Earthworm and Land-Use Legacy Effects on Belowground Carbon in the Managed Northern Forest

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- Fifteen species of earthworms found in Vermont forests
- Earthworms alter ecosystems but may also stabilize soil carbon

Funding support for this project was provided by the Northeastern States Research Cooperative (NSRC), a partnership of Northern Forest states (New Hampshire, Vermont, Maine, and New York), in coordination with the USDA Forest Service. http://www.nsrcforest.org

Project Summary

Northern Forests have the potential to offset a measurable fraction of anthropogenic carbon by sequestration. A large portion of total carbon storage is belowground and prior land use has a long-lasting effect on soil carbon storage. Losses of carbon, especially those associated with tilled agriculture, have persisting negative effects on carbon stores. Due to this influence, much of the northern forest with a history of past agricultural use is experiencing a net gain in soil carbon. However this function is threatened by exotic earthworm invaders which have caused considerable ecosystem-wide changes to soil and vegetation structure in northern hardwood forests. Most findings document short term carbon losses after an invasion event, primarily through the indirect impact earthworms have on the decomposition rates of these soils. Other research suggests that earthworm-created stable aggregates may mitigate these losses through the long term physical protection of carbon, specifically within microaggregate (<250 µm) structures. The objectives of this study were to (1) survey a variety of forested regions in the state of Vermont to determine the extent of current earthworm invasion, (2) quantify the amount of physically protected structures within 8 hardwood forest stands and analyze the extent that earthworm presence may influence these values, (3) conduct a controlled investigation on the effect of one earthworm species on an earthworm-free undisturbed forest soil, (4) determine the land use history of 18 monitored forest stands, and (5) prepare outreach materials on the earthworm situation. The survey showed that earthworm presence is expansive across Vermont forests and that higher species diversity correlated with reduced forest floor depth, higher mineral soil carbon, reduced microaggregate proportions, and higher microaggregate carbon concentrations. The controlled study corroborated these findings with the total pool of microaggregate associated carbon increased due to passage through the earthworm gut, while the proportion of these structures remained unchanged. Prior land use included cultivation, pasture and farm woodlot. Only one of the 18 sites has been continuously woodland. Sites with the highest worm density and species richness had a history of agricultural land use (although not all former-ag sites had earthworms). Depending on the forest soil's starting concentration, the quantity of carbon present within microaggregates is likely to increase with earthworm activity, thus increasing a more stable form of carbon in these soils. More work is clearly needed to understand the earthworm invasion patterns and the means of better controlling populations of the most aggressive species.

Background and Justification

- Northern forests have the potential to offset a measurable fraction of anthropogenic carbon (C) by sequestration.
- A large portion of total C storage is belowground and prior land use has a long-lasting effect on soil C storage.
- Much of the northern forest with a history of past agricultural use is experiencing a net gain in soil C.
- However this function is threatened by exotic earthworm invaders which have caused considerable ecosystem-wide changes to soil and vegetation structure in northern hardwood forests.

Earthworms: Good, Bad, or In the Middle?

As a community: Incorporate organic matter into mineral soil
Aerate the soil and enhance water storage
Increase soil aggregation
Accelerate nutrient cycling

Agriculture

Indicator of a soil's health

Northeastern Forests

Agents of change

- Remove forest floor, relocate C lower in soil profile
- Reduce herb layer, affect seed bed
- Change habitat structure, possibly affecting salamanders and birds
- Alter soil temperature, moisture, and water filtration
- Can increase erosion if forest floor is lost

