Chapter

Eastern Poison Ivy (*Toxicodendron radicans* L.): A Bioindicator of Natural and Anthropogenic Stress in Fields and Forests

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Abstract

This chapter considers herbaceous and woody plants near the 1800s era hydrocarbon extraction areas (HEAs) in Wiikwemkoong Unceded Territory (WUT) on Manitoulin Island, Lake Huron, Ontario, Canada. Plant community assessment used patterns of diversity and distribution at five field and six forest sites to assess the response of the plants to HEAs. These sites receive brine episodically from HEAs and natural seeps over the Collingwood Oil Shale Formation. This brine contains high concentrations of chloride and sodium along with total dissolved solids that exceed 100,000 mg/L. Exposure to brine is identified as the causative factor shaping plant distribution, survival, size, leaf bleaching (i.e., chlorosis), and dead branches on woody stems. These sites demonstrate an ecotone of disturbance defined by transition from natural plant community to dominance by eastern poison ivy (EPI, *Toxicodendron radicans* L.). Disturbed sites within brine drainage areas are dominated by EPI, reflecting tolerance to elevated salinity due to rhizome growth strategy. Evaluation of the plant communities and EPI allowed for preparation of a framework that can be used to guide interpretation of response of plants to drainage of brine from HEAs and natural sources beyond WUT.

Keywords: brine, community responses, hydrocarbon, *Toxicodendron radicans*, Manitoulin Island, Canada

1. Introduction

Abiotic and biotic factors can act synergistically to influence growth, longevity, and distribution of plants [1]. Abiotic factors include disturbance regimes, light intensity, availability of water, and microelemental concentrations, among other factors [1, 2]. Biotic factors include competition, predation, and propagule pressure, among other factors [2, 3]. When plants respond to abiotic and biotic factors, the resulting growth, longevity, and distribution can be used to understand the dominant factor(s) affecting success in a habitat. This understanding arises when the abiotic and biotic factors are known, and then analyses can be completed to identify the factor(s) responsible for observed growth, longevity, and distribution. In these settings, it is often feasible to identify one or more plant species as bioindicators, to represent patterns [1–5]. This approach uses existing knowledge on ecological, physiological, and ontological requirements of bioindicator species. Hence, the status of bioindicator species in a habitat can be used as a surrogate to identify the dominant abiotic and biotic factors shaping plants within an area of interest [5, 6].

Studies of plants and plant communities exposed to brine from oil and gas wells, referred to herein as hydrocarbon extraction areas (HEAs), demonstrated the short- and long-term consequences of this type of episodic and/or persistent disturbance [7–12]. Historically, brine was allowed to drain away from HEAs and was then observed to kill all exposed plants [7, 8]. Best practices now involve the capture of brine for safe disposal [7]. Brine from HEAs varies from locale to locale but always contains high concentrations of elements, like Cl >50,000 mg/L, Na >25,000 mg/L, Ca > 10,000 mg/L, Mg >1000 mg/L, SO_4^{-2} > 500 mg/L, and Fe > 200 mg/L with total dissolved solids (TDS) > 100,000 mg/L [7, 13, 14]. When brine drains to adjacent plant communities, most species will show a short-term response involving the leaves turning white, indicating the loss of chlorophyll, referred to as chlorosis, with leaf drop soon thereafter [7, 15, 16]. The process of chlorosis is attributed to the loss of ionic balance in the roots and leaves of the plant, attributable to the high concentrations of elements such as Cl and Na in the brine [12, 15].

A detailed study of the response of plants to long-term exposure of brine was completed by government scientists in former oak (*Quercus* sp.)-dominated forest of Oklahoma, USA [7]. This Oklahoma study documented how herbaceous and woody vegetations were completely absent in areas that received brine run-off during the past, while trees downslope were short and demonstrated dead branches. In contrast, herbaceous and woody vegetation upslope and adjacent to the brine-exposed areas showed no evidence of stress [1]. The authors attributed the loss of ground vegetation and the short height and dead branches of the trees to long-term exposure to brine from HEAs. Another study that documented the response of plants to brine exposure was completed in the Allegheny State Forest in Pennsylvania, USA [15, 16]. This forest patch was dominated by trees such as eastern hemlock (*Tsuga canadensis* L. Carrière), red maple (*Acer rubrum* L.), American beech (*Fagus grandifolia* Ehrh.), northern red oak (*Quercus rubra* L.), and yellow birch (*Betula alleghaniensis* Britton). This forest was exposed to brine from a leaking impoundment over a period of 3 years. The path followed by the brine resulted in the death of all ground vegetation during the first season and all trees within 2 years. Walters and Auchmoody ([15], p. 124) stated: "The swiftness and completeness of the kill attests to the extremely toxic nature of the spilled brine. Ground cover was eliminated immediately, and trees showed visual symptoms of stress during the first growing season...." The last plants to die were the old growth (>300 years old) eastern hemlock and American beech in the drainage area. The extended survival of these large and old trees was attributed to the deep roots providing some tolerance to the brine, but they still died. It was also reported that within 2 years, plants returned to the brine-disturbed forest areas, with typical pioneer species, including ferns, as first to appear, followed by previously evident woody species [16]. Studies that document the response of plants to brine exposure during short- and long-term periods represent an opportunity for learning about species and community response patterns to this type of disturbance [17, 18]. Schindler [18] suggested such severe types of disturbance are useful for learning about responses of species and communities to a disturbance but do not necessarily represent the key variables to help elucidate exact response patterns. Schindler [18] also noted that disturbance regimes can provide a basis to resolve cause-effect relationships and are instructive if the response patterns are indeed outside of the typical normal range. Schindler [18] also suggested that understanding the exact responses of species and communities to disturbance can lead to the development of a predictive framework of responses for low-level disturbance. Using this basis, additional studies of plants associated with HEAs and brine are justified, to resolve growth, longevity, and distribution of plants in these areas, as a basis to refine future rehabilitation activities.

This chapter reports how the distribution of eastern poison ivy (EPI; *Toxicodendron radicans* L.) has been used as a diagnostic indicator to locate lost HEAs that include oil and gas wells in fields and forests. These lost HEAs exist on Wiikwemkoong Unceded Territory (WUT) #26, an area that extends along the entire east shoreline of Manitoulin Island, Lake Huron, Ontario, Canada (**Figure 1**). Portions of Manitoulin Island and WUT are located over the Collingwood Oil Shale Formation (Ordovician origin) containing oil and gas deposits within the porous limestone of the Trenton Formation [19, 20]. Since 2014, members of WUT have been working with Premier Environmental Services Inc. (Premier), to rediscover lost HEAs using an approach that integrates oral traditional knowledge (TK) with plant ecology and chemistry-based analyses [21]. This discovery process has been refined since 2014, with the integration of TK and science to help understand the distribution of EPI along with the status of the plant communities in proximity to candidate HEAs. Direct experience at WUT allowed for the refinement of this understanding of how EPI represents a bioindicator species to represent the responses of other herbaceous and woody plant species in these habitats at 50+ HEAs. Documentation of the response of EPI and plant communities associated with HEAs was achieved with detailed studies of five field and six forest sites, including a groundwater seep in a field and natural hydrocarbon seep in a forest. This representation of the responses of plants to local habitat features provides the basis for learning about the key environmental factors shaping the growth, longevity, and distribution of plants in areas with HEAs and natural seeps.

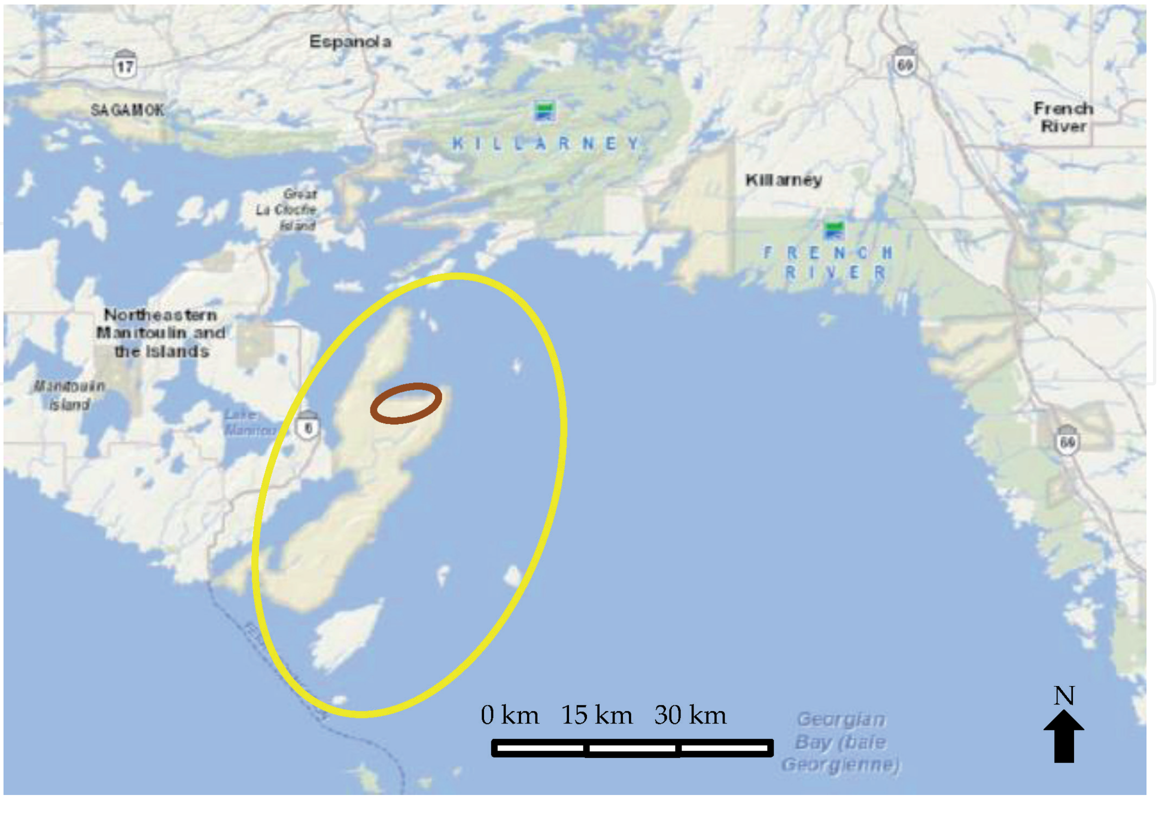

Figure 1.
View of Manitoulin Island, Lake Huron, Ontario. The approximate boundaries (less adjacent lands) of WUT are noted within the yellow oval, along the entire eastern end of the island. The general area of the five field and six forest sites are within the brown oval.

