mining impacts to reduce the resilience of forests to disturbance caused by mining.

Keywords: boreal forest; copper-nickel mining; environmental impact of mining; sulfide mining; wilderness ecology

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1. Introduction

Boreal forests are one of the world's leading purveyors of ecosystem services including carbon storage and clean water [1]. Boreal forests have a large impact on climate at local, regional, and global scales [2]. They also harbor globally significant wildlife populations [3], and large tracts of unlogged primeval forest that show how natural disturbances and landform variability interact to maintain biodiversity [4–6]. Therefore, human-induced threats to the boreal forests are an important topic of investigation. Moreover, mining has been identified (in addition to other factors including climate change, atmospheric deposition and invasive species) as one of the major environmental threats to boreal forests worldwide, due to widespread presence of ancient rock formations that contain metallic ores [7].

Although most of the studies done to date have concentrated on aquatic impacts, there is a smaller but still significant body of knowledge of mining impacts on terrestrial ecosystems. Well-known cases of heavy metal pollution of forests via aerial deposition from smelting have occurred in North America and Europe [8,9], and although unmitigated pollution from smelting is no longer common, these historic episodes of smelting provide basic information about ecosystem response to heavy metals. Studies of impacts of mining on various measures of environmental quality and reclamation, for cases with acid mine drainage, open-pit, and underground iron mining, have been published for northern forests [10–12]. In addition, there is a much larger body of ecological knowledge that can be synthesized to scope mining-related issues related to terrestrial impacts of mining that have previously received little attention.

The ecological footprint of mining in a broad sense includes issues such as CO_2 emissions, water use, and biodiversity, which can have important regional and global impacts and have well developed procedures for scoping issues [13]. The ecological footprint also includes the geographical footprint—which is of most concern when evaluating impacts of mines adjacent to parks and wilderness areas—the topic of this paper.

The geographical footprint of mining can be separated into primary and secondary areas (Figure 1). The primary footprint is the area directly impacted by the mine(s), processing/rock crushing facilities, tailings areas, buildings, roads, parking lots, and energy transmission network built to accommodate the mines and workers. Some of these impacts are well known, for example, mined soils have higher bulk density and lower porosity, and therefore more erosion and road networks built for mines are a major contribution to changes in ecological processes [14]. Exploration—taking cores of bedrock across the landscape to map areas of ores with high concentrations of metallic elements that are economically feasible to mine—is part of the primary footprint. However, it consists of numerous small (<0.1 ha) disturbances systematically distributed across the landscape.

The secondary footprint comprises adjacent areas affected through mining activities and changes in the landscape that can propagate ecological changes for various distances away from the primary footprint (Figure 1). This includes such items as fragmentation and changes in forest type within the primary footprint, changes in wildlife migration and habitat use patterns, noise, light, windblown dust, dispersal of invasive species established on the mine site, and watershed areas affected by water withdrawals and mine drainage [15]. Distances and spatial pattern of impacts in the secondary footprint vary by type of impact, and spatial pattern can be directed by flow of water and air, or ecological processes such animal movements, and seed dispersal away from the mine site (Figure 1).

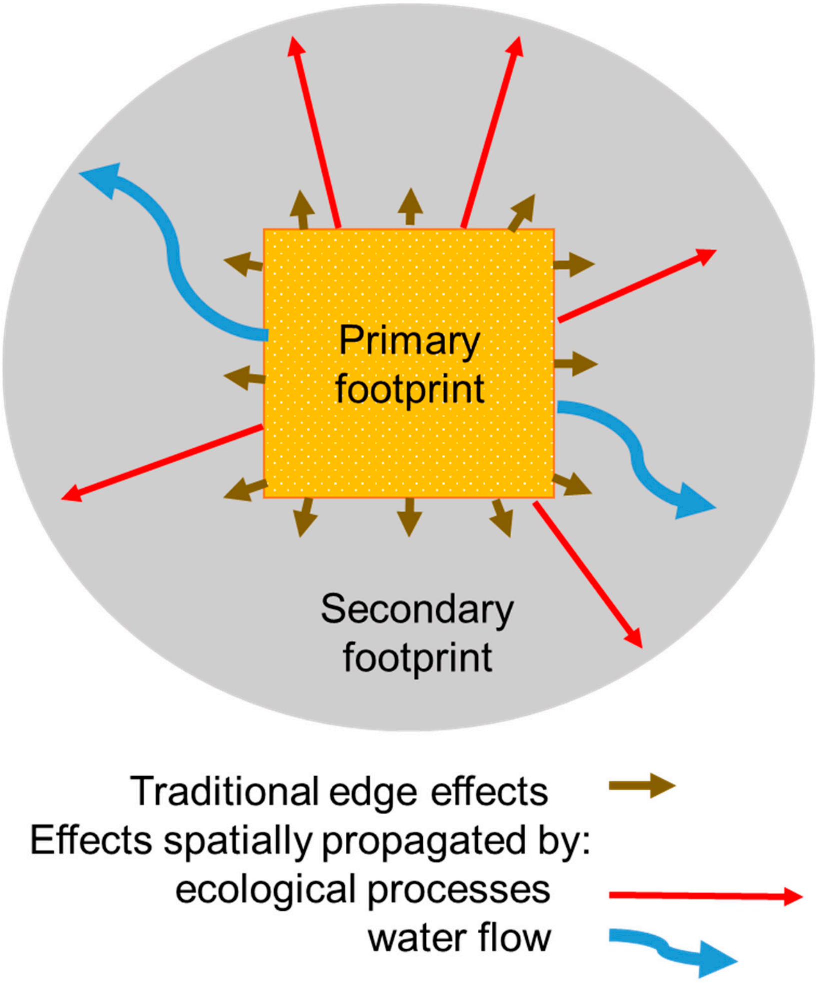

Figure 1. Conceptual diagram of spatial arrangement of primary and secondary footprints of mining. Short brown arrows represent traditional edge effects (modification of light and temperature); blue arrows represent spatially propagated effects due to water flow; red arrows represent propagated effects due to ecological processes, e.g., seed dispersal, wildlife migration, and trophic interactions.