Earthworms and forest understory

- Hinesburg Town Forest (HIN)
- 6 species found, 153/m^2

- Atlas Partnership, Eden (SQU)
- 1 species found, 12/m^2

Characteristics of the 18 'carbon' plots established with prior NSRC funding*

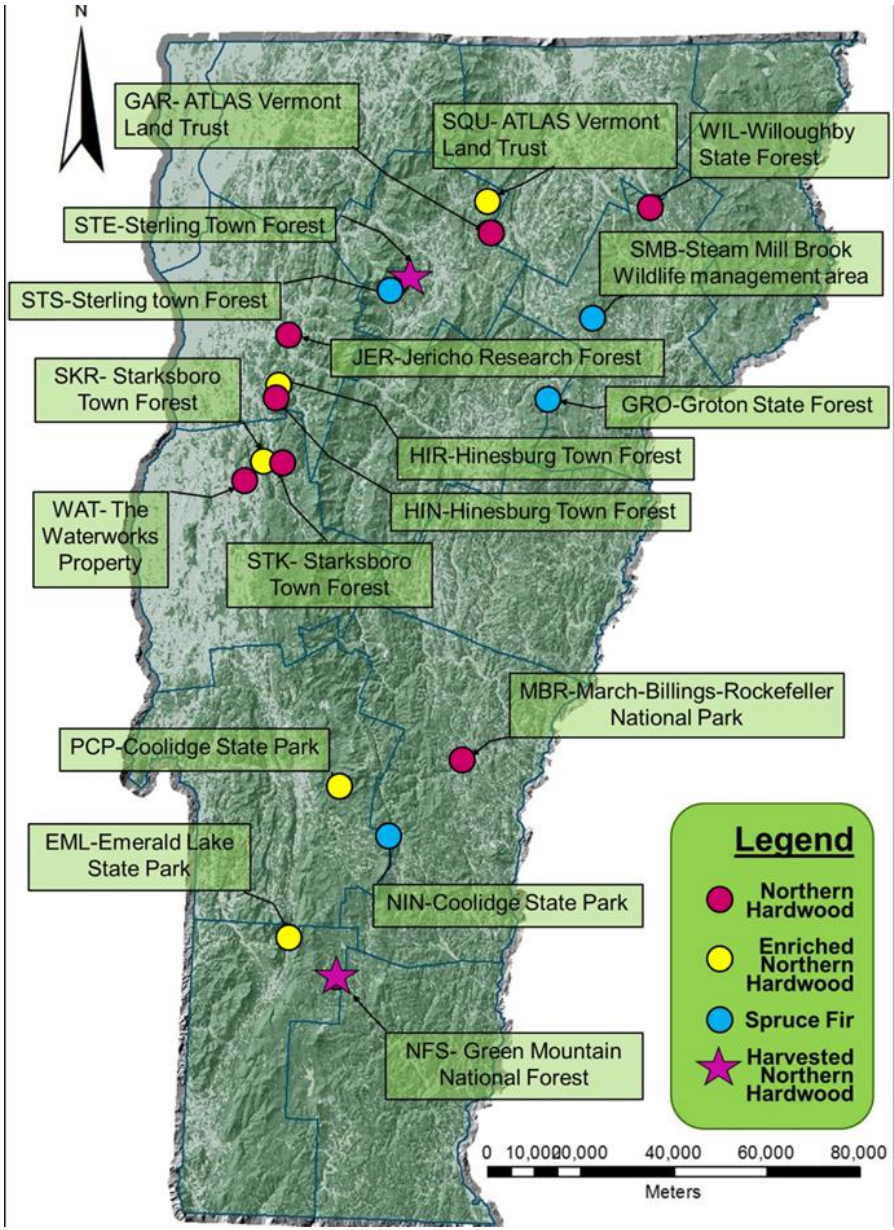
Site abbr.	SITE	Forest Community	Elevation Center [m]	Average Aspect [deg.]	Average Slope [deg.]
EML	Emerald Lake State Park	Enriched Northern Hardwood	299	142	21
GAR	Atlas Partnership 'Garfield'	Northern Hardwood	488	97	16
GRO	Groton State Forest	Spruce-Fir	425	245	3
HIN	Hinesburg Town Forest 'Poor'	Northern Hardwood	403	326	5
HIR	Hinesburg Town Forest 'Rich'	Enriched Northern Hardwood	370	349	21
JER	Jericho Research Forest (UVM)	Northern Hardwood	154	269	18
MBR	Marsh-Billings-Rockefeller National Park	Northern Hardwood	397	90	24
NFS	Green Mountain National Forest	Northern Hardwood	493	50	14
NIN	Coolidge State Forest 'Ninevah'	Spruce-Fir	552	182	7
PCB	Coolidge State Forest 'PCB'	Enriched Northern Hardwood	651	193	10
SKR	Starksboro Town Forest 'Rich'	Enriched Northern Hardwood	349	278	24
SMB	Steam Mill Brook Wildlife Management Area	Spruce-Fir	649	254	5
SQU	Atlas Partnership 'Square'	Enriched Northern Hardwood	589	100	15
STE	Sterling Town Forest (Stowe) 'Hardwoods'	Northern Hardwood	528	250	6
STK	Starksboro Town Forest	Northern Hardwood	333	215	13
STS	Sterlling Town Forest (Stowe) 'Spruce-Fir'	Spruce-Fir	524	94	6
WAT	Waterworks	Northern Hardwood	237	279	18
WIL	Willoughby State Forest	Northern Hardwood	465	79	7

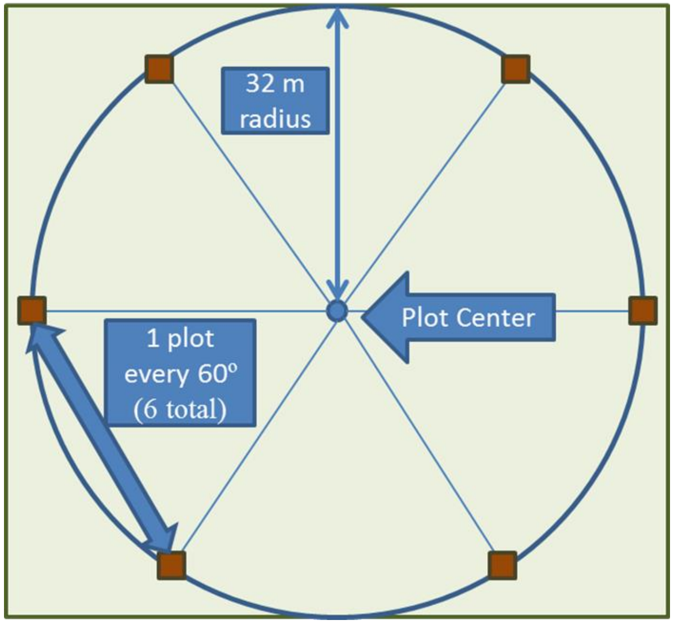
*Ross, D.S. and S. Wilmot. Soil carbon and other quality indicators in managed northern forests. Northern States Research Cooperative, Theme 1. 8/1/2007-7/30/2009.

Methods

- Survey at 18 established sites (map in next slide): 6 50x50 cm plots excavated to 20 cm and worms identified by species.
- Survey at 20 additional sites: 5-10 30x30 cm plots excavated at each site and worms identified by species.
- Carbon in soil aggregates (9 of 18 established sites): standard methods for water stable aggregates and carbon by elemental analyzer (see M.E. Knowles M.S. thesis for more details).
- Mesocosm study: Influence of *A. tuberculata* on carbon and aggregation in undisturbed forest soil cores: see below and M.E. Knowles M.S. thesis
- Land use history: combination of historical analyses and on-site field analysis