2. Taxonomy and physiological basis for study

Eastern poison ivy is a member of the Anacardiaceae family (sumac-cashew) and distributed across Eastern North America, whereas western poison ivy (*Toxicodendron rydbergii* (Small ex Rydb.) Greene) is distributed across Western North America [22, 23]. These two species are morphologically variable (e.g., leaf color, size, shape), and they can hybridize within overlapping habitats. Eastern poison ivy shows varied growth forms, with the most common as a woody rhizome that grows underground in all directions, with no nodes but roots and leaves at varied intervals. This variable rooting leads to the establishment of patches over large areas and varying types of soil. An alternate form of EPI demonstrates a woody vine that will climb trees and other hard surfaces. Both growth forms are identified as shade-intolerant and are often found in habitats with direct sunlight such as the edge of forests, along roadways, disturbed areas, fields, and wetlands. Both forms produce the toxin urushiol as a defense mechanism, and these toxins often cause contact dermatitis in two of three humans following exposure to as little as 1 nanogram [24]. These toxins are released from the roots and leaves to the air as oil droplets [24]. On Manitoulin Island, EPI is most commonly found along edges of forests and farm fields, roadways, and other disturbed areas [25]; EPI is considered a rare species in natural forests with closed canopies and wetland areas on the island [25], as this species prefers direct sunlight [22, 23].

All species within the *Toxicodendron* genus show some tolerance to soil salinity, and this provides the plants with the ability to maintain viable populations within disturbed habitats [22]. Kuester et al. [26] reported that elevated tolerance to soil salinity was a common characteristic of successful weed species in North America. The United States Department of Agriculture (USDA) Plants Database (http://plants.usda.gov/charinfo) provides a standard definition to represent how plants tolerate soil salinity. Such representation of plant tolerance to soil salinity reflects studies of plant growth performance that classified species among four tolerance categories (zero, low, medium, high), to represent range of responses. These USDA responses include zero tolerance to soil solutions with electrical conductivity of 0–2 dS/m, low tolerance to 2.1–4.0 dS/m, medium tolerance to 4.1–8.0 dS/m, and high tolerance to >8.0 dS/m. Plants are defined to tolerate salinity if there is zero to slight reduction in growth (<10%). Eastern poison ivy demonstrates an ability to tolerate elevated concentrations of soil salinity, often within the medium tolerance category [22, 23].

Such reports of tolerance of EPI to soil salinity include a range of responses, depending on the locale of the study [22, 23]. It is likely this range of responses is a direct response to rhizome growth forms with roots and stems extending over large areas. This pattern indicates that the rhizome allows the plant to tolerate a wide range of soil salinities, as well as other forms of local disturbance. The presence of rhizome growth form was identified as the causative factor for rapid reestablishment of EPI after flooding destroyed surface stems and leaves [27, 28]. The observation of tolerance of EPI to environmental disturbance, due to ecological and physiological adaptations, justifies the consideration of EPI as a candidate bioindicator species. The use of EPI as a bioindicator species identifies that the phenological response patterns of the species to different environmental, ecological, and physiological factors is understood. This chapter demonstrates the current understanding of the responses of EPI and plant communities near HEAs and two natural seeps and represents an illustrative example of plant phenology in field and forest ecosystems.

3. The setting

At WUT, oral history combined with TK led to the initial documentation of old and un-abandoned HEAs that were observed to be harming native vegetation as well as fouling agricultural fields. Specifically, resident observations included woody vegetation downslope of old HEAs that were dead or showed dead branches and short height compared with specimens in adjacent habitats that were live and taller. Other observations included livestock that shun hay cut from a field with an HEA releasing an oil-water slurry downslope through the field. These observations led to the abandonment of these HEAs. After these HEAs were abandoned, Premier was invited to participate in the discovery of lost HEAs, and this recent work represents the basis for this study.

It is prudent to briefly review the history of how HEAs were established at WUT during the 1800s, reflecting oral history, government reports, scientific articles, photographs, and letters written by Jesuit missionaries. This history also reveals that an extremely large forest fire occurred across Manitoulin Island during 1865, with areas on WUT having nearly all woody stems burned, and this land described afterward as fully cleared, whereas some wet areas and shorelines were spared [25, 29]. This regional fire disturbance at WUT likely aided development of HEAs, through enhancement of access following the loss of dense forest tracts. A second regional disturbance within the WUT forest has been the recent loss of ash (*Fraxinus* spp.) trees due to invasion by emerald ash borer (EAB, *Agrilus planipennis*). This beetle from Asia invaded southern Canada during the early 2000s and now has spread extensively within North America [30]. At WUT, most ash have perished during the last decade, including black ash (*Fraxinus nigra* Marshall), green ash (*F. pennsylvanica* Marshall), and white ash (*F. americana* L.) due to the EAB infestation.

Initial advancement of HEAs at WUT occurred during the summer of 1865 while other portions of the island burned [31, 32]. The first HEAs were planned to focus on oil and followed the McDougall Treaty involving WUT and Upper Canada, signed during 1862; it is noteworthy to identify that the WUT community did not fully embrace this treaty as only two community members actually signed the document [32, 33]. After this treaty, staff from Milwaukee Petroleum Company arrived at WUT on May 1 of 1865 to negotiate access. After access was tentatively granted by WUT, John Ward, an experienced pioneer in oil well drilling from Oil Springs, Ontario, arrived about a month later. Mr. Ward focused the drilling activity on limestone outcrops found in close proximity to natural oil seeps evident along Smith's Bay shoreline, an area directly accessible by boat. This initial extraction activity yielded a "schooner load" of oil that was shipped south with a request for 500 wooden barrels to be shipped north. However, the oil extraction ended during autumn in 1865 when the Wiikwemkoong community members asked the oil men to leave on short notice; their equipment was reportedly left behind [31, 33].

Representatives from the oil industry returned to WUT during the early 1880s and proceeded to develop a large number of HEAs despite opposition from the community [33]. This development was approved by the Government of Canada, as oil well licenses facilitated access to WUT for lease areas along the recently described Trenton Formation. When these 1880s HEAs were prepared, the initial disturbance involved road construction, as land away from the shoreline was targeted. After roads were prepared, HEAs were constructed in agricultural fields and forest settings. In agricultural fields, site preparation was a relatively simple activity, while forest settings required additional effort. It is probable that some of these forest areas used for HEAs in the 1880s were burned during 1865 and included younger trees. After a site was cleared, then a wooden oil rig was built around the extraction point. A wood barrel was then usually placed next to the rig, to collect the oil-water slurry; natural gas wells also had a collection barrel. These barrels allowed for the separation of oil and water via gravity, but it is not clear if it was necessary to separate water from the natural gas. Abandonment studies to date have revealed collection barrels in agricultural fields which were placed on grade, while in the forests, they were buried. Collection barrels documented at WUT in fields had dimensions with a width of 3–4 m and height of 3–4 m, while barrels abandoned during 2016 in forests had widths of 3–4 and depth up to 6 m [21]. This design implies the larger barrels needed to be placed below grade, to support the weight and facilitate gravity separation of the oil and water slurry [21].

All wells were drilled by hand, with help from horses. Abandonment studies led by WUT from 2014 to 2017 years revealed the depth of the drilled holes ranging from 105 to 130 m for oil sites and up to 337 m for natural gas [21]. The presence of porous limestone of the Trenton Formation across WUT provides a simple explanation why the HEAs involved this range of depths. These depths also reveal that the wells could have been more shallow, as it is now known that these depths penetrated the hydrocarbon-bearing strata and then entered the deep groundwater strata [34]. It was reported [34] that drilling of hydrocarbon wells in Ontario during the 1800s and 1900s included the systemic problem of over-drilling oil strata followed by penetration of deep groundwater. When an oil well is over-drilled, it is often associated with initial high yields of an oil-water slurry; however, the longevity of the well is shortened due to the high volumes of water that are interacting with the oil at depth. In the case of the natural gas wells at WUT, it appears they did not produce excessive quantities of water, based on abandonment activities [21].

