Rapid Ecological Restoration for Aggregate Sites: Replication of Mature Hardwood Forests

*CONDENSED VERSION**

Interim Report

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Submitted for the Board of Directors,

The Ontario Aggregate Resources Corporation (TOARC)

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1.0 INTRODUCTION

TOARC, Walker Industries Inc., and other collaborators in Ontario's aggregates industry have been in a unique position to support innovative research aimed at discovering practical techniques environmental managers may use to produce high-quality habitat and support biodiversity consistent with late-successional hardwood forests. We created the Rapid Ecological Restoration for Aggregate Sites (RERAS) study to explore hypotheses that can be experimentally tested and applied to industrial practices. This 4-year study aims at closing the knowledge gaps that make hardwood forest restoration in southern Ontario so slow and uncertain to succeed.

The RERAS project seeks to understand the limits and opportunities that face land managers trying to achieve some of the ecological functions and values associated with mature, well-developed ecosystems such as hardwood forests, but within environments undergoing rehabilitation, afforestation, or other management aimed at offsetting or recovering from environmental degradation. More specifically, we seek to learn whether a "transplant surgery" paradigm for ecosystems may have value in industrial practices. We hypothesized that, in general, valued properties of ecosystems that take a long time to mature may be encouraged to develop within recently disturbed environments provided that managers treat the desired outcome of succession like a vital organ, not a machine to be easily built or repaired.

Principles of successful organ transplantation in animals include:

- Knowledge-based matching of recipients to donors
- Careful respect for the physiological limits of systems being operated upon
- Strategic after-care based on reducing stress faced by transplants from hostile environmental factors (i.e. differences between conditions at hand versus those previously adapted to)

1.1 THE HYPOTHESIS

Our hypothesis predicts that equivalents for each of these principles hold for achieving success in the direct translocation of a bulk "ecosystem" – an integrated whole rather than a collection of parts – from late-successional environments to earlier-stage ones. When successful – due to good site matching, strategic timing and placement of operations, and appropriate after-care by editing fine-scale habitat conditions ("microhabitat") to more closely the donor environment – ecosystem translocation may offer unprecedented hope for effectively accelerating succession by bypassing intermediate stages. This may produce valued co-benefits of late-stage ecosystems including habitat for distinctive biodiversity. Our experimental work tests many specific predictions of this general hypothesis, within a system of heritage hardwood forest and surrounding former-forest, previously managed for agriculture and aggregates development but now targeted for rehabilitation or afforestation initiatives.

1.2 THE VALUE IN "BULK" TRANSLOCATION OF LATE-STAGE ECOSYSTEMS

Industrial processes for extracting natural resources must sometimes strip and reuse ecosystem products with high ecological value arising from centuries of spontaneous succession. This value often goes unrealized, such as stockpiling practices that unintentionally terminate living elements in soils. Where true, changing management strategies to utilize under-valued materials through direct translocation to appropriate recipient environments may be conducive to efficient resource recycling and conservation. Potential benefits for managers adopting ecosystem translocation projects hinge on how well the inherent biological structures (e.g. microbial networks in soil; plant composition) can resist and recover from stressors imposed by:

i) Excavation and translocation itself;
ii) The new physical environment; and
iii) The new suite of species interacting with the translocated organisms.

The intent of our experimental design was to narrow down the field of possibilities regarding the outcome of relocating bulk quantities (**see Figure 1**) of mature forest topsoil, and to determine how biodiversity present in this "living mulch" (**hereafter "LM"**) responds to different qualities of:

i) the potential recipient environments, such as management history and relative stage of ecosystem development; and
ii) microhabitat modifications, such as creation of woody debris (**hereafter "WD"**) or shading structures (**hereafter "SS"**).

***Figure 1**: Example of operators extracting Living Mulch (LM) from a donor site then redistributing it at a recipient site*

This report reflects years one and two, with full analysis set to occur over the next several months, meaning the conclusions and applications suggested here are tentative.

1.3 SUCCESSION THEORY

The heart of succession theory suggests organisms are constantly dispersing, causing open ground or recently disturbed soils to eventually become colonized by pioneer species (including microbes, plants and animals), many of which share similar functional traits related to survival and reproduction ("life-history") including stress tolerance, rapid growth and reproduction, and long-distance dispersal. Pioneer organisms inevitably change the environments they grow in, however, in ways that reduce the stressors experienced by subsequent colonists, including through contributing to soil formation and ground cover by a variety of organic structures (living and dead). The resultant patchiness of resources and stressors (physical, chemical, and biotic) in the environment tends to favour establishment and growth of different species with different traits compared to the pioneer wave, including more productive growth, increased competitiveness and, eventually, woody growth and higher tolerance of shade when young.

Not all environments produce soils capable of supporting tall trees, or remain disturbance-free long enough for such growth to occur, but in landscapes where such broader factors are suitable, woody stands of trees with pioneer-like traits tend to eventually establish at high density (a successional stage, or sere, referred to as "stand initiation"). The shading and other environments alterations resulting from such stands growing quickly creates microhabitats unlike any that came before, and most residing vegetation cannot survive (reaching a peak at a stage called "stem exclusion", when there is minimal light, and biodiversity, on the floor of the forest).

Pioneer trees are naturally short-lived, for trees, and the mortality of this initial cohort is sped along by storms, forest usage and other factors, which help transition the developing forest into a third stage, "understorey re-initiation." During this sere, growing gaps in the canopy alongside heterogeneous light and litter conditions on the ground support emergence of new, diverse communities of plants and many other organisms. These include forest specialist species, adapted to either tolerate high shade or capitalize on spatial patches or time windows featuring mixed or moderate shade (e.g. spring ephemeral wildflowers, such as wild leek).

1.3.1 FIVE STAGES OF SUCCESSION

Within forested regions, disturbed landscapes such as farmland, pits and quarries usually regenerate forest cover over time. Although the processes involved in this are continuous and variable, ecologists typically recognize a pattern of transitional stages that follow each other in a predictable series (each stage is thus a "sere"), as discussed above. Here, we identified five distinct seres (S1-S5) relevant to the development of Niagara Escarpment forests. S1 is **primary succession**, or ecosystem development from a position of no vegetation and no soil. S2 is **stand initiation**, when ground conditions have evolved to support a moderate to high density of woody species but these have yet to produce a canopy layer. S3 is **stem exclusion**, when woody species grow tall and exclude most other resident vegetation through impacts on light and litter-layer conditions. S4 is **understorey re-initiation,** when gaps in the canopy form due to weather disturbances, natural tree death, or management, and a diversity of new colonists with adaptations to mixed shade and woody debris microhabitats begins to establish. S5 is **old-growth** or "climax community", when shade levels continue to shift and emerging forest floor microhabitats – including complex woody debris accumulations, rich litter layers, and pit-mound landforms – encourage persistence of a diverse assemblage of well-adapted species, i.e. the characteristic biotic communities of Ontario's primary hardwood forests at maturity. The diagram below illustrates natural succession occurring over hundreds of years, with superimposed labels corresponding to the stage studied here.