Earthworm Survey at 18 Established Sites



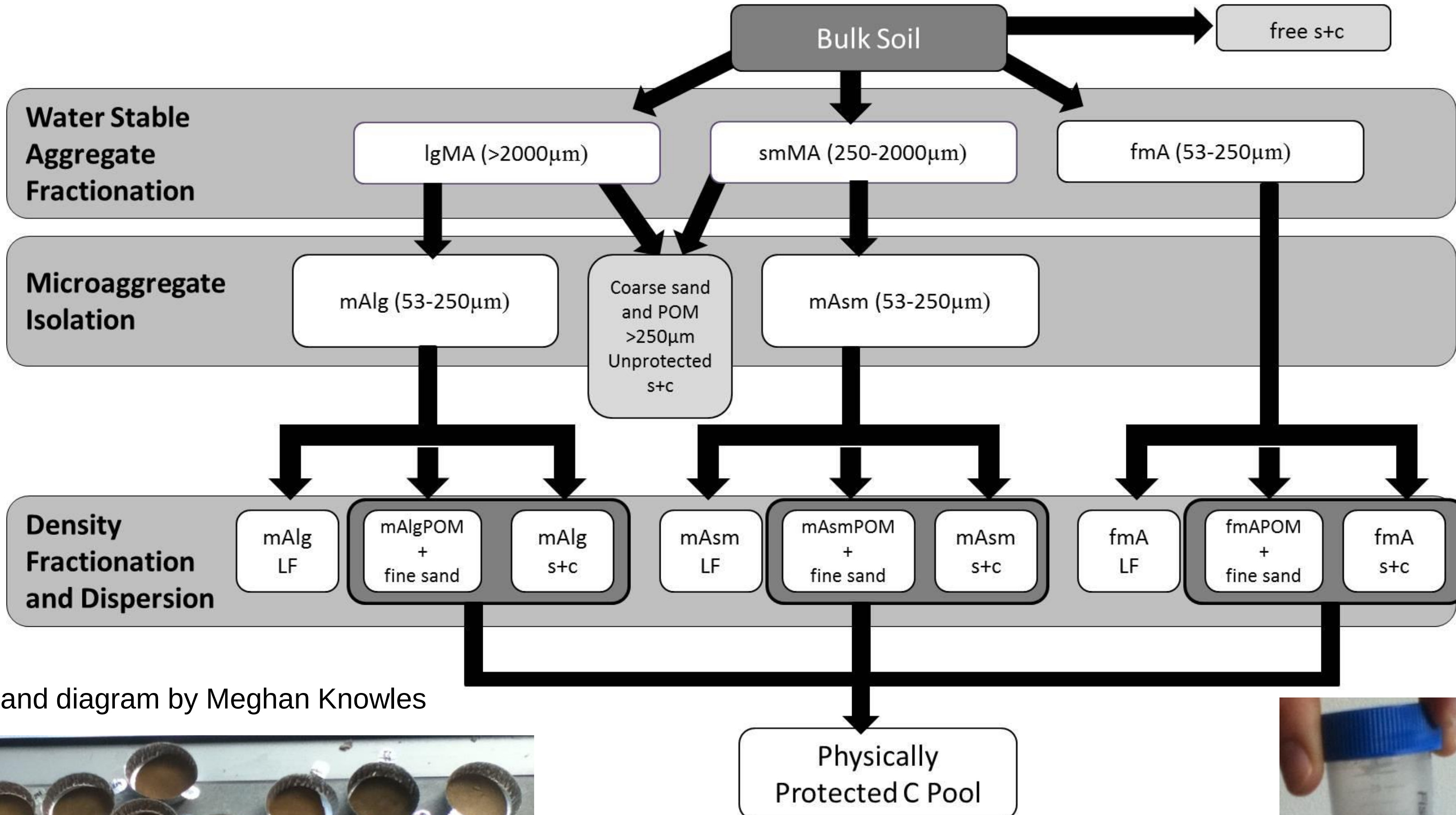


The Digging

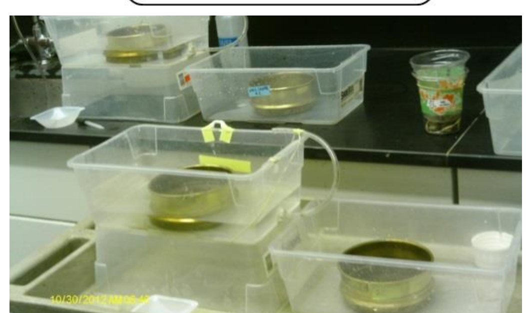
The Sorting

Photos and illustrations by Meghan Knowles

Aggregation Analysis Methods



Photos and diagram by Meghan Knowles



Core Collection from Waterworks for Mesocosm Study

<u>Criteria</u>

- No earthworms
- Low variability
- Few rocks

- 20 cores for 2 durations (4 weeks, 4 months)
- 10 cores/duration
- 5 pairs (n=5)/duration

Photos by Meghan Knowles

Results/Project outcomes Earthworm survey results

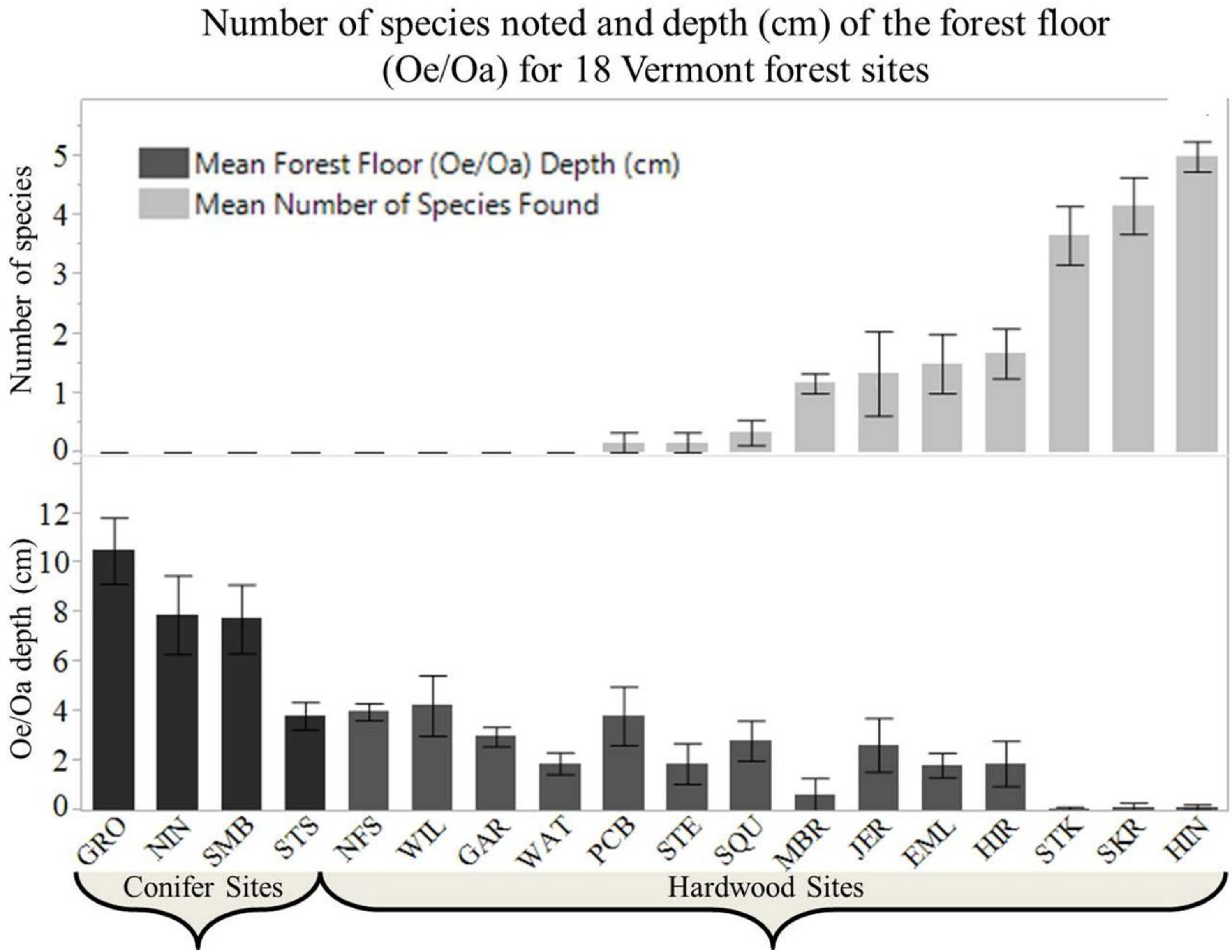
- 10 of 18 established plots had earthworms (11 species)
  - *Amynthas agrestis*, *Aporrectodea rosea*, *Aporrectodea trapezoides*, *Aporrectodea tuberculata*, *Aporrectodea turgida*, *Dendrobaena octaedra*, *Dendrodrilus rubidus*, *Lumbricus rubellus*, *Lumbricus terrestris*, *Octolasion cyaneum, Octolasion tyrtaeum*
  - Highest numbers were at STK (319 per m^2)
- 14 species found at the 20 additional sites
  - *Allolobophora chlorotica*, *A. agrestis*, *A. rosea*, *A. trapezoides*, *A. tuberculata*, *A. turgida*, *D. octaedra*, *D. rubidus*, *Lumbricus festivus*, *L. rubellus*, *L. terrestris.*
  - First reports from Vermont for: *Octolasion cyaneum*, *Amynthas tokioensis* and *Amynthas hilgendorfi*.