Hydrocarbon extraction at WUT ended in 1905, after 20+ years, when the men were evicted and the structures burned [21]. Pipes at HEAs were often cut below grade. Then, some pipe holes were filled with soil and rock, and graded, to reduce risk from falling in to these hazards. This history identifies that all known HEAs were burned, indicating a common disturbance history for the forest and field settings. This 1905 burning followed the 1865 forest fire, representing key disturbance events shaping the plant communities associated with most HEAs at WUT. After this period, many HEAs near or within forests experienced regeneration, although the species composition of trees differs from historical forest composition (described below). In contrast, HEAs located in agricultural fields were often maintained as fields, through regular cutting of the herbaceous vegetation. Studies [15] at WUT documented that for seven HEAs, the soil concentrations of hydrocarbons were elevated in close proximity to HEAs, but these concentrations rapidly declined with distance from the HEAs. This elevation of hydrocarbons at an HEA was attributed to extraction while the lower concentrations attributed to bacterial degradation of hydrocarbons downslope. These low concentrations of soil hydrocarbons downslope from HEAs provide additional evidence that it is brine causing disturbance to the plant communities [21].

This study considers the diversity and distribution of plants and EPI associated with HEAs located in forest and field settings at WUT, as described in **Table 1**. These plant associations reflect past field surveys that focused on the common plants [25] near HEAs. Initial observations at HEAs revealed that the plant community was less diverse and these plants were distributed in what was documented as a predictable manner in proximity to HEAs and this led to the preparation of this study [21]. Hence, this study does not focus on the morphological or phenological aspects of plant specimens near or around HEAs. However, aspects of morphology and phenology are considered while interpreting the diversity and distribution of plants in forest and field settings associated with HEAs.

Site (current habitat)	Plant association with EPI	HEA
A (forest)	Ostrich fern (*Matteuccia struthiopteris* L.), balsam poplar (*Populus balsamifera* L.)	Wood crib
B (forest)	Marsh horsetail (*Equisetum palustre* L.), balsam poplar	Metal pipe
C (forest)	Ostrich fern, balsam poplar	Metal pipe
D (forest)	Smooth Solomon's seal (*Polygonatum biflorum* Walter), balsam poplar	Metal pipe
E (forest)	Common lady fern (*Athyrium filix-femina* L.), balsam poplar	Wood crib
F (forest)	Common lady fern, balsam poplar	Wood crib
G (field)	Red osier dogwood (*Cornus sericea* L.)	Metal pipe
H (field)	Timothy *Phleum pratense* (L.), Virginia strawberry (*Fragaria virginiana* Duchesne)	Metal pipe
I (field)	Timothy, Virginia strawberry	Metal pipe
J (roadside ditch)	Raspberry (*Rubus arcticus* (L.), Virginia strawberry	Metal pipe
K (field)	Virginia strawberry	Natural seep

At each site, the main plant association with EPI and HEA is noted along with the type of HEA.
Plant identifications follow the standard guide for Manitoulin Island [25].

Table 1.
Summary of forest and field sites considered in this study.

4. Chemistry of water from HEAs and seeps

Studies of oil and gas wells generally, as well as for those located across the Trenton Formation, revealed brine is readily evident and the chemistry reflects local limestone composition [19, 20, 35]. Hence, wells within a short distance can show variations in concentrations of key elements. General features of brine within the Trenton Formation describe this water as having a near neutral pH (5.5–7.0) with elevated concentrations of elements that can be described generally as follows: Cl >100,000 mg/L, Na >50,000 mg/L, Ca > 20,000 mg/L, Sr. > 5000 mg/L, Mg >2000 mg/L, K > 2000 mg/L, Ba >2000 mg/L, Bo >1000 mg/L, SO_4^{-2} > 500 mg/L, and Fe > 300 mg/L [19, 35]. This general composition of brine represents concentrations of elements that are potentially harmful to aquatic and terrestrial life and why this water is regulated under Ontario's *Oil, Gas and Salt Resources Act*. This need to control the release of brine can be illustrated by considering the Cl surface water quality guideline in Canada to protect aquatic life during short-term exposure is 640 mg/L and long-term exposure is 120 mg/L [36] while brine may contain Cl at >100,000 mg/L. Thus, water from HEAs can be regarded as hazardous to plants and wildlife, even in small quantities. Water samples collected by WUT confirmed the presence of brine at HEAs.

5. Results

Integration of available information from WUT, scientific literature, and field inspections allowed for the identification of a list of plants associated with HEAs in field and forest habitats (**Tables 2–4**). The first forest habitat type is dominated by balsam poplar (*Populus balsamifera* L.) and the second forest habitat dominated by balsam fir (*Abies balsamea* L.) and eastern white cedar (*Thuja occidentalis* L.). When the plant associations with HEAs were identified, they were intended to represent spatial patterns concerning the general plant community found in each area, as

Plants found in poplar forest settings within 30 m of HEA	**Plants within 5 m of HEA**				**Plants within 1 m of HEA**			
	A	**B**	**C**	**D**	**A**	**B**	**C**	**D**
Apple (*Malus domestica* Borkh.)	X	X	X	X				
Arctic sweet coltsfoot (*Petasites frigidus* L.)								
Balsam poplar (*Populus balsamifera* L.)	X	X	X	X		X	X	X
Balsam fir (*Abies balsamea* L.)			X	X			X	
Bebb's sedge (*Carex bebbii* Olney ex Fernald)								
Black ash (*Fraxinus nigra* Marshall)	X	X	X	X				
Black cherry (*Prunus serotina* Ehrh.)								
Black medic (*Medicago lupulina* L.)	X			X				
Black spruce (*Picea mariana* Mill.)				X				
Blue-joint (*Calamagrostis canadensis* Michx.)								
Bur oak (*Quercus macrocarpa* Michx.)								
Canada goldenrod (*Solidago canadensis* L.)	X	X	X	X				
Canada thistle (*Cirsium arvense* L.)								
Cinnamon fern (*Osmunda cinnamomea* L.)								
Chestnut sedge (*Carex castanea* Wahlenb.)			X					
Columbine (*Aquilegia canadensis* L.)			X					
Common buckthorn (*Rhamnus cathartica* L.)				X				
Common dandelion (*Taraxacum officinale* Ledeb.)	X	X	X	X				
Common ragweed (*Ambrosia artemisiifolia* L.)								
Common evening primrose (*Oenothera biennis* L.)								
Common lady fern (*Athyrium filix-femina* L.)								
Common milkweed (*Asclepias syriaca* L.)								
Common mullein (*Verbascum thapsus* L.)								
Common raspberry (*Rubus arcticus* L.)	X	X	X	X				
Common yarrow (*Achillea millefolium* L.)								
Daisy fleabane (*Erigeron annuus* L.)								
Eastern bracken fern (*Pteridium aquilinum* L.)								
Eastern cottonwood (*Populus deltoides* W. Bartram ex Marshall)								
Eastern poison ivy (*Toxicodendron radicans* L.)	X				X	X	X	X
Eastern white cedar (*Thuja occidentalis* L.)								
False Solomon's seal (*Maianthemum racemosum* L.)								
Green ash (*Fraxinus pennsylvanica* Marshall)								
Ground juniper (*Juniperus communis* L.)				X				
Golden sedge (*Carex aurea* Nutt.)	X	X						
Heal-all (*Prunella vulgaris* L.)								
Lesser burdock (*Arctium minus* Bernh.)								
Longroot smartweed (*Polygonum coccineum* Muhl. ex Willd.)								
Mapleleaf viburnum (*Viburnum acerifolium* L.)	X	X	X					
Marginal wood fern (*Dryopteris marginalis* L.)				X				
Marsh horsetail (*Equisetum palustre* L.)		X	X			X	X	
Multiflora rose (*Rosa multiflora* Thunb.)								

Plants found in poplar forest settings within 30 m of HEA	Plants within 5 m of HEA				Plants within 1 m of HEA			
	A	B	C	D	A	B	C	D
New England aster (*Symphyotrichum novae-angliae* L.)			X	X				
Northern bugleweed (*Lycopus uniflorus* Michx.)								
Northern red oak (*Quercus rubra* L.)								
Orange daylily (*Hemerocallis fulva* L.)	X							
Ostrich fern (*Matteuccia struthiopteris* L.)	X				X			
Quaking aspen (*Populus tremuloides* Michx.)								
Red maple (*Acer rubrum* L.)			X				X	
Red osier dogwood (*Cornus sericea* L.)								
Riverbank grape (*Vitis riparia* Michx.)	X	X	X	X			X	
Rough bedstraw (*Galium asprellum* Michx.)								
Sensitive fern (*Onoclea sensibilis* L.)								
Silver maple (*Acer saccharinum* L.)								
Smooth Solomon's seal (*Polygonatum biflorum* Walter)				X				
Spotted jewelweed (*Impatiens capensis* Meerb.)	X	X	X	X				
Spotted joe-pye weed (*Eutrochium maculatum* L.)								
Staghorn sumac (*Rhus typhina* L.)								
St. John's wort (*Hypericum perforatum* L.)								
Stinging nettle (*Urtica dioica* L.)		X		X				
Sweet white clover (*Melilotus officinalis* L.)								
Sugar maple (*Acer saccharum* Marshall)								
Tall buttercup (*Ranunculus acris* L.)				X				
Tamarack (*Larix laricina* Du Roi)								
Virginia strawberry (*Fragaria virginiana* Duchesne)	X	X	X	X			X	
White ash (*Fraxinus americana* L.)				X				
White birch (*Betula papyrifera* Marshall)			X	X			X	
White oak (*Quercus alba* L.)								
White spruce (*Picea glauca* Moench)								
White trillium (*Trillium grandiflorum* Michx.)								
Wild carrot (*Daucus carota* L.)	X	X	X	X				
Yellow daylily (*Hemerocallis lilioasphodelus* L.)								
Yellow hawkweed (*Hieracium piloselloides* Vill.)			X	X				
Yellow sedge (*Carex flava* L.)								

