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PRACTICE AND TECHNICAL ARTICLE

The effects of mycorrhizae on phosphorus mitigation and pollinator habitat restoration within riparian buffers on unceded land

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Agricultural pollution, especially phosphorus (P) can cause eutrophication of freshwater quality. Riparian buffers are best management practices (BMPs) which intercept agricultural pollution. However, they are frequently degraded by reduced biodiversity. P mitigation in riparian buffers can be enhanced through mycorrhizal inoculation and cyclical coppicing. We report on a myco-phytoremediation project that investigates mycorrhizae's effect on vegetation's ability to lower legacy soil P, soil water P, and increase woody biomass P uptake. It also aimed to restore pollinator habitat through planting a diverse, native plant palette (32 species), blooming from February to November. Planting and offering culturally relevant plant materials to the Abenaki contributes to their land rematriation process. The study was located on unceded Abenaki territory at Shelburne Farms, within 300 m of Lake Pitawbagw (Lake Champlain) which is impacted increasingly by P pollution from colonial and conventional agricultural practices. Along a drainage way three treatment plots were installed: buckthorn vegetation (OIV) left in place as the control, and two restored diverse multi-synusium plant communities, consisting of either uninoculated (RV) or inoculated with 19 mycorrhizal species (RVM). After 2 years, soil water soluble reactive P extracted from lysimeter samples was not affected by treatment but varied over time. However, water extractable SRP (WEP-SRP) and TP (WEP-TP) followed this trend RV > OIV > RVM which was inversely and linearly related to mycorrhizal density. Plants are best harvested in late summer when P concentrations are highest. Restoration science can flourish through reciprocally partnering with Original Peoples who hold expertise in ecological reconciliation.

Key words: mycorrhizae, phosphorus, pollinator habitat, restoration, riparian buffer, unceded land

Implications for Practice

- Integrating Original Peoples' expertise supports rematriation efforts in the context of restoration.
- In riparian buffers mycorrhizal inoculation and cyclical coppicing are innovative practices for removing legacy phosphorus.
- Diverse pollinator habitat can be restored by manual removal of non-native species without synthetic chemicals.
- Multi-synusium, native plant palette design should consider mycorrhizal and pollinator plant associations.
- Applying a diverse set of evaluation criteria for restoration projects can lead to reflective practice.

Introduction

Ecological Restoration Objectives and Success Criteria

Ecological restoration involves assisted recovery of damaged or degraded ecosystems to their predisturbance state (Clewell et al. 2002). While this may be a lofty goal, returning ecosystem structural and functional attributes is more realistic. Clewell et al. (2002) provide nine criteria (prefixed by C) by which restoration success can be measured (Box 1). We recommend two additional indicators be added to assess a site's restoration (prefixed by R) success. First we assert that restoration efforts must satisfy a needed mitigation function (R10). Second, we recommend practitioners address the social injustice inherent in the environmental damage (R11). Although some of Clewell's criteria (C1–C5) can be addressed in the design, design outcomes, and proposed criteria may require adaptive management and monitoring.

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Box 1 Criteria to assess the success of ecosystem restoration.

The goal of restoration is to return a damaged ecosystem to a state prior to degradation. While the goal is clear, assessing whether restoration has been successful is more complex. Clewell et al. (2002) defined a set of nine evaluation criteria, labeled here as C1 to C9. Roughly divided they refer to biotic (plants) and abiotic conditions, and to more dynamic characteristics of the restored ecosystem, such as functioning and resiliency.

The biotic factors associated with plant choices are:
C1: Species assemblage is characteristic of the community structure of the reference ecosystem.
C2: Species are indigenous.
C3: All functional groups are present.

In the northeastern United States (known as Turtle Island by many Original Peoples) (Hunt & Stevenson 2017), it is now a crucial practice to choose indigenous plants (C2) in order to maintain trophic relationships (Tallamy 2017). When a natural, pristine system is chosen as a reference, achieving C2 and C3 could be inherent in the location choice if the areas have not been affected by a rapidly changing climate. Regardless reconciliation restoration suggests that most ecosystems can no longer be restored to their natural state and plants need to be chosen that can survive the abiotic conditions (C4) created by disturbance. This restored community may not resemble a pristine natural system. One example is the severe soil structure and vegetation alterations caused by invasive earthworms (Hale et al. 2005) which likely reduces the palette of native plants that can survive the invasion. This relates to C7 (below), *potential threats to the restored system are eliminated*. Certain threats to ecosystems, such as invasive worms, may not be easily eliminated. In this study, the buffer we restored is downhill from a composting facility which will not be removed due to land owner preferences despite accessible regenerative alternatives.

Functional and developmental characteristics
C5: The system functions according to its developmental phase.
C6: The ecosystem is integrated with the surrounding landscape matrix.
C7: Potential threats to the restored system are eliminated.
C8: The system is resilient.
C9: The system has potential to continue indefinitely under current environmental evolving conditions.