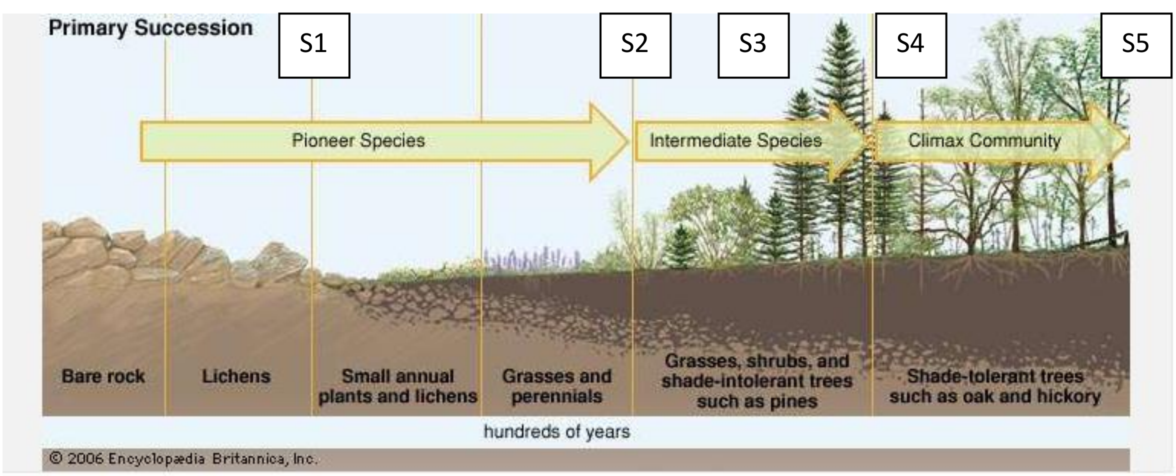

Figure 2: *A diagram illustrating the natural stages of primary succession*

1.3.2 BENEFITS TO LAND MANGERS

If the ecosystem transplantation hypothesis is valid, applying it within industry will help managers of recently disturbed environments produce substantial biodiversity, functions and other valued properties of long-established ecosystems (i.e. old growth seres) over a shorter timeframe than required for natural regeneration. Ecosystems rich in late-successional features are potential donors of such recently disturbed recipient sites, especially in areas planned for land-use changes.

For example, some areas licensed for aggregates development support very mature sugar maple stands with rich native understorey communities and soil resources that may provide an exceptional "ecosystem donation" (prior to scheduled forest clearance and extraction of underlying aggregates, and as an alternative to long stockpiling of the material for later use as general "fill"). Potential recipient landscapes exist in surrounding areas that were originally forest but then farmed or mined, and are presently undergoing management to meet site rehabilitation or afforestation goals.

2.0 EXPERIMENTAL DESIGN AND METHODS OVERVIEW

The research timeline, funded over four (4) years, required the first year to properly install the experiment; a second year for relevant ecological processes to stabilize and produce potentially reliable patterns; a third year, to intensively collect data from response variables describing states of the experimental system; and a fourth year, to collect follow-up data and interpret all results. By evaluating which specific hypotheses best predicted the observed responses, the analysis produced in year 4 will generate both theoretical conclusions and best-practice recommendations.

We designed a field experiment to test three (3) fundamental hypotheses:

i) Direct translocation of bulk LM from an old-growth donor ecosystem to more recently disturbed environments promotes the development of ecological functions and structures typical of the donor forest (e.g. species composition of understorey plants)

ii) The degree to which LM application produces a similar ecosystem to the donor forest depends on the extent to which recipient environments are engineered to provide ground-layer habitat conditions that are broadly similar to the donor environment (e.g. artificial shade structures)

iii) The degree to which LM application produces a similar ecosystem to the donor forest depends on whether succession at recipient locations has already produced habitat conditions similar to the donor forest (e.g. a late-sere recipient location such as a mature tree plantation may respond more positively than a recent extraction site)

2.1 DONOR FOREST AND RECIPIENT SITES

Experimental manipulations began in October 2017 at field locations near Duntroon, Ontario, with monitoring and analysis required through 2019-2020. Areas licensed for extraction in Walker Aggregates' Duntroon quarry provided us with an exemplary sugar maple tract in this now-uncommon "old growth" class, to serve as the LM donor forest (D+) in our experiment. We expected that recipient environments at earlier stages of development would likely differ in their responsiveness to LM translocation and microhabitat modifications, depending upon which specific sere was treated. We therefore sought to include in our experiment recipient environments spanning a range of earlier seres (referred to as S1-S5).

2.2 LOCATIONS OF RECIPIENT SERES

We selected four (4) locations within six (6) km of **D+,** each of which represented a different stage ("sere") of forest development. **S1** is a former gravel pit undergoing spontaneous primary succession for the past 25 years. **S2** is a former farm field afforested with diverse native hardwoods to help offset biodiversity impacts of a new quarry, planted in 2015-2016. **S3** is a former field afforested with conifers ca. 1985. **S4** has a similar history to S3 but with planting date ca. 1940. **S5** is a parcel of old growth forest adjacent to D+ but outside the limits of the new extraction. S5 will help determine the extent to which outcomes of LM-translocation are attributable to shock from excavation or transport rather than stress imposed by new environmental conditions. **Table 1, Figure 3,** and **Figure 4** (below) present additional information about D+ and seres S1-S5**.**

Table 1: *Niagara Escarpment field locations near Duntroon, Ontario, utilized in the living mulch (LM) and microhabitat experiment*

Table 1: Niagara Escarpment field locations near Duntroon, Ontario, utilized in the living mulch (LM) and microhabitat translocation experiment

Code	Location name	Location type	Site description	Area (ha)	UTM (Zone 17T)
D+	LM Donor forest	Primary *Acer saccharum* stand	Primary upland (c. 450 m a.s.l.) *Acer saccharum* forest, with sections requiring clearing prior to licensed aggregate extraction; two such patches (N, S) were partially excavated to extract bulk LM (i.e. forest floor litter and topsoil layers) for immediate relocation to recipient seres in Oct. 2017	6.0	559709.00 m E 4915535.00 m N
S1	LM Recipient Sere 1: Primary succession	Disused gravel pit	Site of limestone sand and gravel extraction (c. 1940-1990) located < 7 km NE of D+; undergoing spontaneous succession, having never been rehabilitated	1.5	565109.00 m E 4919943.00 m N
S2	LM Recipient Sere 2: Afforestation at stand-initiation	Old field afforested in 2015	Native deciduous and coniferous trees planted on former farmland (< 0.5 km N of D+) to help offset clearing of D+; field underwent spontaneous succession for 5 years prior to planting with 20 tree species, which was followed by 2 years of irrigation and weed-control	6.0	559640.00 m E 4915723.00 m N
S3	LM Recipient Sere 3: Afforestation at stem-exclusion	Old field afforested c. 1985	*Pinus strobus* + *Picea glauca* plantation, established along edges and patches of the licensed extraction site (< 1 km NE of D+) that will not be extracted, and which required soil stabilization; not managed for wood production	1.5	559965.00 m E 4916232.00 m N
S4	LM Recipient Sere 4: Afforestation at understorey reinitiation	Old field afforested c. 1940	*Pinus resinosa* + *Picea glauca* plantation, established on former farmland < 4 km E of D+, to help stabilize soil; not managed for wood production	1.3	563981.00 m E 4916209.00 m N
S5	LM Recipient Sere 5: Old-growth forest	Primary *Acer saccharum* stand	Mature forest that is contiguous with and identical to D+, but outside the planned extraction zone (<0.5 km W of D+)	4.5	559439.37 m E 4915438.26 m N