Earthworm survey results for the 18 carbon monitoring plots

Site Code	Survey Date	Average Percent (%) Moisture (±SE)	Average Mineral Soil Temp. (°C) (±SE)	Average Epigeic Worms/m^2	Average Endogeic Worms/m^2	Average Epi-Endogeic Worms/m^2	Average Anecic Worms/m^2	Average Total Worms/m^2	Number of species noted	Fraction of plots worms found	Average Forest Floor (Oe/Oa) Depth (cm)	Average pH*
EML	18-Jun-13	22.86±2.20	13.61±0.12	2	15	1	0	17	3	4 of 6	1.85	6.3
GAR	6-Jun-13	30.18±2.47	12.49±.030	0	0	0	0	0	0	0 of 6	3.00	4.0
GRO	15-Aug-13	NA	NA	0	0	0	0	0	0	0 of 6	10.50	4.6
HIN	3-May-12	47.65±3.06	14.28±2.84	10	130	5	13	153	6	6 of 6	0.17	4.5
HIR	31-May-12	27.64±2.4	15.23±0.83	4	4	7	1	16	4	5 of 6	1.92	4.4
JER	6-Jun-12	30.37±2.16	16.33±0.83	2	31	4	0	37	5	4 of 6	2.67	3.9
MBR	4-Jun-13	20.16±1.91	16.26±0.77	118	1	2	4	121	3	6 0f 6	0.67	5.7
NFS	19-Jun-13	29.95±1.26	13.72±0.22	0	0	0	0	0	0	0 of 6	4.00	3.9
NIN	20-Aug-13	17.58±2.22	17.47±0.31	0	0	0	0	0	0	0 of 6	7.92	3.9
PCB	19-Aug-13	34.71±4.84	16.98±0.71	0	1	0	0	1	1	1 of 6	3.83	4.6
SKR	13-Jun-12	34.27±2.31	16.69±.038	29	49	23	4	103	7	6 of 6	0.17	4.4
SMB	2-Aug-13	38.5±3.55	15.67±0.93	0	0	0	0	0	0	0 of 6	7.75	3.3
SQU	20-Sep-12	25.12±2.12	13.97±0.28	0	12	0	0	12	1	2 of 6	2.83	4.8
STE	3-Jul-12	28.46±3.89	18.51±0.18	2	0	0	0	2	1	1 of 6	1.92	4.9
STK	19-Jun-12	37.14±4.76	19.08±0.69	23	226	66	3	319	4	6 of 6	0.08	5.2
STS	31-Aug-12	23.08±2.44	18.79±0.41	0	0	0	0	0	0	0 of 6	3.83	4.3
WAT	11-Oct-12	16.04±1.54	10.73±0.22	0	0	0	0	0	0	0 of 6	1.92	4.1
WIL	12-Oct-13	NA	NA	0	0	0	0	0	0	0 of 6	4.25	3.7