These settings included site A with wood crib, site B with pipe that was bubbling natural gas, site C with pipe draining water to long drainage channel, and site D representing a dry pipe in a forest.

Table 2.
Representation of common plant species found at different distances from HEAs in forests dominated by balsam poplar [25].

well as the plant species tolerant of these habitats, within ~5 m and within 1 m of an HEA. These community associations show how diverse plant communities become depauperate with increased proximity to the HEAs and how EPI is consistently the most common species within 1 m of HEAs.

Using Ontario's Ecological Land Classification (ELC) strategy [37] and the lists of common plants associated with the HEAs (**Tables 2–4**), the ecosites associated

Plants found in white cedar-balsam Fir forest within 100 m of HEA	**Plants within 5 m of HEA**		**Plants within 1 m of HEA**	
	E	**F**	**E**	**F**
American basswood (*Tilia americana* L.)				
Apple (*Malus domestica* L.)				
Arctic sweet coltsfoot (Pe*tasites frigidus* L.)				
Balsam poplar (*Populus balsamifera* L.)	X	X	X	X
Balsam fir (*Abies balsamea* L.)	X	X	X	X
Bebb's sedge (*Carex bebbii* Olney ex Fernald)				
Bebb's willow (*Salix bebbiana* Sarg.)				
Black ash (*Fraxinus nigra* Marshall)	X	X		
Black cherry (*Prunus serotina* Ehrh.)				
Black medic (*Medicago lupulina* L.)				
Black raspberry (*Rubus occidentalis* L.)				
Black spruce (*Picea mariana* Mill.)				
Blue-joint (*Calamagrostis canadensis* Michx.)				
Canada goldenrod (*Solidago canadensis* L.)	X			
Canada thistle (*Cirsium arvense* L.)				
Cinnamon fern (*Osmunda cinnamomea* L.)				
Chestnut sedge (*Carex castanea* Wahlenb.)				
Columbine (*Aquilegia canadensis* L.)				
Common buckthorn (*Rhamnus cathartica* L.)				
Common dandelion (*Taraxacum officinale* Ledeb.)	X	X		
Common ragweed (*Ambrosia artemisiifolia* L.)				
Common evening primrose (*Oenothera biennis* L.)	X			
Common lady fern (*Athyrium filix-femina* L.)	X	X		
Common milkweed (*Asclepias syriaca* L.)				
Common mullein (*Verbascum thapsus* L.)				
Common raspberry (*Rubus arcticus* L.)	X	X		
Common yarrow (*Achillea millefolium* L.)				
Daisy fleabane (*Erigeron annuus* L.)				
Eastern bracken fern (*Pteridium aquilinum* L.)	X	X	X	X
Eastern cottonwood (*Populus deltoides* W. Bartram ex Marshall)				
Eastern poison ivy (*Toxicodendron radicans* L.)			X	X
Eastern white cedar (*Thuja occidentalis* L.)	X	X		
False Solomon's seal (*Maianthemum racemosum* L.)	X	X		
Green ash (*Fraxinus pennsylvanica* Marshall)				
Ground juniper (*Juniperus communis* L.)	X	X		
Golden sedge (*Carex aurea* Nutt.)				
Heal-all (*Prunella vulgaris* L.)				
Hoary willow (*Salix candida* Flügge ex Willd.)				
Large-toothed aspen (*Populus grandidentata* Michaux)				
Lesser burdock (*Arctium minus* Bernh.)				

Plants found in white cedar-balsam Fir forest within 100 m of HEA	**Plants within 5 m of HEA**		**Plants within 1 m of HEA**	
	E	**F**	**E**	**F**
Longroot smartweed (*Polygonum coccineum* Muhl. ex Willd.)				
Northern maidenhair fern (*Adiantum pedatum* L.)				
Mapleleaf viburnum (*Viburnum acerifolium* L.)	X	X		X
Marginal wood fern (*Dryopteris marginalis* L.)				
Marsh horsetail (*Equisetum palustre* L.)				
Multiflora rose (*Rosa multiflora* Thunb.)				
New England aster (*Symphyotrichum novae-angliae* L.)				
Northern bugleweed (*Lycopus uniflorus* Michx.)				
Northern maidenhair (*Adiantum pedatum* L.)	X	X		
Northern red oak (*Quercus rubra* L.)				
Orange daylily (*Hemerocallis fulva* L.)				
Ostrich fern (*Matteuccia struthiopteris* L.)				
Pussy willow (*Salix discolor* Muhlenb.)				
Quaking aspen (*Populus tremuloides* Michx.)				
Red maple (*Acer rubrum* L.)	X	X	X	X
Red osier dogwood (*Cornus sericea* L.)				
Red spruce (*Picea rubens* Sarg.)				
Riverbank grape (*Vitis riparia* Michx.)	X	X		
Rough bedstraw (*Galium asprellum* Michx.)				
Sensitive fern (*Onoclea sensibilis* L.)				
Shining willow (*Salix lucida* Muhlenb.)				
Silver maple (*Acer saccharinum* L.)				
Smooth Solomon's seal (*Polygonatum biflorum* Walter)				
Spotted jewelweed (*Impatiens capensis* Meerb.)	X	X		
Spotted joe-pye weed (*Eutrochium maculatum* L.)				
St. John's wort (*Hypericum perforatum* L.)				
Stinging nettle (*Urtica dioica* L.)				
Sweet white clover (*Melilotus officinalis* L.)				
Sugar maple (*Acer saccharum* Marshall)	X			
Tall buttercup (*Ranunculus acris* L.)				
Tamarack (*Larix laricina* Du Roi)				
Virginia strawberry (*Fragaria virginiana* Duchesne)	X	X	X	
Western bracken fern (*Pteridium aquilinum* L. Kuhn)				
White ash (*Fraxinus americana* L.)				
White birch (*Betula papyrifera* Marshall)	X	X	X	
White spruce (*Picea glauca* Moench)				
White trillium (*Trillium grandiflorum* Michx.)				
Wild carrot (*Daucus carota* L.)				
Yellow birch (*Betula alleghaniensis* Britton)	X	X		
Yellow daylily (*Hemerocallis lilioasphodelus* L.)				

Plants found in white cedar-balsam Fir forest within 100 m of HEA	Plants within 5 m of HEA		Plants within 1 m of HEA	
	E	F	E	F
Yellow hawkweed (*Hieracium piloselloides* Vill.)				
Yellow sedge (*Carex flava* L.)				

These settings included site E with wood crib and site F with wood crib.

Table 3.
Representation of common plant species found at different distances from HEAs in forests dominated by eastern white cedar-balsam fir forest along the shoreline of Cape Smith [25].

Plants found in field settings at WUT with 100 m of HEA	Plants within 5 m of HEA					Plants within 1 m of HEA				
	H	I	J	K	L	H	I	J	K	L
Apple (*Malus domestica* L.)	X	X	X	X						
Black raspberry (*Rubus occidentalis* L.)		X	X							
Bedstraw (*Galium aparine* L.)		X	X							
Black locust (*Robinia pseudoacacia* L.)	X					X				
Calico aster (*Symphyotrichum lateriflorum* L.)		X	X		X					
Canada anemone (*Anemone canadensis* L.)		X								
Canada goldenrod (*Solidago canadensis* L.)	X	X	X	X	X					
Columbine (*Aquilegia canadensis* L.)		X			X					
Common buckthorn (*Rhamnus cathartica* L.)										
Common dandelion (*Taraxacum officinale* Ledeb.)	X	X	X	X	X		X			
Common ragweed (*Ambrosia artemisiifolia* L.)	X	X	X	X	X		X			
Common evening primrose (*Oenothera biennis* L.)		X	X		X		X			
Common milkweed (*Asclepias syriaca* L.)		X	X		X					
Common mullein (*Verbascum thapsus* L.)										
Common raspberry (*Rubus arcticus* L.)		X	X	X			X			
Common yarrow (*Achillea millefolium* L.)		X	X							
Crawe's sedge (*Carex crawei* Dewey)		X								
Daisy fleabane (*Erigeron annuus* L.)		X	X							
Eastern poison ivy (*Toxicodendron radicans* L.)				X		X	X	X	X	X
Ebony sedge (*Carex eburnea* Boott)		X	X		X					
Glossy buckthorn (*Rhamnus frangula* Mill.)										
Hairy goldenrod (*Solidago hispida* Muhl. ex Willd.)		X								
Heal-all (*Prunella vulgaris* L.)			X		X					
Houghton's goldenrod (*Oligoneuron houghtonii* Torr. & A. Gray ex A. Gray)										
Lesser burdock (*Arctium minus* Bernh.)		X	X	X						
Little bluestem (*Schizachyrium scoparium* Michx.)	X	X	X		X					
Little green sedge (*Carex viridula* Michx.)										
Multiflora rose (*Rosa multiflora* Thunb.)	X			X		X				
New England aster (*Symphyotrichum novae-angliae* L.)	X	X	X	X	X					