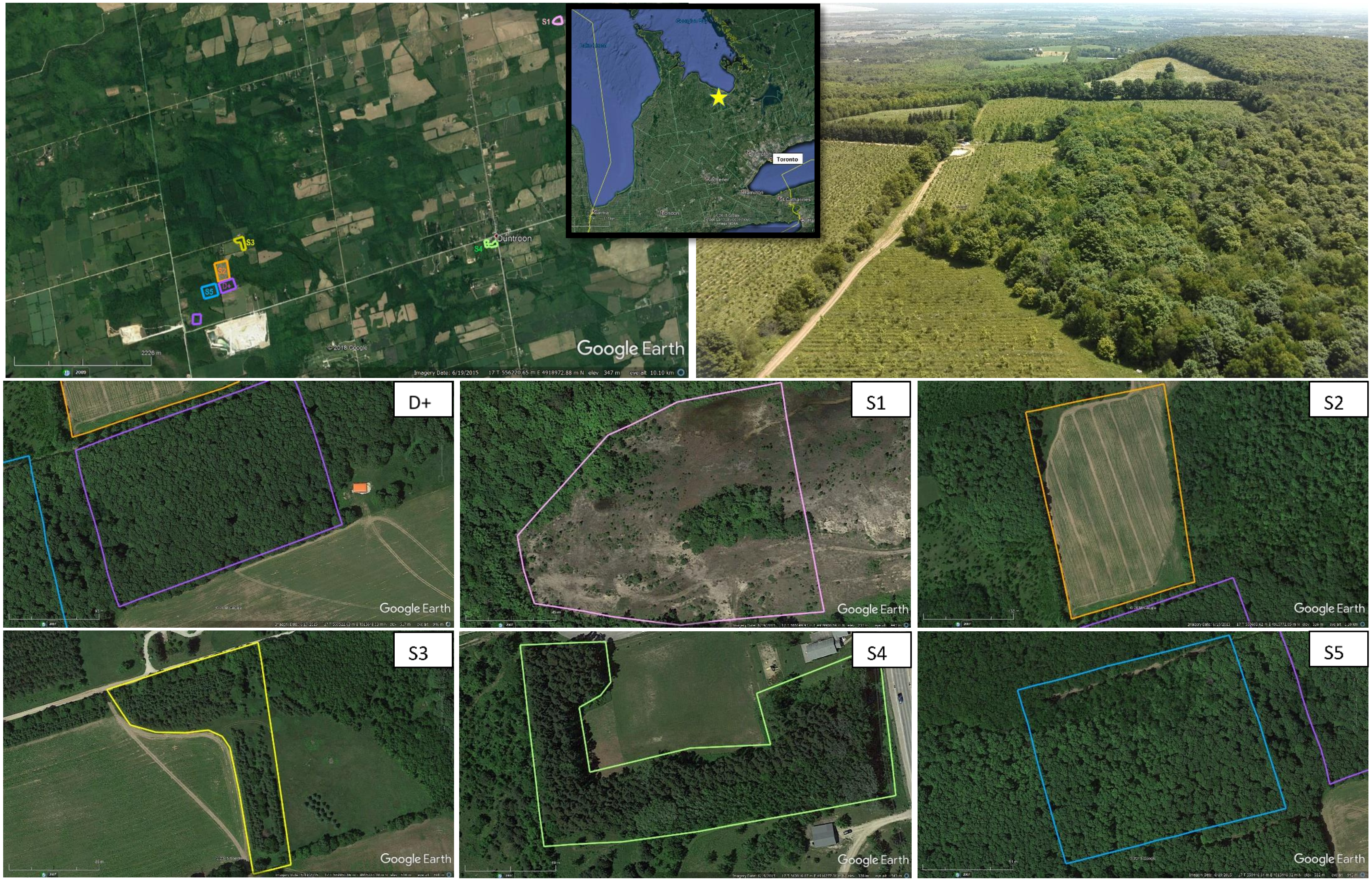

***Figure 3**: Overhead satellite imagery of the donor forest (D+) and recipient seres (S1-S5) incorporated into the living mulch and microhabitat translocation experiment (Duntroon, ON, Canada). Produced using Google Maps.*

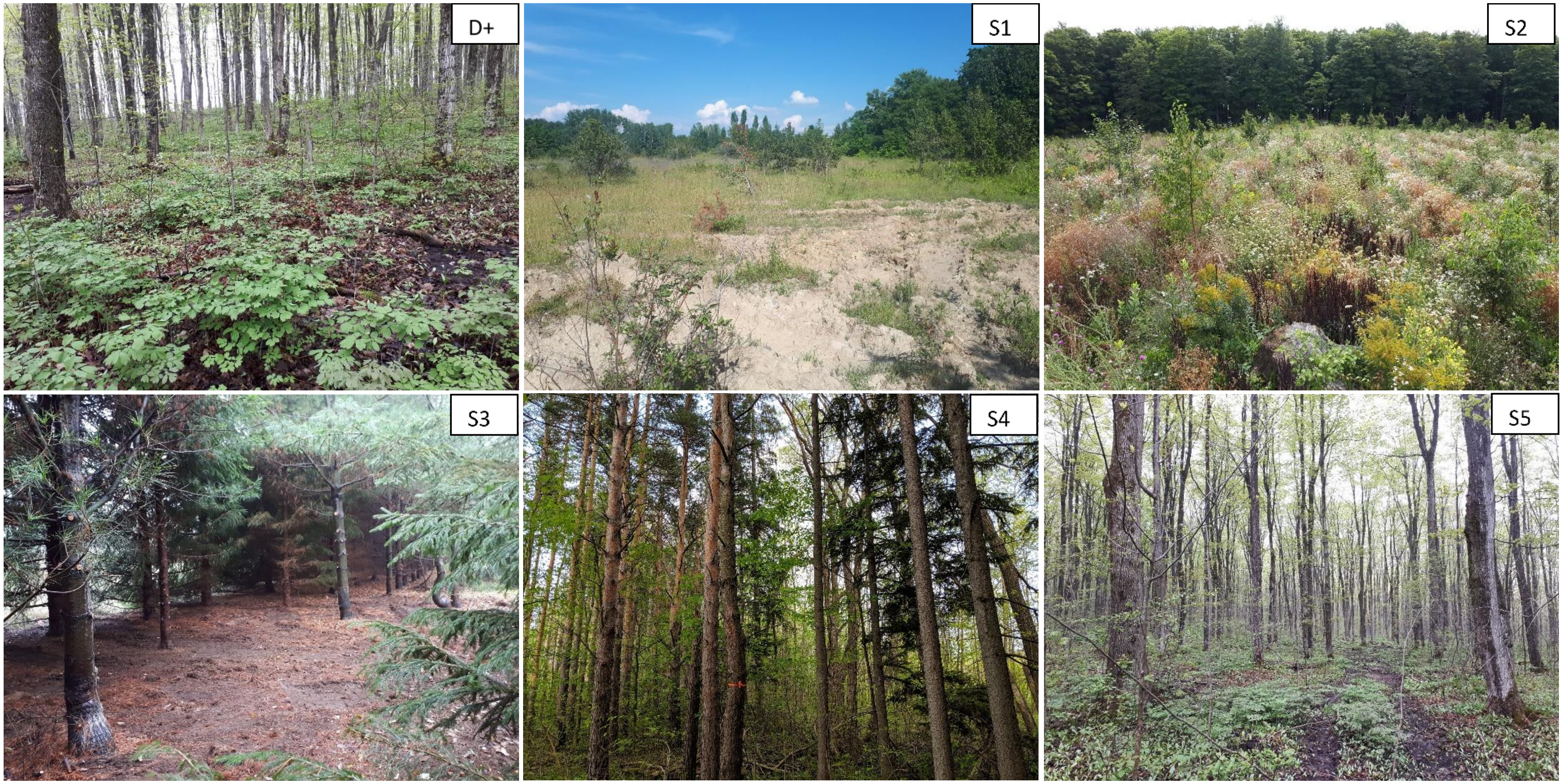

Figure 4: *Donor (D+) and recipient seres (S1-S5) incorporated in the living mulch and microhabitat translocation experiment (Duntroon, ON Canada)*