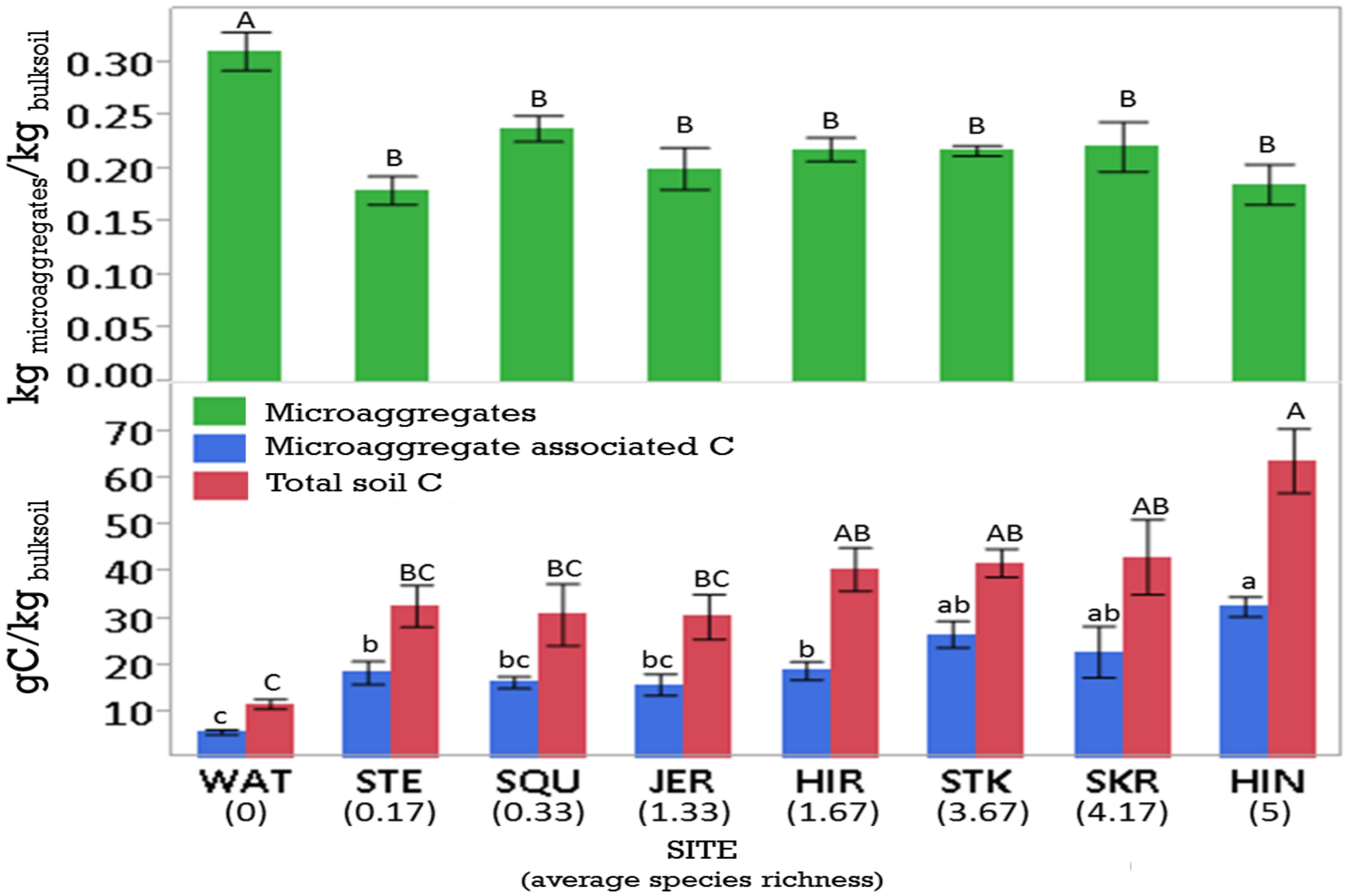
Earthworm Presence and the Forest Floor

(Forest floor depth generally decreased as species richness increased)

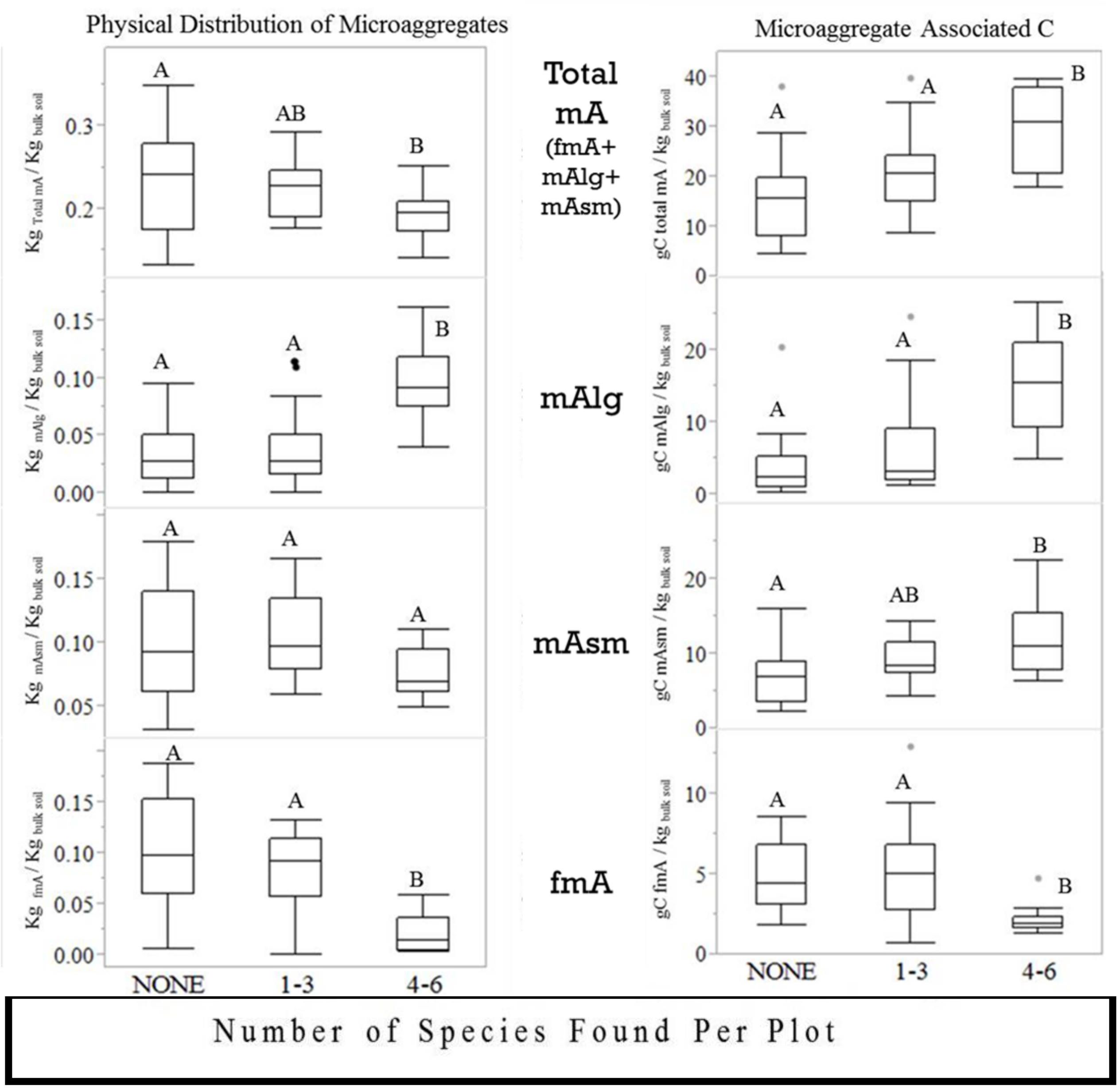


Aggregate and carbon analysis from 8 hardwood sites

- Relatively consistent amount of microaggregates across sites
- Microaggregate (mA) associated carbon (C) tended to increase with earthworm species richness
- Waterworks (WAT) unusually low in total C and mA-associated C