The importance, duration, reversibility, magnitude, and size of impacts are important to consider, with items such as traffic noise, air pollution, barrier effects, riparian and terrestrial fragmentation and habitat loss [16]. The effects in the secondary footprint gradually decline with distance from mines and the associated infrastructure, and the various types of impacts should always be defined in terms of ecological impacts judged to be significant and the distance and spatial pattern within which those effects are estimated to occur. Please note that primary and secondary footprints are subject to initial impacts as well as subsequent ecological cascade effects, which can originate from direct effects in the primary footprint and propagated effects in the secondary footprint (Figure 2).

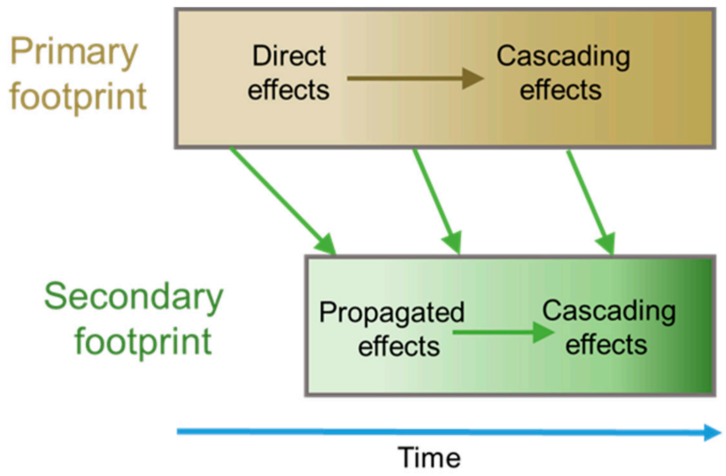

Figure 2. Relationship of direct effects in the primary footprint leading to ecological cascading effects in the primary footprint, and to spatially propagated and cascading effects in the secondary footprint.

Mining will also interact with climate change, which is expected to be large magnitude in high latitude, boreal areas of the world. Warmer climate means more extremes in precipitation leading to more drying of tailings ponds and blowing dust, and more extreme flow events that transport waste products from mining. Also, warmer temperatures will cause more oxidation, and more formation of acid byproducts for mines built in acidic ores, such as sulfide ores [17].

Here we consider a case study of environmental impact issues on terrestrial ecosystems potentially resulting from proposed copper-nickel mines with sulfide-based ores next to an iconic wilderness area in the southern boreal forest of northern Minnesota—the Boundary Waters Canoe Area Wilderness (BWCAW)—a designated wilderness under the federal wilderness law of 1964 and BWCAW law of 1978. Forests of the BWCAW and the surrounding Quetico–Superior Ecosystem (QSE) including Superior National Forest and Voyageurs National Park in the U.S., and Quetico Provincial Park in Ontario, Canada, are in the southern boreal (also termed near-boreal or hemi-boreal) forest zone of central North America. Boreal tree species such as jack pine (*Pinus banksiana* Lambert), black spruce (*Picea mariana* (Miller) BSP), balsam fir (*Abies balsamea* (L.) Miller), paper birch (*Betula papyrifera*) and quaking aspen (*Populus tremuloides* Michx.) constitute ca 90% of the tree cover, while species that span the temperate-boreal ecotone such as white pine (*Pinus strobus* L.), red pine (*P. resinosa* Aiton), northern white cedar (*Thuja occidentalis* L.) and black ash (*Fraxinus nigra* Marshall) account for most of the remaining tree cover, and temperate tree species such as red maple (*Acer rubrum* L.), northern red oak (*Quercus rubra* L.), basswood (*Tilia Americana* L.), and yellow birch (*Betula alleghaniensis* Britton) are close to the northern edge of their range with spotty occurrences [18]. The area has long, cold winters and short cool summers, and sits on shallow soils on top of glacially sculpted bedrock of the Canadian Shield, with a very high density of lakes, swamps, and water courses, so that aquatic/terrestrial interactions are profoundly important to the terrestrial system [18]. Similar lake country extends across the North American continent from northern Maine (U.S.) and Newfoundland (Canada) westward through the northern Great Lakes and northwestward to northern Saskatchewan, Alberta, and the Northwest Territories of Canada. Similar terrain also occurs in Europe, principally Sweden, Finland, and adjacent Russia.

The complex ecological interactions caused by inserting an industrial complex adjacent to a wilderness area in a boreal forest landscape have not been well scoped, and few reviews of effects of mining on forests have been published in comparison to aquatic impacts. Although several reclamation studies for mining spoil heaps have been published [19–21], few analyses exist for forests within the secondary footprint. The purpose of this review is to scope potential impacts to terrestrial ecosystems that could occur due to copper-nickel exploration and mining in the primary and secondary footprints in the QSE, and in particular, impacts likely to affect the BWCAW that is embedded within the QSE.