With the exception of C6, these parameters are dynamic. A few snapshots along the restoration trajectory may not provide sufficient evidence of improvement. In this study we restored a riparian buffer strip whose function is to reduce nutrient loading from agricultural land. It is not naturally integrated into the surrounding landscape, but provides a sharp contrast with the adjacent agricultural field. In order for these ecotones of transition to function, other mutualisms need to be considered such as: pollinators, seed dispersers, and mycorrhizae. If these mutualists are unable to disperse from nearby natural habitats, then it may be beneficial to deliberately and actively reintroduce them (Handel et al. 1994) to the ecosystem being restored. Additionally, restoration efforts focus on establishing species that not only can grow under existing conditions but that can also initiate autogenic processes which improve ecosystem functioning (Perrow & Davy 2002) and resilience.

Frequently, like in this case study, restoration is done not just for restoration sake, but with the additional purpose to mitigate the pollution caused by past and current land practices. We add this crucial indicator informally described by social scientists as harm reduction. R10: The system satisfies a mitigation function. Our study was designed for the mycorrhizal fungi and plant species to intercept, uptake, and thereby mitigate the P pollution before it entered the water body. This intervention complements our next suggested criteria of R11: recognizing the need to repair social injustice inherent in the environmental damage. In this case some of the social injustices include attempted genocide, removal from homelands, lack of access to ancestral lifeways, forced attendance at conventional boarding schools, and generational silence to survive eugenics (Couzelis 2013). These atrocities correspond to social imbalances interconnected with colonial land use and modern agriculture. Hence, any research design needs to acknowledge the culture of the Original Peoples upon whose land the research is done, integrate their indigenous expert knowledge when it is offered and reciprocate with reparations that support their rematriation (R11). This aligns with the "Five Shifts" paradigm of Trisos et al. (2021) which emphasizes the importance of cultivating a decolonial ecological ethic (see Boxes 2 & 3 for more on this).

Selecting reference conditions (C1) for restoration projects in formerly glaciated regions of North America is challenging, because plant communities responded to post glacial climate change. Even before colonization, Original Peoples affected the landscapes (Allison 2007) during several eras which differed in their climax plant communities (Box 2). We selected a reference condition that likely existed during the Wabanaki Renaissance.

Box 2 Know the history of the site.

The study site is located at Shelburne Farms in *N'dakkina* (Abenaki word for their ancestral territory including Vermont), on Lake Pitawbagw (Lake Champlain). The indigenous history of the area began after the last glaciation when the ancestors of the Abenaki moved their seasonal hunting, fishing, and gathering camps north and east as the glaciers retreated (Wiseman 2001, 2005). From 12,500 BP to the arrival of European settlers in the seventeenth century, the Abenaki ancestors followed the retreating shorelines of Glacial Lake Vermont and the Sea of Champlain while the dominant vegetation shifted several times as the climate changed. Pollen core studies in Vermont showed the succession from boreal forests dominated by *Picea spp*. (spruce), *Abies spp*. (fir) to mixed hardwoods, *Pinus spp*. (pine) and *Tsuga spp*. (hemlock) systems (Frink & Zierblis 1996), and finally to hardwood forests (Doherty et al. 1989; Haviland & Power 1994). At the height of their technological development during the Wabanaki Renaissance (1000–500 years ago) Abenaki developed agricultural practices from tending patches of wild foods (Robinson 2007). The land at this time was managed by Western Abenaki peoples through polyculture cropping and agroforestry involving seven sister mounded plantings amidst forest openings (Wiseman 2005, 2018). Early in the seventeenth century 90% of Wabanaki were killed, likely infected by smallpox introduced by European settlers, and then forcibly removed from the land (Erica Huyler 2000; Wiseman 2005) after which colonizer land practices replaced those of the Wabanaki.

As Wabanaki land was increasingly occupied by Europeans, forested landscapes were cleared for agricultural pastorage and cropland (Frink 1994) transportation infrastructure (highways, bridges, fences) linked all cultivated land which was tilled for cash crops and heavily grazed by domesticated cattle, swine, and poultry with monoculture fields to sustain them. In the 1840s the colonially named "Champlain Valley" became the state's wool production center which led to more land clearing and farm consolidation. Railroads in the 1840–1850s spurred increased sheep flock and dairy herd size for perishable products like milk, cheese, and butter. By this time hillier lands had been cleared for three generations, pastures were intensively used and exhausted, all leading to soil erosion. In the late nineteenth and early twentieth century, roads and ditches (connected to tile drainage systems in farm fields) were installed without being actively vegetated (Erica Huyler 2000) and thereby were subject to invasion by exotic species (Hughes & Cass 1997). These practices contributed to P pollution at Shelburne Farms, a Vanderbilt legacy preserved amidst various economic and social challenges. It became a "model farm" to experiment with the latest agricultural and scientific practices. As a National Historic Landmark it is now a significant tourist attraction and community partner with 1,400 acres of diversified farmland. The high soil P concentrations were exacerbated by superphosphate applied to the farm's crop fields and pasturelands under the USDA-sponsored Agricultural Conservation Program. In the late 1950–1960s Dutch elm disease killed hundreds of elms. Non-native species such as buckthorn and *Acer platanoides* (Norway maples) took their place along roadways and field edges (Erica Huyler 2000), continuing the land transformations set in motion by colonial land practices. Our research addresses the need to know more about how to reduce legacy P by restoring riparian areas now dominated by buckthorn to a plant community which existed around the time of the Wabanaki Renaissance.