Aggregate and C Analysis-48 plots



The 6 plots from each of the 8 hardwood sites were pooled.
A greater number of earthworm species showed an increase in the amount of C within microaggregates.

mA: microaggregate
fmA : free mA (not part of macroagg.)
mAlg: large mA
mAsm: small mA
(both part of macroaggregates)

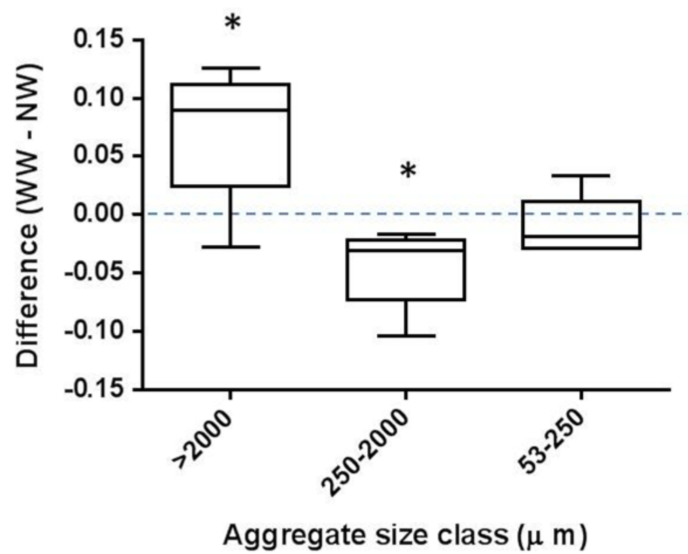
None (n=19 plots)
1-3 (n=18 plots)
4-6 (n=11 plots)

Mesocosm Core Opening – 4 months

Photos by Meghan Knowles

Left: control   Right: worms

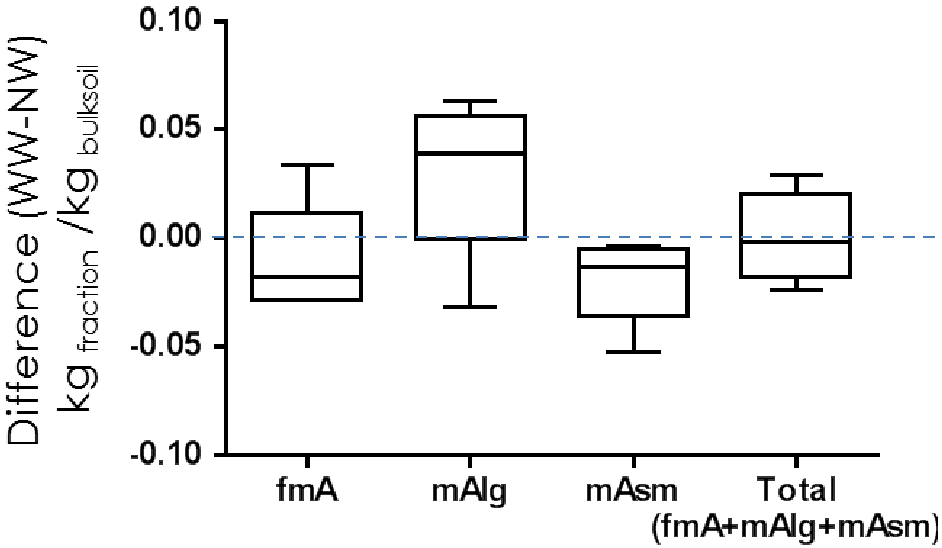
- All worms survived
- About ½ were found estivating
- All worm cores had baby worms and cocoons
- Main effect was on large macroaggregates (see below, ‘difference’ is paired cores ‘with worms’ – ‘no worms’)



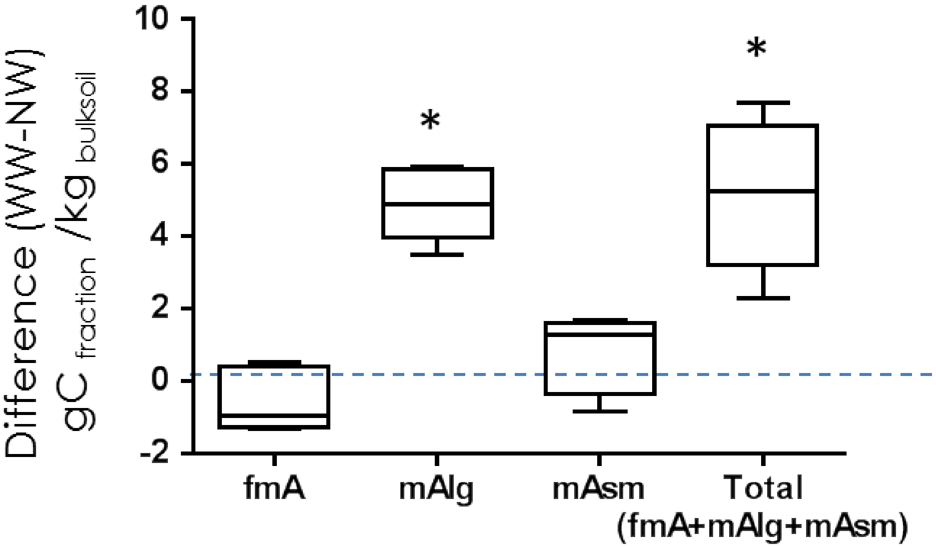
C Enrichment of Microaggregates

Earthworms did not significantly alter microaggregate proportions (left graph).
However, they recreated microaggregate structures rich in C (right graph).