Plants found in field settings at WUT with 100 m of HEA	**Plants within 5 m of HEA**					**Plants within 1 m of HEA**				
	H	**I**	**J**	**K**	**L**	**H**	**I**	**J**	**K**	**L**
Ohio goldenrod (*Oligoneuron ohioense* Frank ex Riddell)		X								
Orange daylily (*Hemerocallis fulva* L.)		X		X						
Poverty oatgrass (*Danthonia spicata* L.)	X	X	X							
Prairie smoke (*Geum triflorum* Pursh)		X	X							
Red osier dogwood (*Cornus sericea* L.)	X					X			X	
Riverbank grape (*Vitis riparia* Michx.)	X	X	X	X	X	X				
Shrubby cinquefoil (*Dasiphora fruticosa* L.)	X	X	X							
Smooth blue aster (*Symphyotrichum laeve* L.)										
St. John's wort (*Hypericum perforatum* L.)		X	X							
Staghorn sumac (*Rhus typhina* L.)										
Stinging nettle (*Urtica dioica* L.)		X	X							
Sweet white clover (*Melilotus officinalis* L.)	X									
Tall buttercup (*Ranunculus acris* L.)		X	X		X					
Timothy (*Phleum pratense* L.)	X	X	X	X	X		X			
Virginia strawberry (*Fragaria virginiana* Duchesne)	X	X	X	X	X	X	X			
Upland white goldenrod (*Oligoneuron album* Nutt.)										
White clover (*Trifolium repens* L.)	X	X	X	X	X					
White snakeroot (*Ageratina altissima* L.)										
Wild bergamot (*Monarda fistulosa* L.)		X	X							
Wild carrot (*Daucus carota* L.)		X	X	X			X			
Woolly panic grass (*Dichanthelium acuminatum* Sw.)										
Yellow daylily (*Hemerocallis lilioasphodelus* L.)		X		X						
Yellow hawkweed (*Hieracium piloselloides* Vill.)	X	X	X		X					

These settings included site H with a pipe actively draining oil brine, site I with capped pipe, site J with pipe with no cap and no brine, site K with pipe in roadside ditch, and site L as patch of EPI in field representing a groundwater seep.

Table 4.
Representation of common plant species found at different distances from HEAs in field settings [25].

with HEAs at WUT were identified. This included forest dominated by balsam poplar reflecting past forest clearing efforts during the hydrocarbon extraction period of the late 1800s. These forest areas now represent Fresh-Moist Poplar Deciduous Forest (FOD8-1) with balsam poplar as the dominant species. Other tree species include conifers such as eastern white cedar, balsam fir, white spruce (*Picea glauca* Moench), black spruce (*P. mariana* Mill.), and red spruce (*P. rubens* Sarg.). Deciduous species include American basswood (*Tilia americana* L.), American elm (*Ulmus Americana* L.), black cherry (*Prunus serotina* Ehrh.), red maple, red oak, staghorn sumac (*Rhus typhina* L.), sugar maple (*A. saccharum* Marshall), tamarack (*Larix laricina* Du Roi), white birch (*Betula papyrifera* Marshall), and white oak (*Q. alba* L.); ash species included black ash predominantly in wetlands along with green ash and white ash in well-drained areas. Nearly all ash species have died recently due to infestation by EAB. Most American elms were also dead at WUT, due to past exposure to Dutch elm disease. In contrast, bur oak (*Q. macrocarpa* Michx.) is a tree only periodically found in these forests, as it has been previously reported to prefer soil conditions on limestone alvars along areas with recent fire history on Manitoulin Island [25, 29].

Using ELC [37], the shoreline forest areas of Smith's Bay were identified as Fresh-Moist White Cedar-Balsam Fir Coniferous Forest (FOC4-3). That is, the dominant tree species are eastern white cedar and balsam fir along with smaller coverage of species such as balsam poplar, white birch, red maple, and yellow birch; the herbaceous ground cover is depauperate and sparse, likely due to the closed canopy. Oral history revealed these shoreline areas did not burn during the 1865 fire and were dominated at the time by eastern hemlock and yellow birch in poorly drained areas, while eastern white pine (*Pinus strobus* L.) and red pine (*Pinus resinosa* Aiton) dominated the well-drained soils. Due to forestry, eastern hemlock, red pine, and white pine are now essentially absent from the shoreline of Smith's Bay with HEAs. Small areas of remnant eastern hemlock pine forests still occur at WUT but were not targeted for HEAs, as they are in remote areas with very limited access.

The ELC [37] interpretation identified the hay fields as cultural meadow (CUM) due to the long history of regular cutting. Although these fields have been cut on a regular basis for more than 100 years and show very few trees, the plant community includes a diverse array of other herbaceous species likely from seed dispersal, such as prairie smoke (*Geum triflorum* Pursh) along with typical grasses such as timothy (*Phleum pratense* L.).

Each area around the former oil well pipes and wood cribs in forest and field settings show depressions in the soil that vary from 5 to 30 cm in depth. This observed pattern of soil subsidence suggests compaction during HEA installation and past hydrocarbon extraction activities. Recent abandonment activities revealed that these areas demonstrate compacted soil to depths ~ 5 m below grade [21]. Most metal pipes reported in this study have been abandoned and had well depths >110 m, while the wood cribs were variable in construction, and some abandoned with well depths >110 m [21].

At forest site A, a rotted wooden crib (~1.2 × ~1.2 m) was found and inferred to be an HEA with no well in the structure. In this area, the dominant plants (>75% coverage) were ostrich fern (*Matteuccia struthiopteris* L.) along with a few other herbaceous species with the overstory dominated by balsam poplar; other trees in close proximity included balsam fir, red maple, and red osier dogwood. The ostrich fern was replaced by nearly complete cover (>95%) of EPI within 3–4 m of the crib (**Figure 2**). It is noteworthy to identify that specimens of EPI showed mostly bright green leaves and tall plants within 1 m of the crib, while the few specimens of ostrich fern that remained showed leaves with chlorosis (**Figure 3**). In addition, the ostrich ferns closest to the crib were ~¼–½ of the height of the specimens a few meters away from the crib; some EPI adjacent to the crib also showed chlorosis and stunting (**Figure 3**). This reduction of height of ostrich fern was attributed to the HEA. At this site, the balsam poplar was absent within 2–3 m of the crib. The balsam poplar in proximity to the crib demonstrated dead branches on the side facing the crib (**Figure 4**). For this crib, the soil was completely devoid of plants and covered by detritus and leaf matter (**Figure 5**). This pattern of herbaceous and woody plant dieback with robust EPI around HEAs was consistently evident across all forest sites.

Forest site B was in proximity to a metal pipe that contained water with bubbling natural gas. The dominant herbaceous plant in the area was marsh horsetail (*Equisetum palustre*) with the overstory dominated by balsam poplar; other trees were balsam fir, red maple, and red osier dogwood. At site B, the marsh horsetail was essentially absent within about 2–3 m of the pipe with EPI as the dominant (>90%) plant in this area. The balsam poplar was also absent within 2–3 m of the

Figure 2.
Views from August 2, 2016, show site A in the forest dominated by ostrich fern as groundcover that transitions to EPI in close proximity to a rotted wood crib from the 1800s. The view in the figure shows how EPI within 5 m of the wood crib was mostly healthy, except for some small EPI specimen with partial chlorosis represented by yellow leaves (yellow arrow). However, the ostrich fern demonstrates white and green fronds, also indicative of partial chlorosis (white arrow). Also, some ostrich fern shows stunted size and chlorosis (blue arrow).

Figure 3.
Views from August 2, 2016, show site A in the forest dominated by ostrich fern as groundcover that transitions to EPI in close proximity to a rotted wood crib from the 1800s. The view in Figure 2 shows how EPI within 5 m of the wood crib were mostly healthy, except some small EPI specimen with partial chlorosis represented by yellow leaves. However, the ostrich fern demonstrates white and green fronds also indicative of partial chlorosis (white arrow). Also, some ostrich fern shows stunted size and chlorosis. Figure shows the area within 1.5 m of the crib where the density of all plants declines with total chlorosis evident on ostrich fern (white arrow).

pipe, and balsam poplar in proximity to the pipe demonstrated dead branches on the side of the tree facing the pipe, in a similar manner as observed at site A. At 1 m from the pipe, coverage was about 95% EPI. At 30 cm from the pipe, the soil was bare and devoid of plants.

Forest site C also demonstrated extensive marsh horsetail and ostrich fern in an area that receives water from a pipe that was initially observed to be dry. At this site, a channel extends from the pipe, and EPI is the dominant plant (>90%) along the edge of the channel, for a distance of at least 50 m. That is, the soil of the channel

Figure 4.
Views from August 2, 2016, show the groundcover and tree overstory at the rotted wood crib at site A. Figure shows a complete absence of live plants within the former wood crib.