It is worth mentioning that the makeup of the hardwood and mixed forest communities of the sixteenth century, prior to European colonization of Vermont, were well known, comprising species still found in current ecosystems such as *Juglans cinerea* (butternuts), *Carya spp*. (hickory nuts), *Corylus spp*. (hazelnuts), *Sambucus spp*. (elderberries), *Prunus spp*. (chokecherries), *Rubus spp*. (bramble berries), and *Eupatorium perfoliatum* (boneset) (Wiseman 2001) which are all mycorrhizal (Weishampel & Bedford 2006; Bunyard 2020). The chosen reference condition for this study was deemed to have little anthropogenic alteration, defined as having no effects of major industrialization, urbanization, and agricultural intensification while only minor modification of biology, hydromorphology, and physiochemistry (European Commission 2003; Valinia et al. 2012). At this time in the relatively open canopy, various shrubs and herbs grew that partnered with arbuscular mycorrhizal (AMF) or ectomycorrhizal (ECM) fungi.

Our project occurs amidst the Anthropocene Extinction when water quality and pollinator habitat is threatened by conventional agricultural and industrial land practices following the forced removal of Original People (Barry & Agyeman 2020). This case study reports on a demonstration project which researches mycorrhizae's effect on the riparian restoration success of a site dominated by *Rhamnus cathartica* (buckthorn). It comments on lessons learned for design and practice, exploring ethical aspects of restoring unceded indigenous lands.

Mycorrhizae may improve legacy P mitigation, often responsible for eutrophication in freshwater lakes (Qiu et al. 2022), increase harvestable P amounts, and facilitate diverse pollinator establishment (Barber & Soper Gorden 2015). Run-off and soil erosion translocate dissolved and particulate P to waterbodies where it causes algae blooms and anoxic conditions. This malaffects ecology of the receiving water and impairs drinking water quality. Eutrophication mitigation strategies which inhibit P loading through ecosystem restoration (Ngatia & Taylor 2019) are needed wherever agriculture abuts freshwater bodies. The Champlain watershed, where this research is conducted, received a D+ in its cleanup report card (Conservation Law Foundation 2018). Similarly, there is a dearth of field data on mycorrhizae's efficacy in riparian buffers for water quality protection (Rubin & Görres 2021). Yet according to a recent

Table 1. Plant palette. Designed and installed for the two restored plots, indicating flowering time, pollinator species hosted, type of mycorrhizal symbiont, flowering schedule, number of individuals installed per plot, and the Abenaki use of the plants (Supplement S1): m, medicinal; e, edible; a, artisanal; c, ceremonial; u, utilitarian. The two species listed under February are not flowering but have catkin or fruits available as food for pollinators at that time. All species are native to VT except the naturalized *Panicum virgatum* and *Sambucus niger*.

Scientific Name	English Names	Abenaki Uses	#/plot	Flowering Month										Mycorrhizae	Hosts
				F	M	A	M	J	J	A	S	O	N		
Trees															
Acer rubrum	Red maple	e,m	1		■	■								AMF	Native & honey bees, Crecopia moths, other moth larvae, birds
Acer saccharum	Sugar maple	e,m	1		■	■								AMF	Crecopia moth, birds
Alnus incana	Speckled Alder	m,c	10		■	■	■							ECM/AMF	Song & water birds
Carya ovata	Shagbark Hickory	e,a	2		■	■	■	■						ECM	Insectivorous birds
Cornus Sericea	Red Osier Dogwood	m,a	19				■	■	■					AMF	Butterflies, Spring Azure, marsh & shore birds
Quercus bicolor	Swamp White Oak	e	1			■	■	■	■					AMF	Song, ground & water birds
Salix nigra	Black Willow	m	1			■	■							ECM/AMF	Mourning Cloak, Viceroy, Red Spotted Purple, Tiger Swallowtail, song birds
Salix petiolaris	Meadow Willow	a	8		■									ECM/AMF	Native bees, bumblebees, honeybees, Mourning Cloak, Viceroy
Tilia americana	Basswood	e,a,u	1		■	■	■							ECM	Native & honey bees, birds
Ulmus americana	American Elm	a,m	10	■	■	■								AMF	Mourning Cloak, Columbia Silk moth, Question Mark, Painted Lady, Comma Butterfly
Shrubs															
Cephalanthus occidentalis	Buttonbush	m	9					■	■	■				AMF	Native bumblebees, honey bees, butterflies, Titan Sphinx, Hydrangea Sphinx
Ilex verticillata	Winterberry	m	4	■	■	■	■	■	■		■	■	■	AMF	Honey bees, butterflies, Elf larvae host, birds
Sambucus nigra	Elderberry	m	8				■	■	■	■	■	■		AMF	Native, bumble and honey bees, butterflies, Titan Sphinx, Hydrangea Sphinx
Viburnum dentatum	Arrowood	a,u	4				■	■	■	■	■	■		AMF	Native bees, bumblebees, butterflies, Spring Azure, birds
Viburnum lentago	Nannyberry	e,c,m	4				■			■	■	■		AMF	Butterflies, Spring Azure, birds
Perennials															
Asarum canadense	Wild Ginger	m	9			■	■	■						AMF	Butterflies, Pipeline Swallowtail
Carex comosa	Longhair Sedge		18			■	■	■	■					AMF	Nesting for insects & birds
Chelone glabra	Turtlehead	m	20						■	■	■			AMF	Hummingbirds, butterflies, Baltimore Checkerspot
Eupatorium perfoliatum	Boneset	m	14						■	■	■			AMF	Native bees, butterflies. Birds
Eutrochium purpureum	Joe Pye Weed	m	21						■	■	■			AMF	Native bees, butterflies, birds
Iris versicolor	Blue Flag Iris	m	18				■	■	■	■				AMF	Hummingbirds, birds
Symphyotrichum novae-angliae	NE Aster	m, e	9							■	■	■		AMF	Butterflies, birds
Wild Seed mix															
Panicum virgatum	Switch Grass									■	■	■	■	AMF	Butterflies, Delaware & Dotted Skipper, birds
Elymus virginicus	Virginia Wild Rye				■	■	■							AMF	Butterflies, Branded Skippers and Satyr, birds
Festuca rubra	Red Fescue					■	■	■	■	■	■			AMF	Birds
Carex vulpinoidea	Fox Sedge						■	■	■					AMF	Birds
Scirpus cyperinus	Wool Grass	m,e,a						■	■	■	■			AMF	Dion Skipper, birds
Scirpus atrovirens	Green Bullgrass						■	■	■	■				AMF	Song, shore & water birds
Bidens cernua	Nodding Bur-Marigold	m								■	■			AMF	Native bees, birds
Eupatorium perfoliatum	Common Boneset	m								■	■			AMF	Native bees, butterflies, moths, birds
Eupatoriadelphus maculatus	Joe Pye Weed	m								■	■	■		AMF	Butterflies, Moth caterpillars,
Juncus effusus	Soft Rush	a							■	■	■			AMF	Birds
Onoclea sensibilis	Sensitive Fern	m						■	■	■	■	■	■		Birds
Verbena hastata	Blue Vervain							■	■	■				AMF	Native Bees
Symphyotrichum novae-angliae	NE Aster	m,e								■	■	■		AMF	Native bees, bumblebees, honey bees, Pearl Crescent