Although all the impacts identified here are expected to occur, the magnitude that may occur is unknown unless further ground-based analyses are carried out. In addition, little is said here about mitigation and reclamation—specifics of these issues should be addressed in an environmental impact statement. The scoping of issues, although developed for a specific case study, should serve as an example for broader application, because much of the circumboreal forests occur on similar landforms. Table 1 serves to summarize all impacts discovered in the literature review; the table follows the same categories presented below, but also shows how these impacts are cross-linked between primary and secondary footprints.

2. Potential Terrestrial Impacts in the Quetico–Superior Ecosystem

2.1. Baseline Impacts on Vegetation in the Primary Footprint

Mining and exploration will directly displace forests and potentially change the composition of any forest remnants within the primary footprint, and some effects will extend into the secondary footprint (Table 1). Magnitude of the impacts will depend on number of acres of timberland (forests on sites productive enough to have the capability of producing commercial timber) removed or fragmented in such a way that it would no longer be suitable for harvest. These impacts are tallied by forest type, for example as shown in the Minnesota Generic Environmental Impact Statement on Timber Harvesting and Forest Management in Minnesota [22].

Mining and exploration could also contribute to change in forest type. Fragmentation and disturbance favor early successional species such as quaking aspen and generalist species such as red maple [23]. This will interact with climate change, which will occur at the same time as mining and is also predicted to change forest types from boreal to temperate and/or reduce forest acreage because shallow rocky soils may support savannas in a warmer climate [24,25]. Therefore, analyses of the current and future area and composition of forest cover for various mining and climate change scenarios will be basic information to help with analyses of other impacts, for example, impacts on biodiversity and wildlife [26,27].

Table 1. Summary of potential mining and exploration impacts on forest and other terrestrial ecosystems. Footprint column shows whether a given impact would be in the primary or secondary footprint, or both. Please note that all impacts with a "2" can occur within the BWCAW. The last two columns show whether a given impact would occur from exploration and/or mining. Please note that exploration for Cu and Ni deposits was/is not allowed within the BWCAW.

Impact	Foot-Print	Explora-tion	Mining
Baseline vegetation impacts			
Loss of forest acreage by type	1	×	×
Forest composition change by forest type	1,2	×	×
Loss of non-forest vegetation by type	1	×	×
Non-forest vegetation change by vegetation type	1,2	×	×
Loss of old-growth forest remnants, acres by forest type	1	×	×
Loss of old forest (80–120 years), acres by forest type	1	×	×
Loss of primary forest remnants, acres by forest type	1	×	×
Fragmentation (additional effects listed below under wildlife and rare species)			
Edge to area ratio due to roads, transmission lines, parking, tailings, buildings, residential and commercial development	1,2	×	×
Environment effects in remaining forest within primary footprint	1	×	×
Changes in native edge versus interior plant and tree species	1,2	×	×
Road salt effects on trees and water	1,2		×
Water flow effects on vegetation	1,2	×	×

Table 1. *Cont.*

Impact	Foot-Print	Explora-tion	Mining
Wildlife, all impacts are per species for the relevant species group			
Area-sensitive mammals, marten, fisher (fragmentation effect)	1	×	×
Area-sensitive birds, warblers, etc. (fragmentation effect)	1	×	×
Loss of nesting habitat by forest type and bird species	1	×	×
Loss of habitat acres by wildlife species and vegetation/forest type	1	×	×
Effects on species sensitive to aquatic and aerial chemistry (amphibians)	1,2	×	×
Effects on wolves and trophic cascades (fragmentation effect)	1,2		×
Effects on deer and deer-moose relationships (fragmentation effect)	1,2		×
Roadkill effects (fragmentation effect)	1,2		×
Road salt effects (fragmentation effect)	1,2		×
Corridor disruption for mobile but non-flying species	1,2		×
Loss of critical stopovers for migrating species	1,2		×
Disruption of landscape pattern of vegetation/habitat	1		×
Noise, light, and vibration effects	1,2	×	×
Rare species			
Direct habitat loss per species	1	×	×
Impacts on local populations and regional stability of metapopulations per species (plants, wildlife, soil dwelling, and saproxylic species)	1,2	×	×
Invasive species			
Transport by equipment and soil movement per species	1	×	×
Potential response to fragmentation per species	1,2	×	×
Soils and productivity			
Acidification by water and air movement	1,2		×
Movement and effects of heavy metals in the soil	1,2		×
Loss of soil complexity	1	×	×
Terrestrial-aquatic linkages			
Accelerated ecosystem aging	1,2		×
Water chemistry effects on landscape arrangement of marshes, sedge meadows, peatlands, bogs, shrub carrs and wetland forests	1,2		×
Changes in water flow effects on landscape arrangement of wetland vegetation types	1,2		×
Heavy metal movement across aquatic-terrestrial boundaries	1,2		×
Cumulative impacts			
Spatial cascade of fragmentation effects including deer, moose, forest type, invasive species interactions	2	×	×
Sensitivity of future trajectory of forest and wildlife impacts to number of exploration sites and total size of primary footprint	1,2	×	×
Synergy among climate change, invasive species and mining impacts potential to overcome ecosystem resilience	1,2	×	×

Vegetation types other than productive forests would also have similar concerns requiring similar analyses, including rock outcrops, dry shrub lands, and especially wetlands including shrub-carr—shrub-dominated wetlands of willow (*Salix* L. spp.), alder (*Alnus incana* (L.) Moench) and dogwood (*Cornus* L. spp.)—sedge meadows, bogs, and marshes [28].