Figure 5.
Views from August 2, 2016, show the groundcover and tree overstory at the rotted wood crib at site A. Figure shows dieback of the balsam poplar branches within canopy (yellow arrows) over the former wood crib. Dieback in these overstory branches indicates root death.

demonstrates bare earth along with patches of EPI and a few specimens of other herbaceous species. The overstory trees in this area are codominant balsam poplar and balsam fir; other trees in the area included red maple, red oak, and eastern white cedar away from the channel. Most balsam poplars along the channel were dead; live balsam poplar was set back from the channel and shows dead branches on the side of the channel. Also the balsam fir close to the channel is short, with a height of <2 m, while balsam fir upslope was up to ~15 m tall.

At forest site C on September 9, 2017, the channel was observed to contain water that appears to have originated from the pipe. This pipe did not generate water until after rain storms from the previous 2 weeks. On this date, red maple saplings growing close to the channel had green leaves and yellow leaves on the same plant. Other red maple found close to the channel was shorter than specimens away from

Figure 6.
View of site C with iron-stained water that originates from a pipe on September 9, 2017. Figure 6 shows an area that is in close proximity to the pipe, with chlorosis evident in red maple sapling (yellow arrow) and EPI (white arrow).

Figure 7.
View of site C with iron-stained water that originates from a pipe on September 9, 2017. Figure shows an area in very close proximity to the pipe, with very low density of plants with those evident showing severely stunted size.

the channel (**Figure 6**). For the EPI in this area, it showed a gradient of responses to exposure to channel, based on distance to the water. Eastern poison ivy specimens that were in direct contact with the water had all three leaves showing red color, while other specimens on the channel above the water line had leaves that were red on the water side and yellow-green leaves upslope of the water. The EPI away from the channel demonstrated less yellow and red color in the leaves with green color evident. In contrast, specimens of EPI found in a short distance upslope had bright green leaves with no discoloration (**Figure 6**). The area closest to the pipe had a few very small plants evident (**Figure 7**). It is inferred the direct contact with water is triggering the rapid onset of chlorosis in leaves. Stunted plant height is attributed to exposure of soil to brine in the past. These phenological responses to brine exposure suggest a mechanism to explain the paucity of plant species, reduced height, and low areal coverage.

Observations at forest site D revealed smooth Solomon's seal as the most common species in close proximity to a pipe that contained no water for a period of 6 months prior to abandonment [21]. A second common plant in the area was nonnative dandelion (*Taraxacum officinale* Ledeb.), likely due to the close proximity to an adjacent abandoned field with extensive dandelion. The overstory trees in this area were codominant balsam poplar and black ash (all dead) with some balsam fir, red maple, red oak, and white spruce. In contrast, the balsam poplar were extensive in the area but absent within 2–3 m of the pipe. The balsam poplar in proximity to the pipe demonstrated dead branches on the side facing the pipe, as observed elsewhere. At 2.0 m from the pipe, coverage was >95% EPI with bare earth and essentially zero plants within 0.5 m of the pipe.

Site E was within the shoreline forest along Smith's Bay, Lake Huron, and contained a wooden crib that measured 1.2 m by 1.2 m and contained water (**Figure 8**). The surrounding forest was dominated by eastern white cedar, while balsam poplar and balsam fir were the most common trees in close proximity to the crib. Following the removal of the wood crib, the area was scanned using electromagnetic induction (EMI: GSSI, Model: Profiler EMP-400). The EMI scanning involves transmission of an electrical field to create a primary magnetic field in the ground. This induced current also then generates a secondary magnetic field in the ground. Both magnetic fields are then quantified as a map of the conductivity of the earth. Soil features such as reinforced concrete impair the performance of the scans, whereas it is well suited for raw soils in the forests. The EMI scans of this site identified no pipes or other metal infrastructure at depth and groundwater close to surface [21]. Abandonment of site F was completed and revealed an oak barrel structure evident below the wood crib that extended to about 9 m depth (**Figure 9**). Below the barrel, an oil well was identified within an eastern white cedar wooden box, and the well was abandoned with cement via pipe to a depth of 130 m ([21]; **Figure 9**).

The herbaceous plant community in proximity to site E was depauperate and sparse within 5 m of the wood crib, likely attributable to the low light levels from the closed forest canopy and heavy leaf litter. Some common lady fern (*Athyrium filix-femina* L.) were evident within 3–5 m of the crib along with EPI. Very few plants were evident in close proximity to the crib, except for some EPI. Balsam poplar growing over the wood crib had dead branches on the side of the crib and live branches on all other sides. The balsam fir that was downslope of the wood crib was short with a maximum height of <2 m, while other balsam fir upslope and adjacent areas had heights of >15 m. No eastern white cedar was evident directly downslope of the wood crib in the drainage path but was upslope.

Figure 8.
Views of site E with wood crib within the shoreline forest of Smith's Bay. Figure is on November 10, 2015, at the time it was found, after it was burned during 1905.

Figure 9.
Views of site E with wood crib within the shoreline forest of Smith's Bay. Figure is from November 1, 2016, and shows the excavation in progress with the discovery of a barrel at ~5 m below grade but still 4 m above the well box [21].

Figure 10.
View of site F near the shoreline of Smith's Bay, Lake Huron, on June 29, 2016. Figure shows how the wood crib exists over a natural hydrocarbon seep, about 20 m upslope from Smith's Bay.

Site F was approximately 100 m west of site E within the shoreline forest of Smith's Bay, Lake Huron, and was about 20 m upslope from the shoreline. Site F included a wood crib that measured 1.8 by 1.8 m and contained water (**Figure 10**). After the wood crib was removed, the area was scanned using EMI, similar to site E. This EMI scanning identified no pipes or other metal infrastructure at depth but suggested that groundwater was close to the surface [21]. During abandonment, no metal well pipe was found, but extensive volumes of groundwater were observed within 1 m below grade. The overstory trees in the area were eastern white cedar; however, no mature specimens were evident at the HEA, as it was dominated by

Figure 11.
View of site F near the shoreline of Smith's Bay, Lake Huron, on June 29, 2016. Figure shows the path where oil-water seepage drains to the shoreline that lacks live vegetation, with white residue along the path.

balsam poplar and balsam fir directly around the wood crib. Balsam poplar growing over the wood crib has dead branches on the side of the crib and live branches on all other sides. The balsam fir that was downslope of the wood crib was short with a maximum height of <2 m, while other balsam fir upslope and adjacent areas had heights of >15 m. No eastern white cedar was evident directly downslope of the wood crib but was evident upslope with a range of heights (<1 m to 15+ m). The area directly downslope of the wood crib lacked live vegetation within an area about 1 m wide (**Figure 11**).

The herbaceous plant community in proximity to site F was depauperate and sparse within 5 m of the wood crib, similar to site E (**Figure 10**). This pattern of low density and diversity of herbaceous species was also likely partially attributable to the low light levels due to the nearly closed forest canopy and heavy leaf litter. Some mapleleaf viburnum (*Viburnum acerifolium* L.) and common lady fern were also evident within 3–5 m of the crib along with abundant EPI. Very few plants were evident in close proximity to the crib, except a few EPI. There was also a channel that drained water from the crib to Smith's Bay that was 1.0 m wide (**Figure 11**). This drainage channel lacked herbaceous species, while EPI was one of the only species periodically evident along the edge. Also balsam fir trees were evident along the channel and were all short (<2 m); no eastern white cedar were evident along the channel. Specimens of balsam fir away from this channel were all tall (10–15 m). Also rocks downslope from the seep show white particulate residue in the path to the water (**Figure 12**). Also, rocks in Smith's Bay also showed this white particulate and lacked submerged aquatic vegetation (SAV; **Figure 13**). It is prudent to note that SAV was absent only along this area of the shoreline (Figure 13).

Abandonment activity at site G initially involved the excavation of the soils around the wood crib. Soils on the upslope side of the excavated pit appeared to be fine textured with little visual or olfactory evidence of hydrocarbons, while the soils on the downslope were coarse and contained free petroleum product mixed with water. A short time after the excavator removed the surficial soil, groundwater with brown hydrocarbons filled the excavation to approximately 2.0 m below grade. A vacuum truck was used to ensure this oil-water slurry did not drain to the shoreline. Follow-up excavations and dewatering determined clay was extensive at depth below the excavation with no pipe or infrastructure evident. The initial

Figure 12.
Views of site F. Figure shows the seepage path from site F to the lake on April 29, 2016, with white foam arising from the wooden crib.

Figure 13.
Views of site F. Figure from October 12, 2016, shows the shoreline of Smith's Bay, Lake Huron, with a gap in the vegetation (black arrow) and a person with orange vest standing in front of the wood crib in the background. Inspections of the rocks in the water demonstrated the presence of white particulate residue from the seep and zero SAV in this area, while adjacent areas had SAV [21].

determination was this site represented a natural hydrocarbon seep. A soil test pit survey was conducted to map the hydrocarbon distribution below grade, and chemical analyses tracked the plume 75 m upslope from the shoreline, where the survey ended. The results from this tracking exercise led to the final determination that this was a natural seep, not a lost HEA, as no evidence of infrastructure was found in the area upslope [21].