survey, restoration practitioners in Vermont are interested in mycorrhizae's potential to promote species longevity and woody vegetation growth. Fifty-seven percent of participants said that there was little funding for monitoring, maintenance, and implementing multi-synusium plant palettes, that is, one in which plants cover multiple forest structure layers. Sixty-seven percent of participants were curious about optimal conditions for mycorrhizae (Rubin unpublished).

Little is known about mycorrhizal bioamendment efficacy within this buckthorn-dominated riparian system. Our goal is to address this knowledge gap. We had several hypotheses. First, restoration with mycorrhizae increases harvestable P amounts (R10). This is important because riparian buffers can be sources of P mobilized from legacy P and thereby contribute to eutrophication in freshwater lakes (Dupas et al. 2015). Second, mycorrhizae can support a diverse pollinator plant community (Table 1). This is important because of the need to restore biodiversity and to facilitate autogenic ecosystem repair (C9). Specifically, we hypothesize soluble reactive P (SRP) in soil water and total P (TP) decrease, with corresponding increased plant P uptake, and improved restored plant community stability.

To achieve our goal we applied a diverse, 19-species (Table S1) ectomycorrhizae (ECM)/endomycorrhizae (AMF) commercial mix (Mycorrhizal Applications, Jericho, VT, U.S.A.) that are likely symbionts of the 32 plants in our palette (Table 1). Although plants can provide P mitigation and biodiversity enhancement (R10), selected vegetation must also provide cultural services to the Abenaki (R11).

Design Phase

Reference Condition: Know the History and Place (C1)

Restoration efforts integrate knowledge of prior land use, mostly post-Columbian uses, and the site's physical setting (i.e. soils). However, the natural and cultural history prior to Columbus is also important to define a reference ecosystem (C1) while honoring Original Peoples' legacy and culture (R11). In our study, the Original Peoples are the Abenaki, part of the Wabanaki Confederation (Box 2).

Physical Setting of Study Site

The restoration site (Figs. 1 & S1) is on poorly drained, glaciolacustrine silty clay Covington soil. These soils are highly erodible, but also farmland of state-wide importance when "improved" by drainage (USDA NRCS 2006). Two drainage systems occur at the site: a cryptic old tile network and a series of drainage channels. The SRP in the drainage way adjacent to our site (Figure S1) exceed Lake Champlain's water quality standard 18-fold (VT ANR & DEC 2017). A 50-cubic-yard compost facility upslope and legacy P are the likely sources delivering P to the channel. Soil in the riparian area has high legacy P with a mean of 872.2 mg P/kg TP. The soil's Mehlich P saturation ratio (0.0137) was lower than the threshold of 0.078 (Pellerin et al. 2006), suggesting low leaching potential.

This landscape is fragmented, characterized by low habitat connectivity and high habitat modification, with only 10% remaining undisturbed (Perrow & Davy 2002). While a dense stand of *Rhamnus cathartica* (buckthorn) dominates riparian vegetation, native *Acer spp*. (maple) and *Fraxinus spp*. (ash) trees are interspersed.