Old-growth and primary forests represent irreplaceable baselines of ecosystem function and species diversity, with several ecological, genetic, cultural, and spiritual values [29]. For example, red pine forests only occupy about 1% of their former acreage [30]. In the Great Lakes Region of North America, a small percentage of the original unlogged forest remains for all forest types, which elevates the importance of unlogged stands both inside and outside the BWCAW [31]. There are many definitions of old growth; Minnesota Department of Natural Resources considers stands at least 120 years old to be old growth and in northern Minnesota, this generally also means that the stand has never been logged, since European settlement occurred relatively late compared to the rest of the state [31]. Old forests (80–120 years old), which represent future old growth, are also important to consider, due to the dynamic nature of boreal forests. Primary forests are those that have never been logged, and may be any age, but have a continuous legacy of natural disturbance (fire, wind, native insect infestation) rather than harvesting [29]. Such forests of fire-dependent species such as jack pine and red pine are common in the proposed mine area. Some old-growth, old and primary forest remnants outside the BWCAW have been or will be impacted by exploration and eventually by mining if the proposed mines are built. The existence of any such forests outside the BWCAW contributes to the ecological integrity of forests inside the BWCAW, since those forests just outside the wilderness reduce edge effects that occur along the wilderness boundary.

2.2. Fragmentation

Fragmentation affects forests through increased edge to interior ratio, leading to increased light and temperatures in a buffer zone that extends into the forest from artificial edges [32]. Edge adapted species, especially weedy species of native and non-native plants and animals, respond positively to the change in environment at the expense of forest interior species and species that use multiple habitats [33]. Although these impacts are at their maximum 5–15 m from artificial forest edges, they can extend up to 40 m into otherwise undisturbed forests [34], and some effects can be propagated longer distances into the secondary footprint (Table 1).

Fragmentation would be caused by exploration activities, the mines, and tailings areas, as well as the roads, transmission lines, pipelines, buildings, and parking lots built to support the mines. Additional fragmentation effects would include increased residential and commercial development and associated traffic. Logging is common in the proposed mining zones; however, logging roads tend to be temporary while many of the roads built for mining will exist for several decades, be wider, have larger edge effects for temperature and sunlight, and greater potential for spread of invasive species and native edge species [33]. Because of lag-time effects in ecosystems, fragmentation effects are likely to persist for a few decades after mines have closed, so that area-sensitive species of plants and animals will continue to decline for a long time—during construction, mining, and a few decades after.

There is a strong interaction between fragmentation and invasive species [35]. A large zone of fragmentation several km in width could lead to a large invasion front of invasive species at the edge of the wilderness (see discussion of "mass effect" under "Invasive species" below). Please note that exploration can introduce invasive plant species systematically across the landscape in many locations, and these could have long-lasting impacts, even if the relatively small openings created fill back in with forest within a decade. Definition for a zone of vigilance and no tolerance of invasive species around the mining/BWCAW interface is needed, even for pre-mining exploration and geological studies.

De-icing road salt needed in a cold climate, needed to accommodate increased traffic, will have impacts on surface and soil water, wetlands, and forests. These effects could include long-term salinization of ground and surface waters [36,37], extending along drainage ways that are crossed by roads, and into all forests along all stretches of roads. Two pathways for road salt damage occur: (1) accumulation in snow windrows along the sides of roads and parking lots during winter that melts in spring, briefly saturating roots with salt; and (2) aerial salt particles that are deposited on twigs and kill buds and foliage of trees [38]. Large trucks associated with mining will require application of salt, also will loft salt higher into the air than regular automobile traffic, and thus dispersal distances into the forests and waterways will be relatively long, potentially entering the secondary footprint. Also, the road edge to forest area ratio (e.g., number of km of heavily used roads per km^2 of forest) for roads that generate a lot of salt could potentially increase over a large primary footprint of mining. Soils around the proposed mines are highly susceptible to salt damage because they are shallow, so that root contact with salty water flowing along the bedrock-soil interface, root damage, and tree death, is a likely occurrence. Several tree species in the area are susceptible to salt damage, principally white pine, basswood, northern red oak, and red maple, while balsam fir, spruce and northern white cedar are relatively resistant to salt damage [37]. White pine damage and mortality from salt has been noted around the proposed mines (Frelich personal observation).

2.3. Wildlife

Changes to habitat structure by industrial activities have important effects on wildlife [39]. Wildlife species living within the primary mining footprint would be directly displaced, due to loss of forest and other vegetation. For example, loss of trees will directly lead to less nesting habitat for birds [40]. Several wildlife species respond to changes in road density, especially permanent roads that would be created in the primary footprint of the proposed mines. Roadkill due to increased traffic and more artificial edges that wildlife species will have to cross would affect some wildlife populations. Noise and light pollution can impact songbirds at variable distances from road networks [41]. Amphibians such as salamanders and frogs that live in forests, especially swamp forests and wetlands, are sensitive to pH and could be negatively affected by acid dust from rock crushing areas as well as movement of polluted soil and surface water [42].

Certain species require large tracts of unfragmented forest [3]. Pine marten (*Martes americana* Turton), fisher (*Pekania pennanti* Erxleben), and area-sensitive (interior forest) bird species, including many warbler species, are likely to experience direct displacement of habitat within the primary mining footprint, with impacts possibly extending some distance into the secondary footprint [33]. Native forest edge species such as deer (*Odocoileus virginianus* Zimmermann), raccoons *(Procyon lotor* L.), and brown-headed cowbirds (*Molothrus ater* Boddaert) [26], and invasive species (plant and animal, see below) are likely to increase in abundance, compete with area-sensitive species within the primary footprint, with effects extending into the secondary footprint.