2.2.1 RECIPIENT SITES IN COMPARISON TO SUCCESSIONAL STAGES

Table 2 below compares each of the selected sere recipient locations to the successional stages of an old growth forest:

Table 2: *Similarities of the S1-S5 locations to natural stages of succession*

Code	Location Type	Successional Stage	Description	Area (ha)
S1	Disused gravel pit	Stage 1 - Primary succession	Ecosystem development from a position of no vegetation and no soil	1.5
S2	Old field afforested in 2015	Stage 2 - Stand initiation	Ground conditions have evolved to support a moderate to high density of woody species	6
S3	Old field afforested in c. 1985	Stage 3 - Stem exclusion	Woody species grow tall and exclude most other resident vegetation through impacts on light and litter-layer conditions	1.5
S4	Old field afforested c. 1940	Stage 4 - Understorey re-initiation	Gaps in the canopy form due to weather disturbance, natural tree death, or management, and a diversity of new colonists with adaptations to mixed shade and woody debris microhabitats begins to establish	1.3
S5	Primary sugar maple (*Acer saccharum*) stand	Stage 5 - Old growth/"Climax Community"	Litter, woody debris and shade levels continue to shift and the best-adapted species produce the characteristic biotic communities of Ontario's primary hardwood forests at maturity	4.5

2.3 APPLYING LIVING MULCH

We began installation of the experiment at the end of October 2017 after most vegetation had entered states of dormancy for winter, but before winter weather could interfere with operations. The work consisted of progressively extracting LM from selected zones within the donor site using light excavation equipment and transporting truckloads of the material to recipient blocks within areas that included small natural clearings at S1-S5 on the same day as extraction **(see Figure 5).**

The excavated LM included forest floor organic litter layers - leaf litter, fine woody debris, some larger coarse woody debris - plus the underlying 30 cm of topsoil (including inherent vegetation, propagules, micro-fauna and microbes). We recovered 1-3 m tall saplings with intact root balls during excavation and hand-planted them in the freshly deposited LM at recipient blocks (ca. 5-7 saplings per block).

Figure 5: *Living mulch translocation and woody debris in action (featuring Luke Elwood of Clearview Nursery)!*

2.4 RECIPIENT BLOCKS

Each recipient block consisted of a **12.5 m x 10 m** area which was cleared of major obstructions (including mowing and herbicide application for the dense herbaceous cover at S2) and then filled with a **30 cm** deep layer of LM (including working around existing trees).

Within S2, we established recipient blocks at five locations within a field previously planted with trees in 2015 and at five locations within a field planted in 2016 (only the 2015-planted blocks were included in the analyses shared here). At each of the other recipient environments (S1, S3-S5), we installed five replicates of the LM recipient block. In total, we installed **30** LM recipient blocks, each corresponding to **125 m^2** of ground area (**see Figure 6**)**.**

The experimental design subdivided each of the LM recipient blocks into **four equal quadrants (6.25 m x 5 m)** to test how outcomes of LM deposition depend on the creation of additional microhabitat structures consistent with the donor forest. In one quadrant per recipient block, we did not impose any additional changes after depositing the LM; we refer to this level of the translocation treatment as **+LM.**

Figure 6: *Example 12.5 m x 10 m quadrant areas. The photograph on the left shows an area that researchers left "not treated" (**NT**) when applying LM nearby (i.e. the photo on the right). Operators cleared the treated area of major obstructions then deposited and evenly distributed a 30 cm deep layer of LM, working around trees.*

2.5 CREATION OF FOREST MICROHABITATS ("AFTERCARE") AT RECIPIENT BLOCKS

Previous studies indicate many woodland species require particular habitat conditions that are unlikely to be available at some recipient locations, such as ample shade to protect forest wildflowers from potentially fatal high-intensity sunlight. Early seres, in particular may impose severe stress upon translocated forest organisms, necessitating means for providing refuge from predominant stressors. The design of the five translocation treatment levels (including **+LM** and **NT**, described above) tests the efficacy of different feasible methods for reducing environmental stress, by following-up LM translocation with installation of microhabitat features similar in function (if not aesthetics) to refuges in the donor forest. Required "aftercare" may include erecting shading agents able to produce a diversity of low-light environments, and/or increasing the abundance of coarse woody debris.

2.5.1 INSTALLATION OF WOODY DEBRIS

To the remaining three quadrants in each block, we introduced approximately **10-15 m^3 of additional woody debris (hereafter "WD")** which we had extracted from D+ in the spring following LM translocation – mainly as fallen trunks, limbs and old stumps spanning a range of sizes and states of decomposition. We distributed the WD sporadically throughout each area to create small piles and other structures resembling natural woody debris formations in D+ **(see Figure 7)**. In spontaneous old-growth forests, such formations provide valuable physical variability to several ground-layer environmental conditions crucial to plants and soil organisms, including light intensity, heat, humidity, and biochemical products of wood decomposition. The second quadrant areas in each recipient block received no additional changes after treatment with additional WD; we refer to this level as **+LM+WD**.

Figure 7: *Example quadrant plots that received woody debris (WD) applications*

2.5.2 INSTALLATION OF SHRUB CLUSTERS

Within the third quadrant of each LM block (after addition of the extra WD), we installed the first of two habitat modifications aimed explicitly at increasing ground-level shading: planting a **shrub cluster (hereafter "SC")**. This consisted of six dogwood saplings (*Swida alternifolia*), each **1 m tall**, planted in a circular formation approximately **1.5 m in diameter**. Alternate-leaved dogwood is a quick-growing native species, hardy to a range of light conditions, and a common component of local hardwood forests at developmental stages ranging from understorey re-initiation through old-growth. The woody growth can vary from tall shrubs (1-2 m) to small trees (4+ m), contributing to ground-shading and facilitating shade-dependent biodiversity **(see Figure 8)**. The after-care principle of the transplant hypothesis predicts that if shading and other SC impacts increase local environmental similarity to D+, more typical forest species from the LM will establish near installed SCs. This treatment level is named **+LM+WD+SC**.

Figure 8: *Example of quadrants that received a cluster of six saplings of the shrub/small tree* Swida alternifolia, *or alternate-leaved dogwood*

2.5.3 INSTALLATION OF SHADE SHELTERS

Given uncertainties regarding the amount of shade to be expected from the planted dogwoods as well as potential negative impacts on LM biodiversity (e.g. due to competition), we established alternative, non-living shading agents at the two seres with no existing tree canopy (S1 and S2). This second type of environmental modification required constructing artificial **shade shelters (SS)** within the remaining quadrant of each LM recipient that had received extra (treatment level: **+LM+WD+SS; see Figure 9**). Contractors built each **SS** using **four peeled cedar posts (12 cm diameter)**, installed to a **height of 1.8 m** in the corners of a **4 m x 4 m** area near the centre of each designated quadrant. They attached, across the tops of the posts, a removable tarp made of black horticultural shade-cloth manufactured to reduce incident solar radiation by 70%. Application of this treatment level requires extending the tarps in early summer but removing them in late autumn, each year or the study, in synchrony with canopy leaf-out and shedding in D+.