The Plant Palette, Mycorrhizae, and Restoration Installation

Mycorrhizal fungi, keystone plant mutualists, assist in P remediation and disturbed ecosystem recovery by establishing nutrient exchange networks crucial to ecosystem function, succession, and resilience (Asmelash et al. 2016; Martínez-García et al. 2017). Myco-phytoremediation is a relatively novel strategy with tremendous potential in P remediation and reconciliation ecology (Suddeth Grimm et al. 2016) which acknowledges that it may not be feasible to restore ecosystems to their original state, but ecosystem function can be reestablished (Michener 2004).

We designed the plant palette to meet the following criteria: pollinator habitat diversity, water quality function (R10), native plants' synusial grouping (C2, C3), likelihood of mycorrhizae-plant mutualism, and flowering throughout the growing season. This palette was informed by inspection of intact, diverse riparian forests during walks and paddles. Members of these vegetation communities were likely present during the Wabanaki Renaissance (Box 2).

Pollinator habitat was crucial criterion for the plant palette because of the extent of contemporary insect decline (Raven & Wagner 2021). Moreover, Wilson (1987) warns that invertebrates are foundational to the trophic web, which if in peril, can lead to ecological collapse. In a literature analysis, Dirzo et al. (2014) found 67% of monitored insect populations show 45% abundance decline.

The plant palette was designed with a diverse flora of 32 native species shown in Table 1 (C2), most of which were in *N'dakkina* (Abenaki word for their ancestral territory including Vermont) prior to European settlement (Box 2; C1). The plants are diverse in growth habit (C3) with 17 herbaceous, 5 shrub, and 10 tree species. The selection includes wetland plants that grow in the study site's poorly drained soils (C4). The palette ensured flowering from February to November, including fast growing, harvestable woody species, known for high nutrient uptake potential (R10 and R11).

Experimental Treatments

In 2020, we installed three research plots in a pseudo replication design along the drainage way. One plot remained unaltered by buckthorn (OIV). The other two were restored with vegetation without (RV), and with mycorrhizae (RVM). Prior to planting, bare root trees, shrubs, and plants were potted in low, 0.16% P pasteurized compost (Vermont Compost, Montpelier, VT, U.S.A.) and left to equilibrate 6 weeks before outplanting in the field. The plants and wetland herbaceous seeds aimed for RVM were inoculated with mycorrhizae. To prepare the two restoration plots, buckthorn was cut in winter 2020 at belt height, and all stumps more than 4 ft from the drainage way were removed by hand tools. All native vegetation on site were left undisturbed. The dry summer after installation required weekly irrigation. In Year 2, the plots were irrigated only twice due to ample rainfall. Continued hand removal of invasive species was required. Additionally, scything wild grasses was essential to release higher synusium plants from light and space limitations in early spring 2021.

To restore diverse pollinator habitat ensuring enough food, forage, and nesting sites (Tallamy 2004) in areas monotypically overgrown with non-native species such as buckthorn (Kurylo et al. 2015), successful nonchemical removal is essential. Forty-two percent of ecological restoration projects rely on herbicides (Weidlich et al. 2020). To avoid water contamination, threatening pollinators, and other organisms, we removed regrowth from cut stumps left near the drainage way three times in two seasons. This accessible, affordable, and efficient method causes a 90% death rate (Fig. S2) (M. Bald 2020, personal correspondence).

Results and Lessons Learned

Early Findings: Mycorrhizae (R10)

We understood that indigenous mycorrhizae in the riparian area were removed when original vegetation was replaced with

Figure 1. Progression of restoration in RV. RV plot before buckthorn and associated invasives removal (top left); same plot soon after planting in May 2020 (top right) showing landscape fabric and a few mycorrhizal species that persisted after the restoration process. Same restored plot in September 2020 (bottom left) and August 2021 (bottom right).

colonial agriculture crops. This research assumed that mycorrhizal colonization of soils would be, by design, different among the treatments. We measured hyphal density using the line-intersect method (Tennant 1975). Though both AMF and ECM grow in this landscape, we focus only on AMF with which the majority of the palette associate (Table 1).

In our plots mycorrhizal hyphal density followed this order: RVM > OIV > RV. Buckthorn associates with specific AMF. It also exudes phytotoxin emodin, which reduces germination and competing mycorrhizal associations (Pinzone et al. 2018). Therefore, plants in RV had few mycorrhizae with which to associate. Adding mycorrhizae to RVM resulted in greater hyphal density suggesting buckthorn's phytotoxins were not affecting restoration plant symbionts.

This project's scope prevented us from identifying mycorrhizae to species. Molecular identification would help to understand specific mycorrhizal restoration plant associations and track mycorrhizal succession and diversity. This is particularly important with respect to C5, the system functions according to developmental phase, considering mycorrhizae's role in the aboveground community and corresponding ecosystem functions.