Most landscapes in the area potentially affected by mining have a characteristic, repeating pattern across the landscape of dry upland forest, rock outcrop, wetland forest, wetlands and aquatic habitats [18]. Many wildlife species move among these habitats on daily and seasonal time scales, and this mosaic of habitat types is partly responsible for the diversity of mammal, amphibian, and bird species present. This pattern could be disrupted in the primary footprint of mining activity, so that impacts on habitat use spread across a larger landscape, due to increased travel distance for wildlife to use different habitat types.

High white-tailed deer populations responding to fragmentation and other changes in the environment [43] have a potential negative impact on moose (*Alces alces* L.) in the primary and secondary footprints, because white-tailed deer carry the deer brainworm (*Parelaphostrongylus tenuis* Dougherty). This parasite does not kill deer, but can kill moose and be a significant negative factor for moose populations when deer densities are high [44].

Roads and associated changes in human activity are a negative factor for wolves (*Canis lupus* [45]). If wolves are displaced from the primary mining footprint, then further concentration of deer in addition to that caused by fragmentation could occur, due to predator avoidance by deer. The resulting trophic cascade would change the rest of the ecosystem including the plant community [46]. Such a cascade with a low wolf, high deer, low plant diversity regime could lead to loss of plant species that are sensitive to deer browsing, such as northern white cedar, yew (*Taxus canadensis* Marshall), yellow birch, and nodding trillium (*Trillium cernuum* L.) and certain orchids and could extend well into the secondary footprint [47].

Wildlife corridors that cross the primary footprint of mining could be disrupted, with impacts propagated into the secondary footprint. For example, lynx (*Lynx canadensis* Kerr) travel tens of km during the year [48] and would be subject to roadkill by increased traffic. Lynx also do not prefer to den in areas with high road densities [49] that would be created in the primary footprint of the proposed mines. Many examples of effects on wildlife species that regularly cross the wilderness boundary and travel through the primary footprint of mining will occur. Finally, fragmentation in the primary footprint will affect stop over places for long-distance migrating species that eventually nest within the BWCAW or beyond, including waterfowl such as ducks and geese, and 23 species of neo-tropical migrant songbird species with declining populations [18].

2.4. Rare Species

Rare species lists need to be compiled for all taxa in the primary and secondary footprints of any mine, including rare species that do not live in the area but migrate across the footprints. This should include state of Minnesota and federal species of concern, threatened species and endangered species [50]. To determine the impact, a survey of the potential mining area within which it is likely that rare species will be directly displaced, should be carried out. There is a high likelihood that some rare species populations will be locally extirpated, which may influence the overall viability of a given species at the ecoregion, state, or federal level. Many rare species have scattered, somewhat isolated populations, which nevertheless form an interdependent network (metapopulation, *sensu* [51]) that allows exchange of individuals and genetic material and maintenance of the individual populations. Disruption of populations outside a designated wilderness or park can have negative consequences for populations inside them, since the regional population structure of a given wildlife species is established in response to natural factors without regard to artificial wilderness or park boundaries.

Soil dwelling species, including insects, worms, bacteria, and fungi that have not yet been discovered probably exist in the mining area. For example, [52] found possibly as many as nine new species of native worms (Enchytraieds) in two days of field work in northern Minnesota and Wisconsin. Saproxylic species (fungi and arthropods living within coarse woody debris) are also sporadically distributed across the landscape, so that forest loss and fragmentation effects can have important negative impacts by disrupting their metapopulations [53]. Therefore, there is a significant chance of losing native biodiversity within the primary footprint, and possibly also lesser effects in the secondary footprint of mining. These soil dwelling and saproxylic species, while not charismatic to the public, play important roles in moderating ecosystem processes such as nutrient and water cycles, and have important effects on wildlife habitat quality [54].

2.5. Invasive Species

Although boreal forests are remote, they are still subject to invasive species [55]. Numerous points of introduction will occur due to exploration and mining at the landscape scale, because human disturbances such as clearing vegetation and road building are well known to introduce invasive species [56,57]. Even with the procedures put in place by Superior National Forest for preventing invasive species (such as cleaning equipment when moving between sites and removing visible individuals that appear near work sites), they are likely to invade in the fragmentation edge zones that are beyond the primary footprint of mining activities. This is because many invasive species have long-distance dispersal abilities and can take advantage of changes in the environment (amount of light, temperature, soil disturbance) that may occur up to 40 m into the forest along roads and other openings created. For example, those invasive species such as European earthworms that can tolerate closed forest conditions, have spread 500 m+ into boreal forests in Alberta, Canada, after being introduced along roads [58].

There can be a large "mass effect" for invasive species, whereby the larger the area fragmented by roads, small disturbances created during exploration, transmission lines, buildings, and parking lots, the more locations where invasive species can become established. Larger masses of invasive species within human-dominated areas lead to greater propagule pressure spreading into adjacent natural areas [59]. This in turn allows the spread of adaptive genes for the local environment to many invading plants, as well as Allee effects whereby individuals of the invasive species support each other through pollination and positive alterations of the environment [60]. Such mass effects can exceed critical mass for establishment of invasive species and facilitate their wave-like spread through the secondary footprint. Furthermore, invasive species, for example the European shrub common buckthorn (*Rhamnus carthartica* L.), are likely to be aided by interactions with increasing deer abundance and other invasive species such as invasive earthworms [61,62]. Guidelines for invasive species management by the responsible agencies should be reviewed for adequacy to address potential invasive species problems at the scale of the proposed mines.