Figure 9: *Example of installed shade shelters (SS) both in terms of the quadrant of ground sampled beneath their cover, and details of the structures themselves*

2.5.4 RECIPIENT BLOCKS NOT TREATED (CONTROL AREAS IN S1-S5)

From a practical perspective, it would not be worth the work of translocating LM if the resultant ecosystem were no closer to D+ than areas left alone. We therefore established control locations, or areas **not treated** with LM but otherwise identical to the areas that were **(treatment level: NT)**. Comparing the **+LM** quadrant of recipient blocks to nearby **NT** areas provides the crucial test that translocating LM can have a real impact on ecosystem development, e.g. by ruling out the possibility that desirable forest species observed in LM blocks are naturally abundant at the study sites, regardless of translocation. **NT** areas were located 5-10 m adjacent to each LM recipient block and monitored using all the same measures as for the treated areas. **Table 3**, below, presents a summary of the five levels of habitat refuge creation within the LM translocation experiment.

Table 3: *Five levels of habitat refuge creation within the Living Mulch relocation treatment*

Table 4: *Five levels of habitat refuge creation within the Living Mulch relocation treatment*

Code	Level	Microhabitat treatment applied	Test of effect
NT	1. No Treatment	None; refers to areas within recipient locations which did not receive relocated materials or other alterations. Sampling of NT was carried out 10-20 m adjacent to the installed Living Mulch Recipient (LMR) plots.	-
+LM	2. Addition of Living Mulch	Living mulch (LM) was excavated in patches from donor forest floor (e.g. upper 30 cm of topsoil, propagule banks, litter layers, etc.) and relocated immediately in bulk to recipient locations (Oct. 2017). Translocated materials were deposited evenly onto 12.5 m x 10.0 m patches of ground, to a depth of 30 cm, working around existing trees but otherwise completely covered resident vegetation and surface features. One quadrant was designated "+LM" and assigned to receive no further alterations.	+LM *vs.* NT
+LM+WD	3. Addition of Living Mulch and Woody Debris	Pieces of dead, fallen trees (e.g. stumps, trunks, limbs) varying in size and decomposition state were collected from the donor forest and relocated to the LMR plots (May 2018). Approximately 15 m^3 of woody debris (WD) was distributed evenly throughout the three remaining quadrants per plot. One quadrant was designated "+LM+WD" and assigned to receive no further alterations.	+LM+WD *vs.* +LM
+LM+WD+SC	4. Addition of Living Mulch, Woody Debris and Shrub Cluster	Six *Swida alternifolia* nursery-stock saplings (1 m height) were planted in a 2 m diameter circular shrub cluster (SC) near the centre of one quadrant which had received WD, in each LMR plot (May 2018).	+LM+WD+SC *vs.* +LM+WD
+LM+WD+SS	5. Addition of Living Mulch, Woody Debris and Shade Shelter	A shade shelter (SS) was constructed near the centre of the remaining quadrant which had received LM and WD, in each LMR plot at locations S1 and S2. Each structure consisted of cedar fence posts installed in the four corners of a 4 m x 4 m area, and cut to a height of 1.8 m. A sheet of black horticultural shade cloth, able to reduce peak incident solar radiation by 70%, was spread across the tops of the posts and used to cover the ground below (May 2018; tarps removed and reinstalled seasonally).	+LM+WD+SS *vs.* +LM+WD

Abbreviations expanded: **LM (living mulch); **NT** (not treated); **WD** (woody debris); **SC** (shrub cluster); **SS** (shade shelter)*

2.6 AFTERCARE

Mature trees are essential components of old-growth forests, but unfortunately, they are rarely able to survive transplantation. Their key role in shaping understorey habitat conditions and the potential absence of equivalent structures in recipient environments means that functionally replicating the missing microhabitat features should be a main consideration in both prescribing after-care and in selecting recipients initially. For example, an environment with some canopy closure or other strong shading elements, even if biologically distinct from the donor system, may offer better chances of success than any environment without such features. Saplings, shrubs, and smaller-stature trees which can be transplanted should be included, but with effort to excise and replant properly.

Woody debris structures varying in size, species composition and decay status play multiple different roles providing habitat refuges for woodland organisms. Translocation after-care aimed at replicating such structures may reduce stress experienced by the LM application and promote establishment of more characteristic forest communities. Although considerable work is required, these and other specific predictions of the transplant hypothesis are straightforward to test.

3.0 ANALYSIS

To test how effectively LM translocation generates ecosystem properties typical of old spontaneous forests at recipient locations undergoing rehabilitation or afforestation, we first needed to identify:

- **i)** which properties of ecosystems would be most significant to investigate;
- **ii)** a suitable donor forest (hereafter "D+") from which we could extract and utilize the "ecosystem" matrix of saplings, woody debris, organic litter and topsoil ("LM");
- **iii)** "after-care" techniques for replicating donor forest microhabitats in a way that is both biologically effective and logistically feasible at industry scale;
- **iv)** recipient environments that are suitable for ecosystem transplantation trials.

We are testing predictions that different interventions will produce different degrees of similarity to the ecosystem properties characterizing D+, and so the scope of ecosystem properties we choose to measure has major implications for what patterns we are capable of finding. One aim of our analysis will be to determine relationships among different response variables, including how well narrow subsets of responses may indicate the status the broader system.

3.1 PLANT COMMUNITY ANALYSIS

We have prioritized assessing the plant communities growing at the study locations as the best immediate indicators of ecosystem status by sample quadrat plots throughout the varying seres (**see Figure 10**).

Plant community analysis include:

- The total number of plant species
- Plant taxonomic identities (e.g. family/genus/species)
- Ground covered and predominant growth forms (e.g. moss/fern/forb/grass-family/woody vine/shrub/tree)
- Biogeographic origins of the species (e.g. native or exotic),
- Life-history strategies (e.g. opportunist vs. strong competitor)
- Relative rates of change in many of these properties over time or space.

Figure 10: *Examples of the small (0.25 m^2) temporary sampling plots laid as frames in which to assess the species composition of the vegetation community -- each plot is traditionally referred to as a QUADRAT in the ecology literature.*

3.2 SOIL PHYSIO-CHEMISTRY ANALYSIS

Comprehensive analysis of physical, chemical and biological features of both manipulated and resident soils is underway. To date, we have collected and stored more than 1000 strategic soil samples from different treatments and time points in the experiment, and have planned extensive analyses in collaboration with SGS Guelph, including quantification of soil pH, P, K, Mg, Ca, Zn, Mn, Cu, B, Fe, ammonium, nitrates and organic carbon.

3.2.1. SOIL BIOLOGY AND "eDNA" TESTING

Soils will also undergo biological analysis utilizing meta-genomic barcoding of environmental DNA, or "eDNA meta-barcoding". This analysis isolates and amplifies tiny fragments of DNA present in soil and enables identification of microorganisms. We are exploring partnership with two young companies from the University of Guelph's Barcode of Life Initiative: AgriSeqSolutions and Precision Biomonitoring. We are planning for initial genetic sequencing and analysis of soil fungal and bacterial communities over winter 2019-20, with insight into the biology of the late-2019 soils expected by spring 2020.