Early Findings on P Remediation

Riparian buffers are best management practices (BMPs) for reducing nutrient loads to water bodies. P is retained in the buffer by particulates settling from overland flow. P uptake by bacteria, fungi, and plants is released after senescence and hence is considered only temporary P storage (Hoffmann et al. 2009). Riparian areas can become P sources when P is remobilized from any of these sinks: decomposition, sediment P remobilization in large storm events where vegetation cover is low, and desorption from Fe and Al oxides (Dodd & Sharpley 2016). Research also indicates that over time perennial vegetation capacity to retain P declines (Dosskey et al. 2010). Phosphorus in plant tissue, soil, and water are indicators of remediation effectiveness. We expected P uptake to be greatest in RVM (Jones et al. 1998) and thus result in less soil P and soil water SRP. Harvest could then remove P permanently from the buffer (Kelly et al. 2007).

We measured soil water SRP in lysimeters samples (Irrometer, Riverside, CA, U.S.A.), obtained during six storms (>12.5 mm/24 hours) during 2020 and 13 such storms in 2021. Six lysimeters were installed in each plot at 20-cm depth, 30 cm from willows or similar sized buckthorn. We expected SRP in RVM to be the lowest of the treatments. Yet there were no significant differences in average lysimeter SRP treatments in each year and within years (Fig. 2A & 2B). The significant differences in SRP between the 2 years was likely due to better growing conditions resulting from additional 100 mm more precipitation volume in 2021. Seasonal variation was as expected; high soil water SRP in spring due to first flush and low in summer when plants were active.

Interestingly, SRP extracted with water (WEP-SRP) from randomly located soil samples during the second year (Fig. 2C), showed more pronounced differences among treatments and on average were higher than lysimeter SRP data (Fig. 2B). There was a significant inverse linear relationship between hyphal density and WEP-SRP (Fig. 2D) ($r^2 = 0.997$, $p = 0.038$). This was not the case for lysimeter SRP data. OIV had significantly greater TP than RVM ($p < 0.001$), RV had significantly greater TP than RVM ($p < 0.001$), and OIV had significantly greater TP than RV ($p = 0.0032$). It is unclear whether this was due to treatment effect or spatial variability typical of soils. Pseudo replication due to limited funding makes the study vulnerable to spatial variability's confounding effects. Additional sources of error might have been mycorrhizal host selectivity beyond plant family AMF/ECM correspondence (Table S1). We applied a commercial inoculum mix. Ideally mycorrhizae are cultured from a neighboring reference system to optimize plant inoculation (Malt & Treseder 2015).

To understand more about host specificity effects, research should employ molecular methods. A comparison between mycorrhizae in our plots and local reference systems could provide valuable information about ecosystem functioning (C6). Degraded riparian zones have abiotic conditions which may lack P-solubilizing bacteria that are part of the mycorrhizosphere biome.

Many restoration projects are underfunded. Thus it is important to be selective about when and how to sample. Temporal and spatial variations need to be considered along with the form of P monitored. Sites should be monitored to capture interannual weather variations, switches from sink to source, disturbance during restoration, known lag time of field P mitigation (Meals et al. 2010; Sharpley et al. 2013), and mycorrhizal succession. Since decades of legacy P cannot be remediated in 2 years we intend to monitor this pilot project long term.

Plant Biomass Concentrations of P, Coppicing, and Harvest Value (R10 and R11)

Coppicing fast growing P accumulating woody vegetation reduces P losses from riparian buffers. This can also yield materials for Abenaki cultural practices (R11) and stimulate regrowth and more P uptake. Following coppicing recommendations in April, that is, taking biomass in spring when plants are dormant, removed 800 mg P/kg of biomass. Coppicing recommendations were given to reduce stress and increase regrowth. This timing does not optimize P removal because P is translocated into roots after senescence. An accompanying mesocosm experiment in late winter showed more P present in willow roots than stems ($p = 0.034$). When coppicing in early September 2021, a few weeks before leaf fall and senescence; however, P concentrations in willow biomass harvested was three times greater than in the April ($p < 0.001$). Hence a clear recommendation for improving riparian buffer function is to harvest in late summer.

While concentration is one variable of potentially harvestable P biomass, production is another. We noticed vegetation in both restored plots were vigorous with a dense ground cover. However, plants were larger in RV. On inspection, RVM was shaded longer by a southeast stand of ash trees, decreasing photosynthesis thus decreasing production and had lower TP than RV. Ostensibly abiotic factors can influence myco-phytoremediation efficacy.

Other plants can also be harvested. For example, the naturalized *Sambucus nigra* (elderberries) harvested from the restored plots were rich in P (3,598 mg/kg of dry mass). Research determining P concentrations in harvestable restoration plant species is needed. While willows and elderberry offer economic return (Wilson 2016) to farmers, restoration sites can also become harvest ways for interested Abenaki. This demonstrates how green infrastructure can transform landscapes to benefit Original People. This is part of the rematriation movement in Vermont where farms, schools, and homesteads grow Abenaki crop seed via NOFA Vermont (2021) and state parks install signage with original place names (Kelley 2021).

Trajectory and Stability of Pollinator Habitat (C8 and C9)

Over 2 years there were 1.7 times the number of species in the restored plots (53) compared to what was planted (32). The additional species likely arose from a seedbank activated during restoration, immigration from neighboring ecosystems, animal seed dispersal, and residual vegetation left in the plots. Plant species in the restored plots remained steady (Fig. 2F) during the study. However, 2 years is too short to assess whether the restored system is resilient and self- sustaining (C8 and C9).