For the BWCAW invasive plant species include Canada thistle (*Cirsium arvense* (L.) Scop.), orange and yellow hawkweed (*Hieracium aurantiacum* L. and *H. caespitosum* Dumort.), common buckthorn, purple loosestrife (*Lythrum salicaria* L.), leafy spurge (*Euphorbia esula* L.), garlic mustard (*Aliaria petiolate* (Bieb.) Cavara & Grande), spotted knapweed (*Centauria maculosa* Lam.), exotic honeysuckles (*Lonicera* L. spp.), narrow leaf and hybrid cattail (*Typha angustifolia* L. and *T. x glauca* Godr. (pro sp.)), and reed canary grass (*Phalarus arunduncaea* L.) [63]. Several of these are already reported within the Superior National Forest and BWCAW, and minimizing seed sources around the edge of the wilderness is key to maintaining the pristine condition of plant communities within the wilderness. In addition, new invasive species not currently being monitored will likely appear. Therefore, analyses of mining impacts should look at exotic species that have traits of invasive species that are locally present and likely to become invasive, or species that have become invasive elsewhere that are present in the vicinity of the mine, but have not become invasive in Minnesota. There are potential interactions with climate change; i.e., some species that are present and limited in extent and success under the current climate could "take off" in a warmer climate [64] and invade the wilderness from the mining sites.

Numerous underground invaders exist, including earthworms—the invasive species group with the largest known impacts on ecosystems in terms of types, magnitudes and spatial extents of impacts on functional ecology of terrestrial ecosystems worldwide [65]. In northern temperate and southern boreal forests, earthworms consume the forest floor (litter or duff layer), making soils warmer, drier, and more nutrient poor, lead to lower plant diversity, and reduced tree growth [66,67]. Thus, soil movement during mining becomes an issue since it is easily possible in the area where mining is proposed (which currently has a spotty distribution of soil invaders) to bring in new earthworm species as well as spread existing species via soil movement. In addition, earthworms can alter post-mining succession of plant species [68], so that novel successional sequences not familiar to ecologists in the QSE may occur due to earthworm presence. Soil movement within the primary footprint could easily lead to spread of underground invasive species into the secondary footprint within the wilderness.

2.6. Soil Disruption and Ecosystem Recovery Time

Soils that took thousands of years to develop will not recover quickly from mining within the primary footprint. Interruption in continuity of soils during exploration and mining occurs in ways that do not happen after fires or logging. Reclamation procedures, while better than nothing, restore minimal soil function, and do not restore the same function as before mining within a human time frame; furthermore, continued human use can be a major factor in delaying recovery [69]. It is possible to develop an index of soil quality for reclaimed sites, although unique aspects of each region need to be taken into account, and any such index can create a standard by which to judge any reclamation treatments that may be developed [70]. Simple communities such as shortgrass prairies recover faster than complex communities such as forests [71].

Windblown pyrite dust or other metallic dust can remain a problem for several decades after mining ceases on Cu-Ni mine tailings [72] and can also cause acidification of soils outside the mine site [73]. Cu and Ni deposition can occur for distances of 3-5 km around contemporary mining sites, such as the Eagle Mine in nearby Upper Michigan USA [74]. Once in the soil system, heavy metals are recycled by plants through litterfall, litter decomposition and root uptake [75]. They are also subject to volatilization and redeposition during forest fires, for example the effects of forest fires on Mercury (Hg) in the forest floor that originated from fossil fuel burning has been studied in northern Minnesota [76]. Acidification of soils can mobilize Aluminum and the resulting cascade of chemical changes can lead to Calcium deficiencies that affect tree growth [77], especially on shallow soils with low nutrient status such as in the BWCAW. The ability of the ecosystem to fix nitrogen can also be reduced [78]. Mycorrhizae—fungi essential to tree growth—would also be impacted by changes in soil chemistry (pH or metal pollution), with large differences in magnitude of direct impacts among taxonomic groups of fungi and in mycorrhizal colonization rates among plant species [79,80]. Recent studies show that certain species of symbiotic microbes are better adapted to help recovery of vegetation after mining, although much remains to be learned [81].

Microtopographical complexity the soil surface in forests includes tip-up mounds and pits, rotten wood at various stages of decay, and variable build-up of humus; it is essential for maintenance of biodiversity of tree seedlings, herbaceous plants, fungi, mosses and microorganisms that in turn are needed for ecosystem function [82]. Microtopography can take centuries to form, or to rebuild on reclaimed soils. Some microtopographical features can persist for 6,000 years [83]. Microtopography can be enhanced artificially, speeding up the recovery process after mining, such as by adding woody debris [84].

Surprisingly, the problem with soil reclamation for the existing iron mines in northern Minnesota is high pH (8.0–8.1), rather than acid soils [85,86]. However, the situation should be different, with low pH around 4 or less for Cu-Ni reclamation [72]. Although reclamation is only an issue for the primary footprint, many interactions could occur between reclaimed areas and the BWCAW. Reclamation could determine what future types of vegetation and wildlife habitat occur just outside the BWCAW, and therefore would impact the wilderness through many types of spatial ecological processes described elsewhere in this paper. On the other hand, the BWCAW would also serve as an "ecosystem seed" that could help restore the reclaimed areas in many ways that are not currently understood [87]. These back-and-forth processes between the wilderness and primary footprint outside the wilderness include seed rain, chemical processes in soil and water that depend on species-dependent leaf litter chemistry, and use of habitats by wildlife species that move across the landscape to habitats within and outside of the BWCAW.