3.3 DECOMPOSITIONAL RATES OF LEAF LITTER IN SOIL

In fall 2018, we collected freshly fallen leaves within the donor forest, dried them, and portioned the material into several hundred 5.00-gram samples. We then transferred the weighted samples to custom-sewn nylon mesh pouches and buried these shallowly, in replicate clusters of 4, throughout D+ and S1-S5. The mesh size of the pouches allows the most common decomposition agents (bacteria, fungi, invertebrates) access to the dried leaf material but keeps the undecomposed leaf remnants intact so that, after a designated period, the samples may be retrieved, re-dried and re-weighted to determine how much of the sample decomposed per unit of time. We buried all litter pouches in early spring 2019 and retrieved the first set of samples for analysis in late autumn 2019, with retrieval of remaining replicates planned for 2020.

3.4 ECOSYSTEM THERMODYNAMICS

Recent engineering innovations have enabled ecologists to begin studying potential indicators of broader ecosystem status (such as stress levels experienced, or current development stage) related to the thermal properties, including the proportion of incoming radiation that is used by organisms to do work, which can be inferred from the amount of heat radiated from the system. Using high-resolution thermal cameras mounted to a remote-operated aerial vehicle, we have been repeatedly surveying thermal properties a subset of the treated areas (S1 and S2), in collaboration with colleagues in the University of Waterloo's Engineering Department. One purpose is to help determine the potential use of this technology for monitoring the progress of ecological restoration, while another is to gain mechanistic insight into relationships between ecosystem structures and functions in our system, including thermo-regulatory properties pertinent to climate change resilience and adaptation.

4.0 INTERIM RESULTS

In our spring 2019 survey, we were able to examine communities including many spring ephemerals within D+ and assess whether there was evidence for the establishment of similar communities within treated and not-treated areas of S1-S5. We also observed, shortly after their emergence, many plants typically comprising the summer flora in the ground-layer, indicating analysis of the spring data would likely grant a fair preview of at least some of the structure of the later-season community as well.

Throughout sampling of spring 2019 from May 15 through June 8, we identified every species of fern, herb, grass, vine, shrub and tree (plus commonly reoccurring moss families) within each of four 0.25 m^2 plots placed at random positions within each of the differently-treated quadrants in every LM recipient block. This added up to 60 small sampling plots per site where no shade shelters had been installed (S3-S5), and 72 plots per site where they had been (S1-S2).

At each sere we also sampled 60 plots within not-treated (NT) areas surrounding the treated areas, for a total of 500 sampling plots across all treatment levels (NT; +LM; +LM+WD; +LM+WD+SC; +LM+WD+SS). We characterized the plant community composition within the donor forest by assessing 160 sampling plots. These individual blocks are detailed in the following photos: **S1-S2 (Figure 11), S3-S4 (Figure 12), and S5-D+ (Figure 13).**

Figure 11: *Not-treated (NT) areas (top) and LM-treated blocks (middle, with example close-up image of a community sample in bottom panel) in S1 and S2 recipient seres.*

Figure 12: *Not-treated (NT) areas (top) and LM-treated blocks (middle, with example close-up image of a community sample in bottom panel) in S2 and S3 recipient seres.*

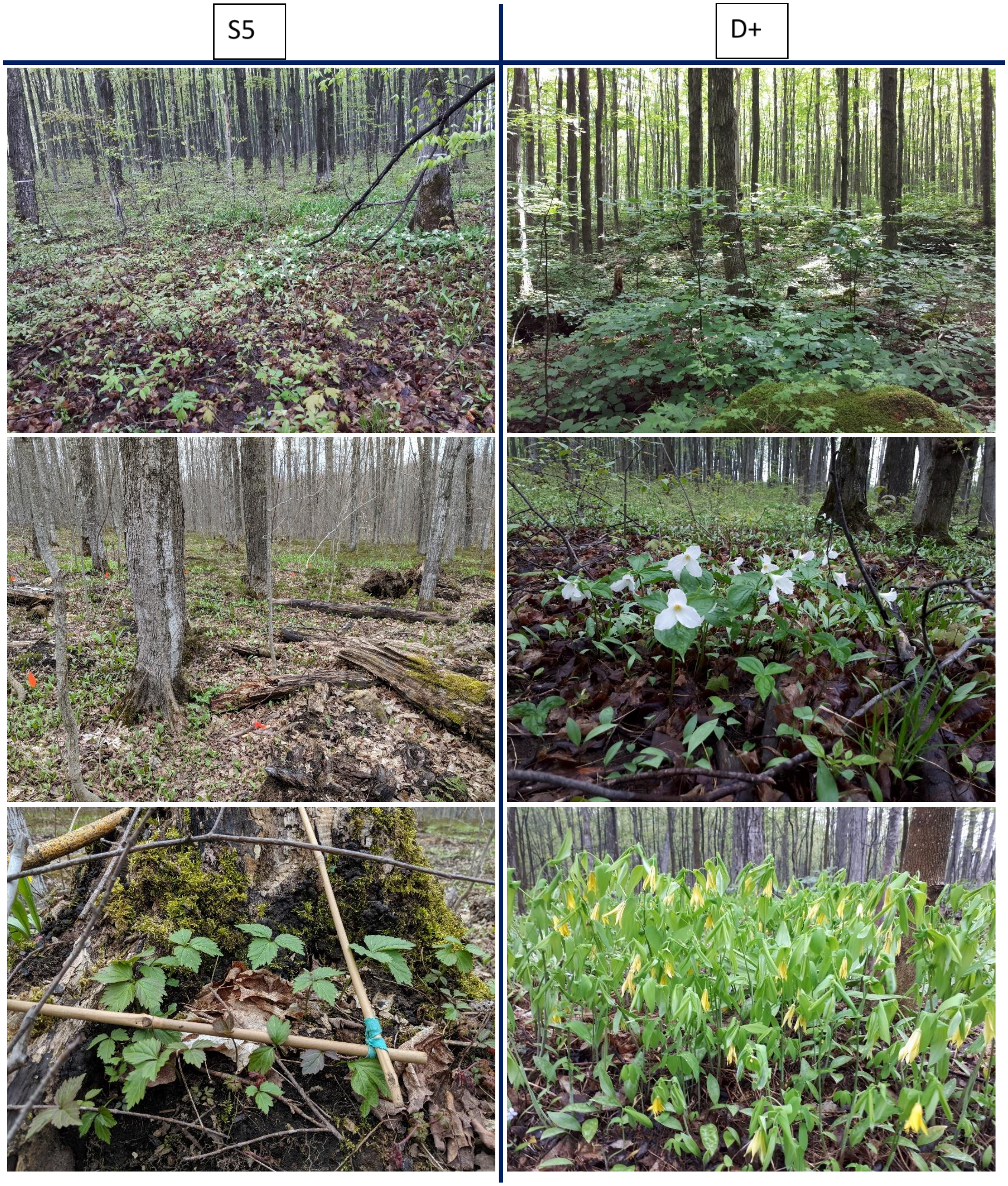

Figure 13: *Not-treated (NT) areas (top) and LM-treated blocks (middle, with example close-up image of a community sample in bottom panel) in S5; images of D+, for comparison (not treated).*

4.1 JACCARD INDEX TO CALCULATE COMPOSITIONAL SIMILARITY

For each plot in S1-S5, we quantified its average similarity to the plots sampled within D+ using the ***Jaccard index***, a mathematical tool also known as "Intersection over Union" which is used in many disciplines to compare pairs of sets with respect to the proportion of elements that shared between sets versus unique to one or the other.