Involvement of the Abenaki (R10)

Abenaki hosted summer fishing and gathering camps for thousands of years at Lake Pitawbagw (Lake Champlain) including at Shelburne Farms. Alnobaiwi, a 501C3, dedicated to preserving Abenaki heritage, conducted a rematriation ceremony at the site in the first summer of the project. We aim not only to restore ecological functions to a landscape damaged from conventional agriculture but also to begin to reconcile social injustices inflicted after colonists' arrival (Box 3).

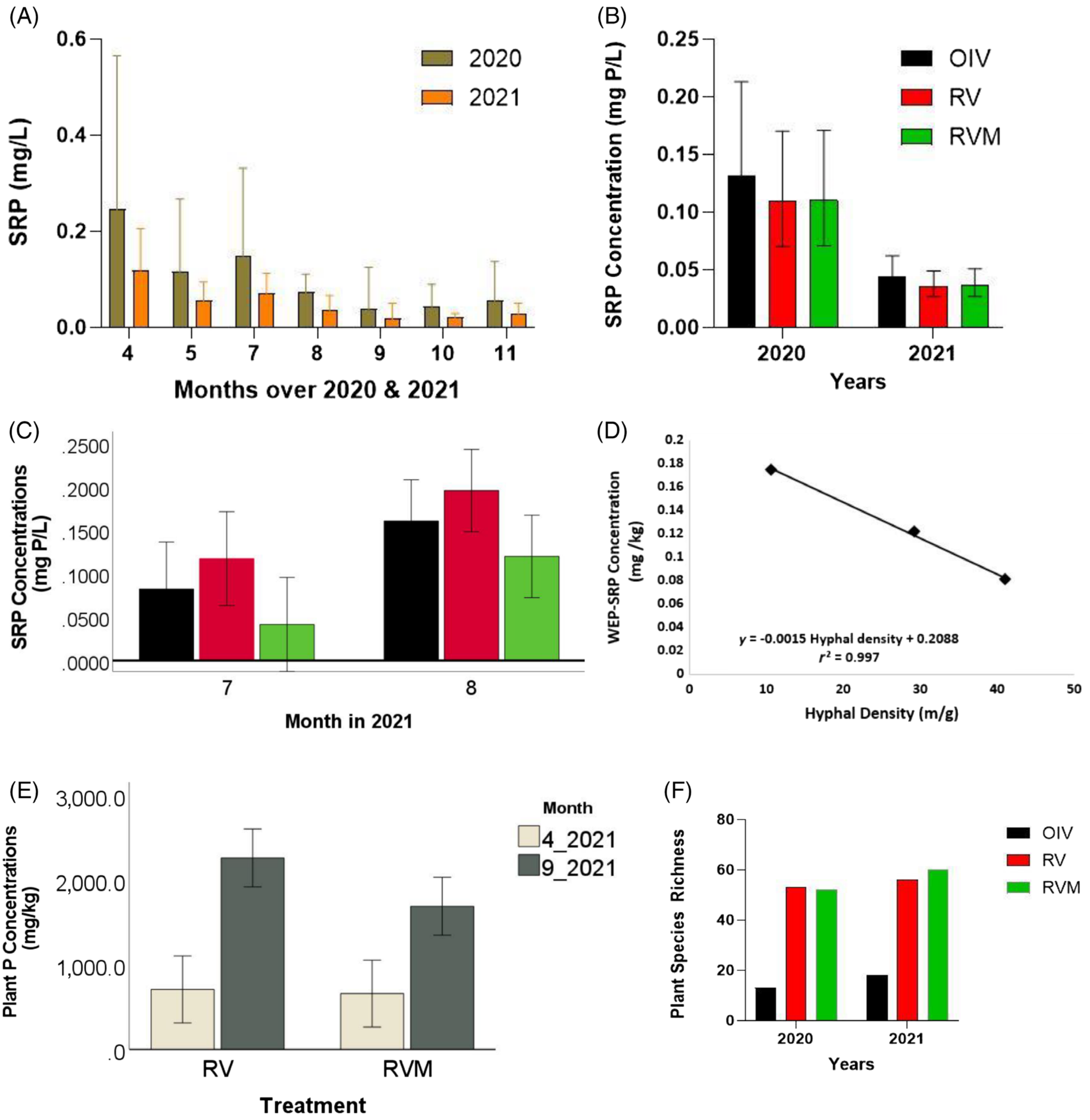

Figure 2. (A) Lysimeter soil water SRP from storms across years broken up into months, pooled across treatments; (B) mean lysimeter soil water SRP for 2020 and 2021 for the three treatments; (C) comparison of water extractable WEP-SRP from soil samples; (D) linear regression WEP-SRP and mycorrhizal hyphal density; (E) comparison of harvested willow biomass P between RV and RVM plots for spring and late summer coppicing. (F) cumulative annual plant species richness among treatments for 2020 and 2021. There are no significant differences in panels A–C. Error bars on all graphs represent ±2 SE. Where there are no legends, the same colors apply as in the legend of panel B.