2.7. Terrestrial-Aquatic Linkages

There are strong interactions among terrestrial forests and wetland forests, streams, lakes, and groundwater in the BWCAW. The potential hydrological and aquatic impacts of proposed mining—including potentially extensive effects into the secondary footprint—have been published elsewhere [88]. Biogeochemical processing of leaf litter and other ecosystem function in headwater streams can be negatively affected by mining [89]. In this case, the primary footprint of the proposed mines would be in the headwaters of one of the major watersheds for the BWCAW [88]. The Quetico–Superior Ecosystem as a whole has an exceptionally large magnitude of forest-aquatic linkages compared to many of the world's ecosystems. Streams (intermittent and permanent), wetlands of spatial extents from 0.01 to 1000s of ha, and lakeshores produce literally tens of km of aquatic-terrestrial interfaces per km^2 of landscape. The entire terrestrial biosphere over most of the Quetico–Superior ecosystem is like a membrane of soil and all the organisms within, lying on top of bedrock, with water flowing through an intricate web of tree roots and associated mycorrhizae. Repeating patterns of dry, mesic, and wet forests occur across the landscapes of the ecosystem at spatial scales of 1–100 m, so that the entire ecosystem consists of dry to wet ecological gradients [18].

The wetland vegetation types exist along a gradient of water chemistry, especially pH, nitrogen and oxygen content [28]. The high pH, high nutrient and high oxygen group includes ash (*Fraxinus* L. spp.) swamps, northern white cedar swamps, sedge meadows, and shrub-carr, while tamarack (*Larix laricina* (Duroi) K. Koch) swamps tend to be intermediate and black spruce swamps and open Sphagnum bogs occur in low pH, low nutrient and oxygen poor conditions (Figure 3). Roads built within the primary footprint can create a dike that prevents flow of water and changes extent and duration of floods, especially in flat landscapes. Roads and culvert systems also transport pollutants [14]. Changes to water flow and/or chemistry caused by mining could upset the balance among these vegetation types, which are interlinked and intergrade with each other along natural chemical gradients across the landscape [18]. This could lead to changes in decomposition and nutrient cycling, as well as tree mortality and downgrading the nutrient status along any forested wetland gradient that was affected. These effects could extend well into the secondary footprint of mining, and if they occurred, would last for centuries.

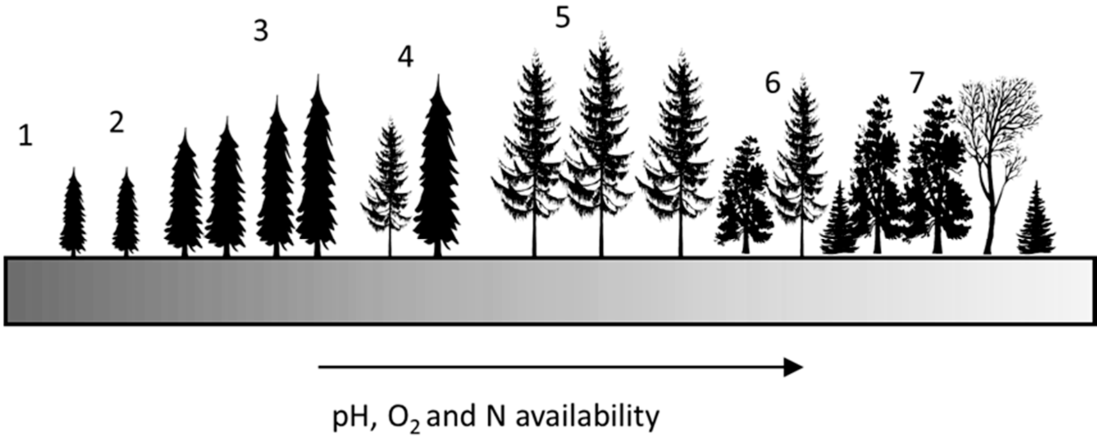

Figure 3. Arrangement of lowland forest type communities along an environmental gradient. Nutrient poor types include: (1) open bog, (2) stunted black spruce and (3) black spruce forest. Medium nutrient types include: (4) black spruce-tamarack forest and (5) tamarack forest. Nutrient rich types include: (6) northern white cedar-tamarack forest and (7) northern white cedar-balsam fir-tamarack-black ash forests, sometimes mixed with shrub-carr and sedge meadows.

Large areas of disruption of water flow, such as installation of roads, pipelines, and transmission lines, draw down of water for mine use during periods of low flow, as well as cumulative impacts of hundreds of small disruptions of ground water flow and quality across the landscape could have significant additive and cumulative effects [88]. Changes in water table—both up and down—caused by disruption of water flow when roads are installed can lead to death of swamp forests [90]. These effects propagate variable distances away from the primary footprint, depending on the configuration of a given watershed, and last for decades to centuries.

There is potential for various mine facilities such as tailings to fail during an extreme rainfall event—and such events are increasing in frequency in much of the world including Minnesota as a warming climate intensifies the Earth's hydrological cycles [91,92]. Extreme rainfall events could lead to large pulses of acid mine drainage moving through swamp forests which would propagate across large swaths of the secondary footprint, and the potential for occurrence could last throughout the period of mining and many years beyond. Accelerated ecosystem aging—either ecosystem acidification [93], or ecosystem retrogression [94]—of wetland forests is a possible cascading effect if any acid drainage occurs, but could occur more locally from windblown dust deposition. Acidification due to production of organic acids in conifer leaf litter and mosses on the forest floor occurs progressively over several thousand years under natural conditions, converting lakes and relatively nutrient rich wetlands (cedar swamps, shrub carrs) to acid bogs, which then fill with floating mats of Sphagnum moss. Please note that fill in of lakes can occur from either high nutrient conditions and eutrophication, or acidification, since the acid-loving Sphagnum moss species can form floating mats that fill increasingly acidic waters. Many of the watersheds have been and will continue to be (under natural conditions), buffered by natural chemical processes against acidification for the next several millennia [6]. However, a pulse of acidic material in windblown dust or water flow could upset the natural buffering system with large cascading consequences for swamp forests, wetlands, and lakes. Acidification that would have taken thousands of years to occur naturally could occur within a few years.