Statistical results of the Jaccard index are in the '***Full Interim Report'***.

4.2 SUMMARY OF RESULTS FROM STATISICAL ANALYSES

One of the most important results from the spring 2019 vegetation data is the close similarity between the D+ plant community and that which emerged in LM-treated areas of S5 (mature hardwood forest apparently equivalent to D+). The closeness suggests that the vegetation residing in the LM was not meaningfully impacted by the physical process of extracting, transporting and depositing the top layer of forest topsoil – likely because these steps were carried to completion in a short period of time (no stockpiling), and after most vegetation had entered winter dormancy (respecting physiology of the system). As such, departures from this pattern at other recipient locations must be due to the new environment, not the translocation process. Knowing this, the most useful lessons derived from vegetation patterns at the four earlier-stage LM recipient locations (S1-S4) are that:

i) LM application without additional alterations to microhabitat features produces a doubling to tripling of species richness at the small-plot scale (i.e. per 0.25 m^2), relative to untreated areas of recipient environments.

ii) The plant communities varied with respect to how similar their species compositions are to those residing in the donor forest (D+), but at every recipient sere LM-treated areas shared significantly more species with D+ communities compared to untreated areas.

iii) In most of the recipient seres, translocating additional coarse woody debris from D+ and using it to install microhabitat structures (designed to provide small-scale refuges with locally higher levels of shade, humidity, soil moisture and wood-decomposing organisms) produced a significant positive effect on the level of similarity to D+ expressed by the plant community.

iv) Planting clusters of alternate-leaved dogwood shrubs as potential agents for shading the translocated LM has yet to exhibit any meaningful effects on the ground-layer vegetation.

v) Constructing artificial shade shelters using cedar posts and horticultural shade cloth, by comparison, had a significant positive influence on the level of community similarity to D+ expressed by vegetation in affected areas of S2 (field afforested in 2015), and we saw a trend towards a similar influence in S1 (dry gravel pit undergoing spontaneous succession).

vi) If the constructed shade shelters provide refuge to translocated D+ biodiversity, the full benefits of such provisioning would likely be more apparent in patterns demonstrated by the late-season rather than early-season plant communities. The mechanisms of SS effects require further investigation but likely include both protecting shade-tolerant plants from high light intensity and producing unfavourable conditions for light-favouring species that would otherwise outcompete translocated woodland species for space, nutrients or other resources.

4.2.1 TESTING PREDICATIONS BY COMPARING OUTCOMES AMONG TREATMENT LEVELS

We analyzed the set of average similarity for all plots sampled in spring 2019 at recipient seres. Using generalized linear model analysis, we also included random effects to account for potential autocorrelation among plots sampled within the same recipient block (or surrounding area), and made previously planned statistical contrasts between different, specific treatment pairs to test predictions.

The test for the prediction that LM application would increase the similarity of S1 vegetative composition to that of D+, for example, is to determine if the average similarity for plots in LM-treated areas of S1 is statistically greater than the average similarity for NT plots in S1. To test the prediction that adding extra WD microhabitat structures would induce an even greater degree of similarity to D+, it is necessary to contrast average similarity in +LM+WD plots against average similarity in the +LM plots. Similarly, the +LM+WD treatment level must serve as the baseline for comparison when determining if yet greater similarity to D+ is produced by installing shrub cluster (SC) or shade shelter (SS) modifications, as these different refuges against excessive solar intensity were only applied to areas that had received WD in addition to LM.

4.2.2 VEGETATION RESPONSES IN THE DONOR FOREST (D+) AND NON-TREATED (NT) AREAS

The pattern indicates that plant communities spontaneously residing in even the earliest successional environment investigated share some species in common with D+, but not many. It also shows that the degree of similarity to D+ increases with afforestation and time, but not by much: even 75 years after tree planting, the composition of understorey vegetation was less than 25% of the high-similarity target value. By comparison, the complete similarity to D+ exhibited by S5 indicates that S5 is a suitable location for serving its function as reference environment, representative of the D+ conditions but protected from future impacts of the quarry expansion.

4.2.3 CRITICAL PATTERNS

Results based on data collected in spring 2019 indicate ecosystem translocations may fast-forward succession at treated lands when combined with strategic sere matching and after-care. Four critical patterns are apparent from both statistical results and compiled example photographs:

1. Translocating LM to S5 (old growth control site) produced plant communities nearly identical to those at D+, suggesting transplant methods had negligible impacts on biodiversity within LM. Therefore, differences in vegetation between D+ and other recipient locations are more likely due to habitat discrepancies than to the physical disturbances experienced during translocation.

2. Regardless of sere or treatment, every recipient block supported species compositions more similar to D+ than to communities in adjacent non-treated areas. This suggests broad utility for LM translocations but demands examining the stability of observed patterns and the roles played by different species and traits.

3. Only some habitat modifications made significant differences, and only at some recipient seres. For example, planting translocated LM with dogwood shrub clusters appears to have had no influence on the similarity of emergent vegetation to that of D+. Installing woody debris at seres S1-S3, by contrast, increased compositional similarity to D+.

4. Erecting shade shelters at S2 significantly increased its similarity to D+, but at S1, this effect was marginal.

Perhaps most importantly, the successional stage of the recipient location had greater influence on vegetative community composition than any habitat amendment. Consider that the average similarity among D+ samples shows maximum similarity to D+ expected at other locations. Not-treated areas at S2 featured communities expressing an average similarity score that was 14% of this “high bar” target, while at both S3 and S4, the corresponding values approached 20%. Translocating LM to S2 yielded an average similarity values that was 40% of the target, increasing to 53% given extra woody debris, and to 59% beneath shade shelters. Translocating LM to S3 and S4 without further amendments, by contrast, produced respective similarity scores 77% and 81% of the target. These differences suggest that although translocating LM from mature forests may advance aspects of succession across a range of recipient seres, using limited donor resources efficiently may require prioritizing translocations to older afforestation sites. Both stronger canopy shading and the relative absence of competitors at mid-successional plantations likely contributed to the powerful effect of translocating LM to S3 and S4.

4.2.4 RICHNESS IN LM-RECIPIENT BLOCKS

Species richness in the LM recipient blocks within S5 was also relatively low (5.6 species per plot), but the LM-blocks in S1-S4 all supported high levels of species richness, particularly in +WD areas. The levels of species richness supported are surprisingly close to the simple sums of the values for corresponding NT areas at each sere plus the 6-7 species per plot observed in the D+ and S5. The respective mean richness values for +LM+WD areas in S1-S4 are 16.9, 13.9, 11.6, and 11.7 species per 0.25 m^2. While this likely oversimplifies the dynamics of the establishing communities, it suggests compositional outcomes (so far, at least) are more driven by additive mixing of the different species pools than by environmental stressors filtering many species from the realized communities.