Our project researched new ways to meet water quality standards set by legislatures where Original People do not yet have much representation and the European honey bee is the best known pollinator. We did not involve the Abenaki early enough. Had we done this, the palette would have been designed more deliberately with respect to plants' relevance to Abenaki culture. As it happened 88% of plants we chose have traditional value to Abenaki (C. McGranaghan et al., Abenaki, personal communication, 2022) while still providing ecosystem services of P uptake and pollinator habitat. Our current collaboration with local Abenaki leaders is a promising move toward continued reparation efforts (V. L. Sheehan & Chief D. Stevens, personal communication, 2022) in facilitating access for harvesting medicine and craft supplies.

Box 3 Learning to decolonize research.

It does not yet come naturally for many scientists to work with Original Peoples in restored systems. Few scientists have endeavored to learn from the Abenaki, the Original People on this land, when addressing the effects of industrial agriculture on water quality and pollinator health. Although we did not initially involve Abenaki in this study to craft the research questions, our process has evolved. The typical colonial approach was taken initially, driven by technical details involved in the restoration research and design. However we now recognize that bypassing Abenaki land expertise limited the scope of our potential approaches to ecological repair.

Trisos et al. (2021) suggest that decolonizing research does not mean to overthrow modern ecological research practices but rather to invite participation of local peoples outside of academia. While Trisos's context concerns Africa, one can extend this to give voice and invite participation of Original Peoples wherever one is. Participatory Action Research (PAR) is a model applied in agroecology in which researchers partner with the people affected by that research (Mendez et al. 2017) in ways in which they are designers in the project as equal stakeholders. The expertise of both researcher and farmer partners is harnessed to pursue a common goal. In this context the farmer and Original Peoples of that land offer research questions and influence the design. This welcomes other views and relationships with the land to uncover more appropriate approaches.

Conducting research from a decolonial, ecological ethic requires scientists to learn more about the colonial and precolonial histories of the land in which they are focused (Box 2). The reasons for this are numerous. For one, historical knowledge will highlight how the land has changed. Second it will facilitate understanding of the social injustices committed and reconciliation needed between the colonial descendants and Abenaki.

Small steps to rematriation (return of land to Original Peoples) can be taken in research projects like this. In our case study, a rematriation ceremony was conducted by Abenaki descendants of the original inhabitants of this land through revitalized communication networks. It is up to descendants of the settlers to dismantle the power imbalance of access wherever and whenever possible. In this light riparian plantings in our research plots can be accessible to the Abenaki. Eighty-eight percent of plants in our palette are recognized by the Abenaki as traditionally used for food, medicine, art, or ceremonial purposes. Sometimes however these exchanges require adaptation to the changing climate of today. For example, coppicing plants like willow for P removal can supply biomass for traditional crafts. While they can be used for furniture, willow waddles, and live stakes, our main aim is to offer them to Abenaki for basket making. That said, willow was not used traditionally by the Abenaki. Their sacred main basket species, *Fraxinus niger* (black ash) is currently threatened by the Emerald Ash Borer (Freedman & Neuzil 2017; Nulhegan Abenaki Tribe 2021). Abenaki basket makers are inventorying the trees, saving seeds, and teaching about the cultural significance and skills in black ash basket making. Willow may be used as an alternative basket making material that can substitute for black ash. Provisioning craft materials, medicine, or food from restoration installations is a gesture toward rematriation. This is a small step in what over time can become a successful reconciliation project which effectively decenters settler-descendent values and instead honors indigenous lifeways. Through, acknowledging historical disruption and all that has ensued in both social and ecological landscapes, repair can be facilitated (Murdock 2018).

Conclusions and Recommendations

Eighty years of conventional agricultural practices cannot be remediated within 2 years. However, mycorrhizae appear to reduce SRP, as evidenced by the inverse linear relationship between mycorrhizal hyphal density and soil SRP concentrations. In the restoration plots, 1.7 times more species than were planted grew. Restored plots had four times more pollinator species than the control buckthorn plots. Eighty-eight percent of plants in the palette are culturally relevant to the Abenaki.

We recommend gathering precolonial site history and local Original Peoples' knowledge to inform the design process. Also consider applying observations of local, site-specific native riparian buffer polycultures to plant palette design with pollinator host needs and Original Peoples' guidance, access, and use in mind. Inoculate plantings with native soil from nearest undegraded wild areas. Apply manual labor rather than chemicals to remove nonnative species, following the three times cut in two seasons approach (Bald, personal communication, 2021). To improve water quality protection, harvest woody species through cyclically coppicing in late summer for P removal (5–45 range kg P/ha), depending on species and planting density (Schroeder 2013). Consider facilitating harvest way access to Original Peoples in support of their rematriation. Key areas for further research are molecular methods to compare the mycorrhizal community used for restoration and the local community. Research is needed to determine P removal potential of perennial species, and quantitative data on pollinator visits to the restored habitat.

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Supporting Information

The following information may be found in the online version of this article:

Figure S1. Site map of Shelburne Farms.
Figure S2. Panel A: RV Treatment plot in summer 2021; Panel B: RV Treatment plot in fall 2021.
Table S1. ECM and AMF fungi species in the Mycorrhizal Applications Mix.
Supplement S1. References from Table 1 and for all of the boxes.

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