Field site H included a pipe that was actively draining an oil-water slurry downslope through a hay field to a wetland-forest complex (**Figure 14**). Since the farmer was not cutting the vegetation around the pipe, black locust (*Robinia*

Figure 14.
View of site H within a hay field on August 8, 2014. Figure shows the oil-water slurry runoff from a pipe. The vegetation near the pipe demonstrated evidence of leaf chlorosis and stunted size, including red osier dogwood that was upslope and had branches over the pipe (blue arrow), black locust (black arrow), EPI (yellow arrow), and multiflora rose (red arrow).

pseudoacacia L.) and red osier dogwood were evident in the area, along with a few small green ash that had not yet been attacked by the EAB. The herbaceous community upslope of the pipe was typical of the field, with dominance by timothy grass. In contrast, the herbaceous community within 1 m of the pipe was dominated (>75%) by EPI. The EPI specimens located about 1 m from the pipe showed bright green leaves, while specimens in contact with the oil-water slurry showed yellow leaves. The soil within 30 cm of the pipe lacked plants; no plants were evident within the path immediately downslope used by the oil-water slurry. Branches of red osier dogwood in close proximity to the pipe included discoloration of the leaves, suggestive of chlorosis. Black locust leaves also included discoloration. The EPI found in association with the oil-water slurry also demonstrated small size and discoloration of the leaves compared with specimens 1 m away from the oil-water slurry. A few specimens of Virginia strawberry (*Fragaria virginiana* Duchesne) and multiflora rose (*Rosa multiflora* Thunb.) were also evident on the edge of the oil-water slurry and demonstrate discoloration of leaves as well as stunted size. The EPI dominates the vegetation along the path followed by the oil-water slurry downslope, whereas the oil-water slurry is not evident on surface at 15 m from the pipe. Even though the oil-water slurry is not evident at the surface, the EPI follows a path to the edge of the wetland forest, approximately 40 m downslope, and was rare on the edges of the path. When the trees in the wetland forest were inspected, it revealed that those trees in the path of the oil-water slurry were shorter and show a high frequency of dead branches compared with the areas on either side despite no other differences in land use or drainage (**Figure 15**). Inspection of the hay field downslope of the pipe identified EPI was the dominant plant (>50% areal coverage) right through the field to the edge of the woodland. Such disparities in height and survival of varied plants downslope of the pipe imply the oil-water slurry is the causative factor responsible for the local plant responses to exposure to the slurry.

Field site I included a pipe that was capped because it was observed to release large quantities of natural gas in the past by the landowner. The herbaceous plant community within 5 m of the pipe was diverse and essentially identical to the adjacent hay field, including Canada goldenrod, common evening primrose

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Figure 15.
View of site H within a hay field on August 8, 2014. Figure shows the forest-wetland downslope of the pipe. The trees in the area were shorter (stunted) and also showed dead stems relative to adjacent areas, and EPI was evident downslope but absent from adjacent field areas.

(*Oenothera biennis* L.), tall buttercup (*Ranunculus acris* L.), and yellow hawkweed (*Hieracium piloselloides* Vill.). However, within 1 m of the pipe, EPI was dominant (>90%). At 30 cm from the pipe, the soil was bare. This pattern of reduced plant diversity and elevated EPI implies that groundwater likely rises periodically around the base of the capped pipe.

Field site J was essentially identical to site I except the pipe lacked a cap. This pipe was observed to contain no water during the 6 months prior to abandonment. The herbaceous plant community within 5 m of the pipe was somewhat similar to the adjacent hay field. However, within 2–3 m of the pipe, EPI was dominant (>90%). At 30 cm from the pipe, the soil was essentially devoid of plants.

Field site K was within a roadside ditch, and the pipe was within 10 m of a residential driveway. This pipe contained no water, but the resident stated it would release water after spring snow melt. This ditch had an array of species evident within 5 m of the pipe, including staghorn sumac; American elm along with specimens of common raspberry (*Rubus idaeus* L.), riverbank grape, Virginia strawberry, and multiflora rose. The plant community was diverse within 1 m of the pipe. At 0.5 m from the pipe, EPI was dominant (>90%). There was bare earth below the EPI vines growing near the pipe.

Field site L was within a hay field. The site is defined by an abrupt ecotone between the field plant community with transition to dominance by EPI (>95%) with a few Virginia strawberry. This patch of EPI measured approximately 3 × 3 m. This patch demonstrated healthy EPI with no bare earth. Detailed inspections were completed within this patch. Initially, the area was inspected using a handheld metal detector, to assess possible presence of a metal pipe below grade. This inspection led to no observations, suggesting no presence of metal. Then the area was scanned using EMI, similar to the studies at sites E and F. The EMI scans of this site identified no pipes or other infrastructure at depth but suggested groundwater was close to surface [21]. After the EMI scans were completed, the patch of EPI was excavated, to further inspect the area for oil-stained soil to a depth of 1 m, to complete the search for a lost HEA, with none found [21]. After, the excavation filled with water, and the EPI patch was attributed to a groundwater seep.

Information on the herbaceous and woody plant communities along with the distribution of EPI observed within forests and fields at sites A to L at WUT allowed for the resolution of the spatial responses of plants to the presence of HEAs, natural hydrocarbon seep, and groundwater seep (**Table 5**). Species that show growth morphology via rhizome or vine seem to show an ability to occur within 5 m of HEAs, such as EPI, riverbank grape, and Virginia strawberry. Since these patterns were resolved across

Response of plants and EPI relative to distance from HEA or natural groundwater seep (as approximate % EPI coverage in an area)				
Setting	**Upslope**	**5–10 m from HEA or seep**	**1–5 m from HEA or seep**	**0 m from HEA or seep**
Field: HEA pipe with cap and herbaceous plants	No response with diverse plant community (<5%)	Diverse plant community (< 5%)	A few plant species evident, some EPI with most species absent (>90%)	No plants
Field: HEA and EPI	EPI absent or rare (<5%)	EPI absent or rare (<5%)	EPI dominant (>90%)	No EPI; no plants
Field: groundwater seep and EPI	EPI absent or rare (<5%)	EPI absent or rare (<5%)	EPI dominant (>95%)	EPI dominant (>95%)
Forest: HEA and herbaceous plants	No response with diverse community (<5%)	Loss of diversity, shorter plants within drainage path (25–95%)	A few plant specimens with EPI dominant (>95%)	No plants
Forest: hydrocarbon seep and herbaceous plants	No response with diverse community (<5%)	No plants in drainage path of seepage to Lake Huron	No plants in path of seepage; EPI evident on edge of drainage	No plants
Forest: HEA and trees	No response with diverse community (<5%)	Sensitive trees absent; tree branches on side of HEA dead; other trees stunted in height	Trees dead; other trees stunted with dead branches near HEAs with dominant EPI (>90%)	No trees
Forest: hydrocarbon seep and trees	No response with diverse community (>5%)	Sensitive trees absent from path of groundwater. Tree branches dead along drainage path. Other trees stunted in height	Sensitive trees absent from path of groundwater. Tree branches dead along path. Other trees stunted in height	No trees
Forest: HEA and EPI	EPI absent or rare (<5%)	EPI dominant, usually >50% of specimens	EPI dominant (>95%)	No EPI and no plants
Forest: hydrocarbon seep and EPI	EPI absent or rare (<5%)	EPI dominant (>95%) along edge of path of groundwater; no EPI in path	EPI dominant (>95%) along edge of path of groundwater; no EPI in path	No EPI

Findings from this study demonstrate the plant communities respond to the HEA and seeps based on water drainage, attributable to brine that contains elevated concentrations of a suite of elements.

Table 5.
Summary of response patterns for vegetation found in association with hydrocarbon extraction area, groundwater seep in a field, and hydrocarbon seep in a forest setting, represented as approximate % coverage of EPI in an area.

forest and field sites, it provides justification for the use of EPI as an indicator species of disturbance. This resolution of general response patterns of plants to this type of disturbance suggests the response patterns could also be used to predict the sites of HEAs, hydrocarbon seeps, or groundwater seeps in areas with oil shale formations.

6. Discussion

Wiikwemkoong Unceded Territory history identifies the community-associated HEAs with disturbed land, and this led to the expulsion of oil men during 1905 [21, 31]. Such identification of disturbance was attributed to the construction of infrastructure like roads as well as clearing of forest in addition to using valuable farmland for HEAs. Community members also described the presence of large barrels used to separate oil from water in fields and forests [21]. The oil men would direct the oil-water slurry through pipes to these barrels. When the decision was made to evict the oil men, the HEAs were burned, and this common disturbance history contributed to the responses of herbaceous and woody plants described in this study. Oral history also identifies that these burned areas were considered scars on Mother Earth that were very slow to recover. However, this recovery of the HEAs was inferred to be slower than expected and resulted in different plants at these sites compared with adjacent areas [21]. Since 109 years passed from the time the HEAs were burned until the initial assessments during 2014, this represents a unique opportunity for learning, to understand how the herbaceous and woody plants responded to this common disturbance history [17]. This understanding arises from un-replicated activity associated with large-scale disturbance of fields and forests at WUT due to the development of HEAs. Such activities represent an opportunity for learning that is consistent to Carpenter's [17] recommendation to consider ecological settings to quantify interactions involving species and document responses of plants and animals to large-scale environmental perturbations. Carpenter [17] recommended that such perturbations, if studied, often provide the chance to document nonrandom change; a reasonable way to interpret such change is with causal inference. In an earlier study [18], a similar idea was expressed about severe perturbations representing a chance to document response of plants and animals but provided the caveat that such events possibly generate unique responses that are difficult to quantify and apply to other settings. Using this documentation of the response of herbaceous and woody plants near HEAs, it pointed to the use of EPI as a bioindicator of the plant community responses to brine as a way to find HEAs. At WUT, it is useful to use EPI as a bioindicator, as it is the only species consistently found within 1 m of HEAs. Other species, such as Virginia strawberry, also show distributions near HEAs, likely attributable to growth morphology via vine. Due to the wide distribution and salinity tolerance of EPI, it is probable this species could be evaluated for use to resolve the response of plants to HEAs beyond WUT.