Change in proportions of dry mass



Change in proportions of C



n=5
(*) represent statistically significant values at $p<0.001$
bars represent minimum and maximum differences from core pairs.

Summary of past land use at the 18 established sites

Site	Land Use Code*	Distance to 1880 farm house (mi.)	Farm dates and Summary of Land Use
EML	2	0.31	1769-1957 back cow pasture, heavy use 1850-1957
GAR	4	1.10	1802-1955 farm woodlot, heavy use incl sugaring; heavily cut since 1950.
GRO	5	0.71	1873-1933 industrial woodland lots for Ricker Mill and RR, later Darling; heavily cut 1873-1933, possibly burnt 1883; 1933 to present state forest.
HIN	2	0.27	1875-1950 farm fields; improved pasture dairy farm with 25 sheep in 1880; 50# sugar in 1880;
HIR	2	0.24	1875-1950 farm fields ; improved pasture dairy farm; 300# sugar 1880
JER	2	0.19	1790-1910 open improved pasture dairy farm fields, abandoned ~1910 perhaps woods pasture, to UVM 1941; selective cutting since; 400# sugar 1880
MBR	2	0.39	1790-1930 improved pasture with perhaps some woods pasture on gentleman farm; wooded since 1940s; 500# sugar 1880;
NFS	2	0.30	1790-1950 improved pasture on intensive dairy farm, 39 cows & 44 shee ; remnant stone walls; abandoned ~ 1950; 900 # sugar in 1880
NIN	1 or 2	0.24	1759 Crown Point road; 1837-1872 Tyson Furnace land cleared and heavily cut for charcoal; 1870s medium scale dairy & 5 sheep farm; stone walls and 25 ac possibly tilled field; abandoned about 1950.
PCB	2	0.19	1838-1940 stone walls and cleared improved pasture; dairy farm; no sugar 1880.
SKR	2	0.19	1810-1940 improved pasture with stone wall perhaps some sugarbush; dairy farm, 1000# sugar; abandoned through 1940s
SMB	3	0.26	1810-1960 back pasture & possibly some woodland, dairy farm, 1000# sugar; to state WMA 1971, selective logged since
SQU	4	0.71	1830-1960 farm woodlot on cow farm with 25 sheep; 400# sugar; farm abandoned about 1960 then woodland selectively cut
STE	2	0.38	1799-1950 formerly Sterling Sterling Hollow improved pasture; diversied farm with 130# sugar
STK	1	0.12	1810-1940 improved tillage with plow layer, with stone wall; dairy farm, abandoned through 1940s
STS	1 or 2	0.40	1799-1950 formerly Sterling Sterling Hollow, old field cleared stone piles perhaps tilled?; diversified farm cows & sheep with 300# sugar
WAT	2	0.77	1791-1832 Bristol Ore Bed cleared for mining of iron ore for forge in Bristol; stone walls and barb wire farming pasture 1840-1930; since 1935 Municipal Forest with reservoir
WIL	4	0.64	1850-1940 back woodlot of farm, 1200# sugar; sawmill at summit 1800s; 1939 CCC camp; back woods always woodlot; 1960 State forest, heavily cut since

*1:cultivation; 2: improved pasture; 3:back pasture; 4: farm woodlot; 5: woodland

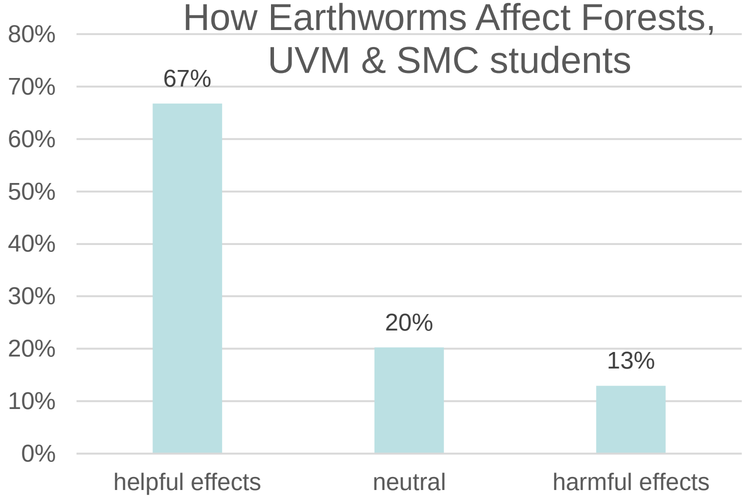
Implications and applications in the Northern Forest region

- Earthworms are found in many of Vermont's forests.
- Sites with the highest worm density and species richness had a history of agricultural land use (although not all former-ag sites had earthworms).
- Highly affected soils had larger pools of microaggregate-protected carbon.
- An endogeic earthworm species, *Aporrectodea tuberculata* rapidly relocated substantial proportions of forest floor carbon into physically and chemically stabilized pools.
- Northern Forest soils are a potential sink for atmospheric carbon and earthworms activity, in the long term, may increase the stability of sequestered carbon.

Potential impacts of earthworms on VT forests is not widely understood

- In a survey of 246 environmental studies students at UVM and St. Micheal's College, 67% thought earthworms had positive impacts on forests, and 13% thought they might have negative impacts.
- After a presentation by a research team member, 99% said they learned something new about the interactions of earthworms and forests, and 70% said they would change their practices based on what they learned.
- These data suggest that greater awareness of worm-forest interactions might inspire action to curb potential impacts.
- Surveys of landowners, composters and resource professionals may be merited.