Beaver (*Castor canadensis* L.), moose, black bear (*Ursus americanus* Pallas), insects and other species can move any toxic element (heavy metals) that may be present across aquatic and terrestrial ecosystem boundaries, by moving vegetation, eating vegetation or fish and depositing the elements elsewhere [95,96]. Also, disturbances such logging, wind or fire may influence movement of toxic elements across terrestrial and aquatic ecosystems in complex ways [97,98].

3. Cumulative Impacts

Synergy among mining impacts reviewed above, invasive species and climate change could exceed the current resilience of the forest, or reduce the current level of resilience, and affect resilience of the forest well into the secondary footprint inside the wilderness (Table 1). Resilience is defined as the ability of an ecosystem to recover to its initial state after being disturbed [99]. For example, forests of the BWCAW are resilient to fire, at the stand and landscape scales. Stands of trees killed are immediately reseeded with native species after fire, and at the landscape scale, fires create a mosaic of forests in different stages of succession that is ideal for maintaining a diversity of wildlife species [18].

In contrast, human activity can speed up forest change to a level too rapid for recovery, or the intensity of human disturbance may be higher than natural disturbances, and may overwhelm the forest's ability to recover [99]. The many types of changes brought about by mining combined with climate change are likely to reduce resilience. Furthermore, the combination of individual impacts lasting for several decades could potentially create a whole new trajectory in future development of the forest for the primary and secondary mining footprints, which would differ from the trajectory without mining to a greater degree as time goes on. Generalist tree species adapted to warmer climates (e.g., red maple) than the current dominant species will be able to take advantage of the changes [100], and create new alternate forest states. Loss of moose could be locally accelerated, and a portion of the moose core habitat in Minnesota could be displaced [101].

Cumulative effects of many small changes in water flow and quality across the landscape could lead to large changes over time. Increased evaporation from a warmer climate combined with changes in water flow due to mining in some areas can lead to change or replacement of wetland forests in primary and secondary footprints. Changes in flow of water, including change in the variability of flow, caused by the large primary footprint of the mines, combined with increased deer grazing on seedlings of certain species of trees, will inevitably kill some wetland forests and cause conversion to other vegetation types, such as shrub-carr, reed canary grass, and hybrid cattail. Increased ecosystem aging or retrogression could occur in areas with low natural pH that may receive additional acidification.

Invasive species propagule pressure from numerous mining exploration sites and roads outside the BWCAW could have significant impacts. It is inevitable that a rising edge to interior ratio of forested patches just outside the wilderness will change the composition of the forest there, and that will propagate into the wilderness through seed dispersal. Such spatial cascades could also affect aquatic-terrestrial linkages into the wilderness. The magnitude of several factors remains to be estimated, including the size of the secondary footprint within the wilderness for various environmental effects, how severely the nearby portion of the wilderness would be affected, what proportion of the wilderness will have some impacts, and what absolute mileage and proportion of the wilderness boundary would be affected.

4. Conclusions and Summary of Wilderness Impacts

There are many reasons to protect wilderness integrity. However, the science-related reasons are seldom discussed [6]. The BWCAW is internationally known for ground-breaking research on forest fires, landscape patterns, biodiversity, wildlife, soils, nutrient cycles, and other ecosystem processes, lakes, climate change, and recreational use of wilderness [18,31,45,99]. Furthermore, the BWCAW provides the baseline for the rest of the landscape which is manipulated by logging, mining, roads, housing, and other human activities. Having a baseline is the most basic principle of science; even in the context of global climate change, the BWCAW shows us how the forests, lakes, and landscape patterns would develop in the absence of direct human manipulation. This role of wilderness and other natural areas as a scientific baseline has become critical in the last few decades, to assess the overall impacts of human activity at local, regional, and global scales. Without these baselines, we are essentially "flying blind" in our ability to manage ecosystems to provide the many types of services needed by humanity [6].

The BWCAW is a pristine area where zero impacts from human manipulation of the nearby environment (other than climate change) are expected. Therefore, any potential impacts are a concern. Of the individual and cumulative impacts listed in Table 1 and given the current knowledge of interconnections in the field of landscape ecology, it is reasonable to state that most (25 of 39, all those with a "2" in the second column of the summary table) will impact the wilderness to some degree. The living portion of the BWCAW ecosystem is a thin membrane with many fine-scale interconnections among paths of water flow, lying on top of undulating bedrock. A large primary footprint of mining activity at the top of the watershed can cause many effects related to water flow and chemistry (including aerial deposition), that will affect everything lower in the watershed. Given the high level of linkages between aquatic and terrestrial components of the ecosystem in the BWCAW, these effects will also extend into terrestrial vegetation. Changes in forest type, soils, and fragmentation, within the terrestrial primary footprint will also impact invasive species, and via spatial propagation into the secondary footprint and subsequent ecological cascades; these will affect vegetation, wildlife, and rare species of plants and animals within the BWCAW wilderness.

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