This study reports the observed responses of herbaceous and woody species to episodic exposure to brine in a setting with a common disturbance history. These observations at WUT identified a pattern of reduced diversity of herbaceous and woody species as well as increased coverage of EPI in proximity to drainage from HEAs and natural seeps in fields, and FOD8-1 and FOC4-3 woodlands. These plant communities demonstrate a spatial response to water that originates from HEAs and natural seeps with rapid transition from diverse plant community to dominance by EPI over short distances despite similar exposure to sunlight and a common disturbance history. The identification of this response pattern involving a reduction of plant diversity and dieback of overstory tree branches was directly attributable to brine found near HEAs and seepage in fields and forests, representing an ecotone that defines the zone of disturbance. Observations from site C during September 2017 demonstrated that chlorosis will start within a few days of the arrival of brine; at this site, the brine is able to travel an extended distance from the source, due to the topography, causing stress and death to plants all along the drainage path. Site G demonstrated the response of herbaceous and woody species that reflects natural seepage of hydrocarbons and brine with similar patterns of species selection leading to nearly full coverage of the area by EPI. In contrast, the capped well at site I showed evidence of very little disturbance at 5 m and the focal presence of EPI directly around the pipe. Species such as Virginia strawberry and multiflora rose that grow with vines appear alongside EPI. Long-term responses include herbaceous plant communities essentially absent in close proximity to HEAs and natural seeps as well as an overstory tree canopy dominated by species somewhat tolerant to salt with dead branches near the source of brine.

Other observations from HEAs identified additional plant associations within these areas. Specifically, all HEAs include a few very mature common buckthorn (*Rhamnus cathartica* L.) and/or glossy buckthorn (*Rhamnus frangula* Mill.). It is inferred the seeds of these nonindigenous buckthorn were accidentally introduced to WUT during the 1800s via transport on equipment used for HEAs [21]. Inspections always reveal that buckthorn has spread extensively outward, in a radial pattern, from each of the HEAs. Hence, when buckthorn is found at WUT, surveys will follow these nonindigenous trees, to see if they lead to large specimens in proximity to an HEA. Another consistent observation is that one apple tree (often *Malus domestica* Borkh.) was always planted upslope from each of the HEAs. Further, in a field with numerous HEAs represented as metal pipes, one apple tree is located upslope and within 10 m of each pipe [21]. Oral history from WUT revealed the oil men regarded an apple tree as good luck and a source of food during the autumn season. At WUT, the presence of a large (>30 cm DBH) apple tree in close association with buckthorn is now used as preliminary indicators of possible presence of HEAs in an area.

Studies at WUT [21] documented soil at HEAs containing elevated hydrocarbon concentrations, especially for soil in contact with wood from the former facilities, whereas soil concentrations of hydrocarbons rapidly declined with distance from HEAs, attributed to bacterial degradation of the hydrocarbons over time [21]. These low concentrations of soil hydrocarbons downslope from HEAs provide additional evidence that it is brine from the HEAs that plants are responding to in these areas. The response pattern of the plants, including EPI, to brine at WUT forms the framework, as represented in **Table 5**, as a guide to find lost HEAs as well as understand influence of brine from natural seeps on plant communities.

A literature review documented a range of responses of herbaceous and woody species to brine from HEAs, but none was found for water arising directly from oil shale formations. The study in Oklahoma, USA, for plants downslope of HEAs attributed responses to the brine from the HEAs [6]. A separate study reported that herbaceous and woody plants recovered initially from a brine leak at an impoundment within 1 year after the leak was stopped with no soil treatments; plant community recovery was attributed to frequent rain washing the brine away [15]. At the site of this brine leak [16], the plant community 4 years later was populated by a diversity of herbaceous and woody species, attributed to the seed bank and live adjacent vegetation [15, 16]. Another study reported treatments for bare soils within 1 m deep former reserve pits used to store drill cuttings, drilling fluid, and brine, as preparation for replanting [12]. This bare earth was disked, mulch added, irrigated, and then seeded with local range grasses as well as planted seedlings. Success of seed germination and seedling survival was higher on mulch-treated soils than untreated soils. Over time, the mulch-treated soils showed declines in the seeded and planted species due to colonization by other local species. This mulch treatment led to the identification that establishment of salt-tolerant plants in the reserve pits following treatment can act as the basis for future plant establishment and reclamation; without treatment, seeding, and/or planting of seedlings, the pits require extended periods before plants naturally establish on these soils. Another study recommended the use of local, native plant species for seeding on land disturbed by hydrocarbon extraction activities, with emphasis on species adapted to the soils associated with the area that often show elevated tolerance to soil salinity [38]. Such seeding recommendations included the use of local sources, due to likely adaptations to regional climate and soils, as the process of reestablishing vegetation on sites disturbed by HEAs is challenging due to the chemistry as well as other physical factors, such as soil compaction [3, 6, 32]. As a means to address challenges for seeding and planting on high-salinity soils, computer software was recently presented to guide such activities [39].

Other areas of study are warranted, to resolve the morphological and physiological response of herbaceous and woody species associated with HEAs and natural seeps, based on observations at WUT. For example, anecdotal observations indicated a trend that herbaceous species near HEAs often had fewer and smaller flowers compared with specimens in adjacent areas. Other plants showed differences in height and leaf size in proximity to HEAs. This study did not provide for the opportunity to quantify the range of possible responses of plants to exposure to brine arising from HEAs. If the source of stress on these plants was not known, the differences in flowering, plant height, leaf size, etc. could be documented as a phenological response to regional factors, not local responses to brine exposure. Such opportunities for documentation of response of plants, including separation of cause between stresses in proximity to HEAs, may be useful in the future. The HEAs may also be resulting in genotypic changes to plants, due to long-term episodic exposure to brine. Plants like prairie smoke (*Geum triflorum* Pursh) have been observed periodically at WUT in close proximity to HEAs, whereas the USDA identifies this plant as having no tolerance to soil salinity. It may be interesting to resolve if prairie smoke has developed tolerance to elevated soil salinity at WUT. Responses of aquatic plants to brine exposure represent another understudied topic. At site F, the brine-oil slurry drained downslope to the shoreline of Smith's Bay. In the area of the shoreline, white residue was evident on the rocks on the shoreline and in the water. This area also lacked SAV, while adjacent areas demonstrated SAV among the rocks. These varied themes represent candidate areas for further study, to resolve the range of apparent responses of plants relative to episodic environmental stress from brine arising from HEAs and separate them from phenological responses to regional processes like climate.

This study resolved the response of plant communities to a common disturbance history as well as the episodic release of brine from HEAs and seeps within about 30 km^2. The resolution of the response of herbaceous and woody species and EPI to HEAs and natural seeps represents a framework that could be applied elsewhere, to assess the intensity of disturbance as well as to find lost HEAs. The ecotone of disturbance at WUT for HEAs is defined by the brine drainage area within a local area of subsidence where EPI is able to dominate the herbaceous plant community. It is probable EPI is able to achieve dominance in these areas due to growth via rhizome and can ameliorate the extreme chemical concentrations in brine. Another consideration at WUT is the native plant community contains very few species tolerant of elevated soil salinity [25] and led to the opportunity for EPI to dominate areas with HEAs. This study has confirmed the distribution of EPI is useful to represent contemporaneous disturbances to herbaceous and woody species attributable to HEAs and natural seeps in forests and fields and applicable to other areas with HEAs.

7. Conclusions

Large-scale disturbance of plant communities at WUT occurred with the 1865 forest fires followed by development of HEAs in forests and fields. These disturbed plant communities at the HEAs were burned in 1905 and were followed by establishment of pioneer plant species such as balsam poplar and eastern white cedar in forests and Canada goldenrod and Virginia strawberry in fields. Areas in close proximity to the HEAs have not developed diverse plant communities during the last 109 years but are dominated by EPI, and this pattern is attributed to the periodic expulsion of brine from HEAs. Such dominance by EPI in these areas demonstrates intolerance of brine by most plants, whereas the EPI flourishes, due in part to some tolerance of salt as well as rhizome growth strategy. With this demonstration of EPI as the dominant species near HEAs, it is a phenological response to local habitats that can be used to rediscover lost HEAs. Studies of natural groundwater seeps located near HEAs were dominated by EPI, and confirmed plant community responses are attributable to exposure to brine. This confirmation that EPI represents a bioindicator for understanding environmental disturbance through the analyses of phenological responses at WUT can likely be applied to other areas with EPI and other salt-tolerant plant species.

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Abbreviations

CUM	cultural meadow
EPI	eastern poison ivy
FOD8-1	Fresh-Moist Poplar Deciduous Forest
FOC4-3	Fresh-Moist White Cedar–Balsam Fir Coniferous Forest
HEAs	hydrocarbon extraction areas
Premier	Premier Environmental Services
TDS	total dissolved solids
TK	traditional knowledge
USDA	United States Department of Agriculture
WUT	Wiikwemkoong Unceded Territory

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