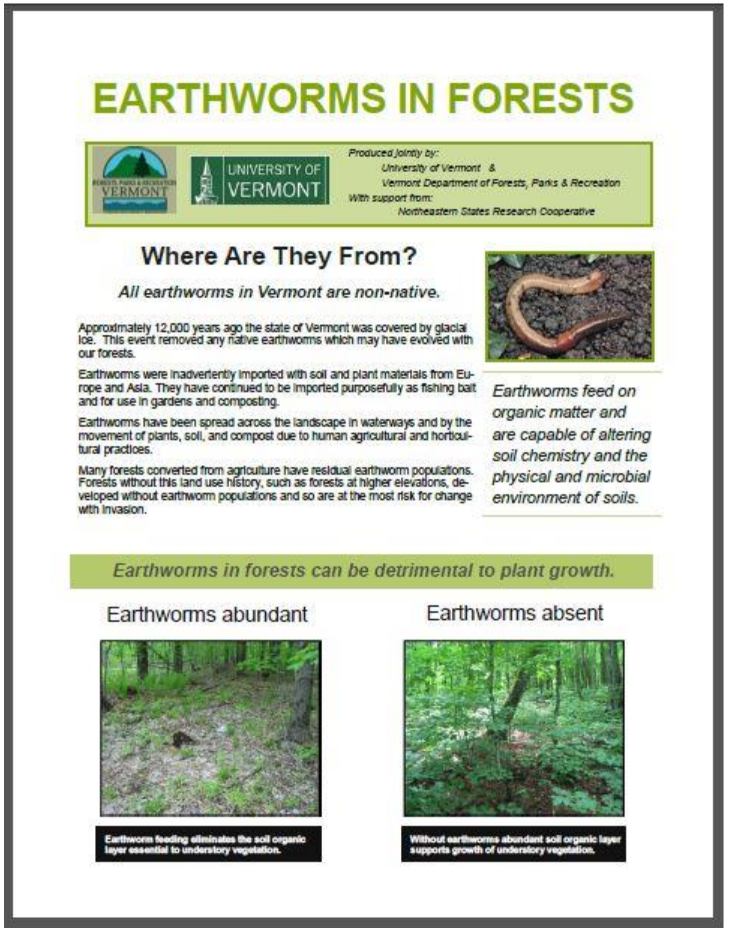
Before presentation by researchers:
How Earthworms Affect Forests, UVM & SMC students



After presentation by researchers:
Students who would change practice or advice to others based on what they just learned about the impacts of earthworms on forests:
70 %

Outreach for landowners and resource professionals

- To inform landowners and resource professionals about the potential impacts of earthworms in Vermont forests, the team created a 6 page outreach pamphlet, highlighting:
  - Impacts of earthworms on the forest floor
  - Basics of forest soil carbon and potential effects of earthworms
  - Summary of research findings
  - Forest management tips
- The pamphlet will be available on UVM and VT FPR websites and advertised via listserves.



EARTHWORMS IN FORESTS

Produced jointly by:
University of Vermont &
Vermont Department of Forests, Parks & Recreation
With support from:
Northeastern States Research Cooperative

Where Are They From?

All earthworms in Vermont are non-native.

Approximately 12,000 years ago the state of Vermont was covered by glacial ice. This event removed any native earthworms which may have evolved with our forests.

Earthworms were inadvertently imported with soil and plant materials from Europe and Asia. They have continued to be imported purposefully as fishing bait and for use in gardens and composting.

Earthworms have been spread across the landscape in waterways and by the movement of plants, soil, and compost due to human agricultural and horticultural practices.

Many forests converted from agriculture have residual earthworm populations. Forests without this land use history, such as forests at higher elevations, developed without earthworm populations and so are at the most risk for change with invasion.

Earthworms feed on organic matter and are capable of altering soil chemistry and the physical and microbial environment of soils.

Earthworms in forests can be detrimental to plant growth.

Earthworms abundant

Earthworm feeding eliminates the soil organic layer essential to understory vegetation.

Earthworms absent

Without earthworms abundant soil organic layer supports growth of understory vegetation.

Future directions

- Not all of the Northern Forest in Vermont is invaded. Effort should be put into protecting ecologically important woodlands. These efforts should include identifying the main vectors into these woodlands and developing best management practices for woodland management.
- Research is needed on the invasion dynamics of *Amynthas* spp., along with the development of best management practices in nurseries to keep horticultural stock free of these earthworms.
- The problem may be further exacerbated by climate change, which will likely expand the range of earthworm invasions to higher elevations that until recently have been worm free.

List of products

- **Peer-reviewed publication**: Reynolds, J. W., Görres, J. H., & Knowles, M. E. (2014). A checklist by counties of earthworms (Oligochaeta: Acanthodrilidae, Lumbricidae and Megascolecidae) in the states of Maine, New Hampshire and Vermont, USA. *Megadrilogica, 17*(9), 125-140.
- **Publication in preparation:** Knowles, M.E., D.S. Ross and J. Gorres. Influence of *Aporrectodea tuberculata* on the carbon, nitrogen, and aggregation properties of a loam forest soil-a mesocosm study. *Soil Biology and Biochemistry.*
- **M.S. Thesis:** Knowles, M.E. 2015. Earthworm presence in northern forests: impact on distribution of soil carbon within aggregate fractions. M.S. thesis, Dept. Plant & Soil Science, Univ. Vermont, 125 pp.
- **Senior Capstone Internship:** Gagne, B. 2015. Are earthworms good for the environment?: a summary of survey data. Senior capstone report, Environmental Program, Univ. Vermont, 18 pp.

List of products (cont.)

- **Presentation:** Knowles, M.E., D.S. Ross and J. Gorres. 2015. Earthworm presence in northern forests: impact on distribution of soil carbon within aggregate fractions. Northeastern Ecosystem Research Cooperative, Saratoga, NY, March.
- **Presentation:** Knowles, M.E., D.S. Ross and J. Gorres. 2013. Earthworm invasion in northern forests: impact on distribution of soil carbon within aggregate fractions. Soil Science Society of America annual meetings, Tampa Bay, November.
- **NSRC webinar:** J. Gorres. Earthworms, hidden agents of forest change. http://www.uvm.edu/~entlab/Greenhouse%20IPM/Workshops/2014/InvasiveEarthworms.pdf
- **University Communications story:** J.E. Brown. Earthworm Invasion. 9/10/2013: http://www.uvm.edu/~uvmpr/?Page=news&storyID=16443
- **Outreach pamphlet**: Wilmot, S., C. Danks, M. Knowles, D. Ross, J. Gorres, C. Cogbill. 2015. Earthworms in Forests. Univ. Vermont and VT Dept. of Forests, Parks and Recreation. 6 pp.