4.2.5 IMMIGRATION FROM HIGH-RICHNESS NOT-TREATED AREAS

The communities in LM-blocks at S1 and S2 are respectively 43% and 59% comprised of “non-LM” species (i.e. residents of the sere) while LM-blocks in S3 and S4 are only 33% and 30% comprised of “non-LM” species. It logically follows that the compositional similarity of +LM communities in the later stage seres should be higher to D+, as there are fewer “non-D+” species to dilute the established mixture.

4.2.6 AFTERCARE STRATEGIES

Microhabitat manipulations as well as selection of recipient seres can thus likely influence the structure of communities emerging after LM translocation both by promoting some species and by constraining others, depending on the context of application. The patterns of community response to our treatments identified so far cannot provide any final word on which ecological processes managers should attempt to manipulate for greatest success. They do generate crucial predictions, however, for testing through continued data collection and further analysis; results of these tests will dictate refined site intervention strategies to maximize desired outcomes, and minimize undesirable ones, when implementing ecological enhancement programs.

4.3 FURTHER BIOLOGICAL AND STATISICAL ANALYSES REQUIRED

Once the remaining data collected in 2019 can be analysed we will be able to comment on vegetation patterns observed and provide a comprehensive suite of soil physio-chemical and biological properties, including meta-genomic barcoding of "eDNA" to assess the composition and functioning of soil bacterial, fungal and invertebrate communities. We will additionally evaluate an experimental assay of litter decomposition rates and pathways, explore thermodynamic indicators of ecosystem stress and adaptation, and more.

5.0 DISCUSSION

Based on interim results, the potential for ecosystem "transplantation surgery" to accelerate transition to later seres within younger woodlands is promising for both extraction sites requiring rehabilitation and for existing tree plantations established to mitigate industry impacts. Given the possible transitional status of observed patterns, the need to extend analyses to a broader suite of monitored responses, intensive effort will be required over the final year of RERAS to assess the full scope of all treatment effects. Results from this study will inform best management practices for maximizing translocation efficacy under different circumstances facing aggregates producers and other land stewards.

5.1 SELECTING SERES VS. ALTERING MICROHABITATS

While modifying microhabitat conditions at LM recipient locations may somewhat increase the power of LM to produce plant communities with high similarity to D+, these effects are dwarfed by impacts associated with the developmental status of the recipient environment. Put simply, more of the plant biodiversity present in forest LM can establish at recipient locations where a semi-closed canopy is already present – even if dominant tree types or ground coverage are dissimilar to the LM-donor – than at more open locations, such as recent afforestation or extraction sites. The nature of this effect may not be so much a case of woodland species preferring the shade, however, as it is a response to much higher immigration pressure of aggressive agricultural weeds to the more open sites.

5.1.1 S1 & S2 RESPONSES

Even under artificial shade mimicking the donor forest, we discovered that vegetation communities in LM-treated areas at S1 and S2 included numerous weed species typical of the surrounding fields, limiting the degree to which the plant community could compositionally resemble D+. This limitation will intensify if the woodland species are ultimately unable to coexist with the field species (which are typically superior competitors until they become limited by low light), emphasizing the need for continued monitoring and analysis of the experimental system.

5.1.2 S3 & S4 RESPONSES

The prognosis is surprisingly much more positive for the older conifer plantations, S3 and S4. Although the mature donor hardwood forest differed strongly from the conifer plantations with respect to canopy composition, ground vegetation, litter layer, and soil chemistry, translocation of LM from the former to the latter consistently produced spring plant communities with very high similarity to the donor forest (i.e. 80-85% of the target level set to represent maximum possible similarity). The plant communities that emerged from the deposited LM likely benefited from the relatively low abundance of other vegetation in the surroundings. Additionally, resident biodiversity present at S3 & S4 tended to be less aggressively invasive than at the earlier successional sites. LM transplants likely benefited from our necessary selection of field sites that already had moderate breaks in the canopy and openings at the ground-layer (i.e. transitioning from stem exclusion to understorey re-initiation stages of succession).

Such gaps were necessary for equipment and personnel access to install the experiment but if LM application is ever to be applied at a larger scale, and mature plantations are targeted as recipients, managers would likely need to create similar openings to ensure moderate diversity of mixed-light environments and heterogeneous ground conditions required by vegetation in old hardwood forests. To complement ongoing forest-creation and site-rehabilitation initiatives, managers with access to LM resources would be wise to consider the benefits of facilitating programs for enhancing the biodiversity and ecological functioning of existing but under-performing forests. This could help maximize industry contributions, both to offsetting unavoidable environmental impacts and to combatting other ongoing ecological crises including biodiversity loss and climate change.

5.2 MOVING FORWARD

With respect to our goals, the current progress of the RERAS research endeavour is on target. Aside from the various practical lessons learned while planning, implementing and initiating monitoring of the translocation experiment, we are now gaining valuable insight into the dominant ecological processes that will likely control the long-term success or failure of different ecosystem translocation strategies. The clearest new knowledge has resulted from careful statistical analysis of large datasets. As the plant community surveys from spring 2019 are the only data we have analyzed fully, our confidence about the ecological patterns is currently restricted to the time period corresponding to ca. 1.5 years post-translocation of living mulch (and one year after installation of all microhabitat modifications). Despite this unavoidable limitation, the analytical approach we developed, and our widened perspective from discovering and interpreting the patterns that have emerged so far, provide a very useful template for our next iteration of data collection and analysis.

We will begin comprehensive analysis of the full set of vegetation surveys collected throughout 2019 over winter 2019-20. One completed analysis, based on plant community data collected in May-June 2019, has produced intriguing and optimistic results. Much of the biodiversity inhabiting mature hardwood forests such as D+ is associated with spring ephemeral plant communities. These are comprised of suites of ground-layer herbaceous species which have evolved to carry out the majority of their yearly growth in the brief period between spring thaw and full leafing-out of the forest canopy in early summer – a life-history strategy called shade avoidance, rather than shade tolerance. We expect such species may have higher tolerance for the earlier-sere recipient environments than do others in the LM matrix and therefore be valuable in applications.

We expect that one more year of monitoring the described spectrum of ecosystem responses, combined with our intensifying analysis of collected data, will place us in a strong empirical position to judge the short-term effectiveness and longer-term prospects for enhancing afforestation by strategically translocating and preserving biodiversity in the uppermost surface layers of old hardwood forests. Our fully informed perspective will provide the firmest foundations possible -- i.e. given constraints imposed by our current 4-year research window – for recommending both general and specific best management practices. The audience to benefit from these recommendations will include aggregate producers but also the wider afforestation, ecological restoration, and natural resource management communities. The final recommended applications and implications will take the form of a final report to TOARC, but also academic papers in both applied and theory-oriented journals, plus media in non-academic publications emphasizing resource-management frontiers and innovations.

If results from our upcoming analyses and 2020 data collection resemble our interim findings, the “transplantation surgery for ecosystems” hypothesis – with its principles of donor-recipient site matching, knowing and working within biological limits, and providing stress-reducing after-care by reducing microhabitat differences between past and present environments – may have pivotal utility in a range of increasingly important land management applications.

Our final report at the end of 2020 will provide these missing links, but if the observed trends continue, the central implication for aggregate resource managers may be that they can maximize the biodiversity and habitat co-benefits of both site rehabilitation and offsetting programs. This would require comprehensively managing "living mulch" type resources such that fresh supply is available for application to strategic locations at strategic time points. This should include existing and planned afforestation projects – likely in combination with stand-thinning management – as they near the end of the stem-exclusion sere, ca. 30-40 years after stand initiation.