Increasing Soil Organic Carbon on Eroded Hilltops: Build or Borrow?

AGVISE Laboratories Soil Fertility Seminars

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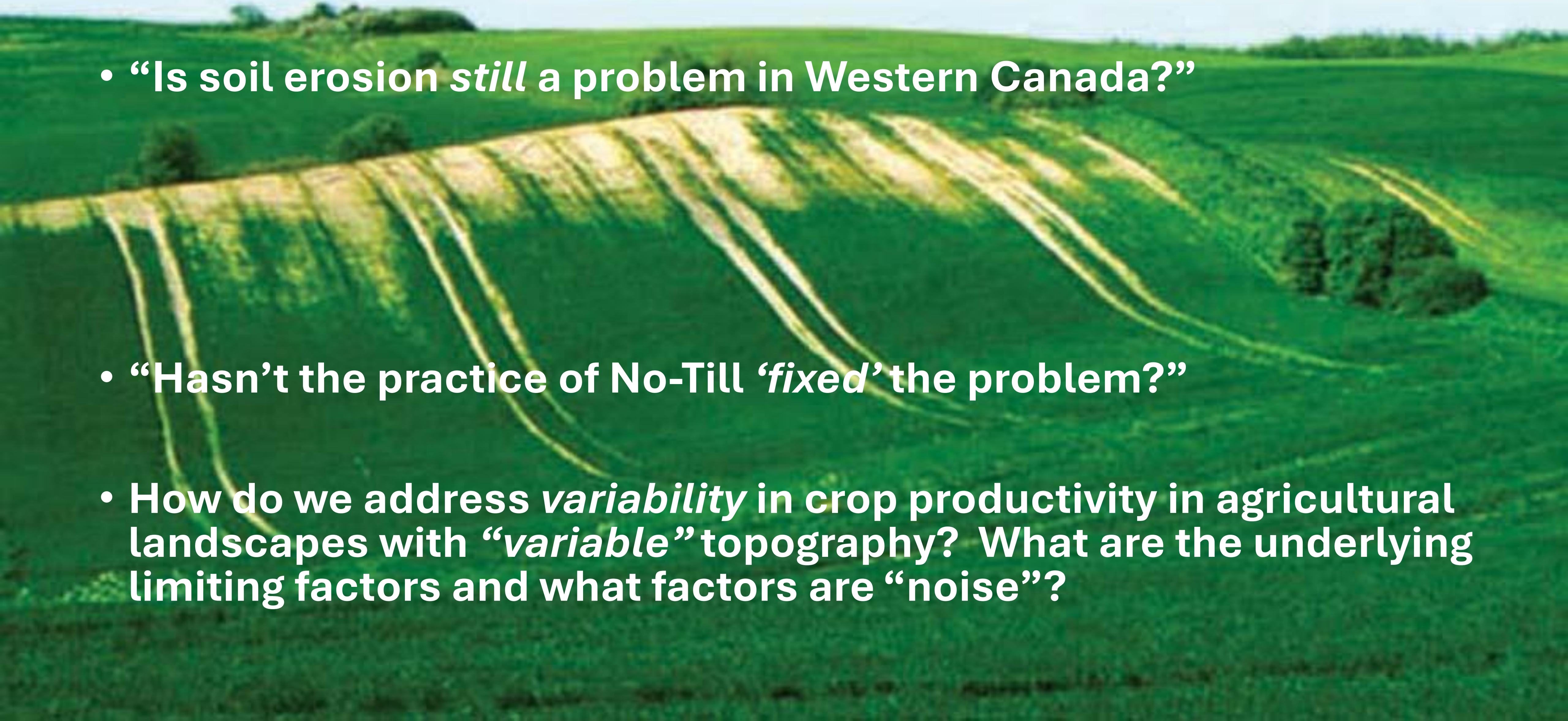
Agriculture and Agri-Food Canada | Agriculture et Agroalimentaire Canada

University of Manitoba

Part 1:
Eroded Hilltops
– how to identify and how best to manage them…

Introduction (How this study began)



- **“Is soil erosion *still* a problem in Western Canada?”**
- **“Hasn’t the practice of No-Till *‘fixed’* the problem?”**
- **How do we address *variability* in crop productivity in agricultural landscapes with *“variable”* topography? What are the underlying limiting factors and what factors are “noise”?**

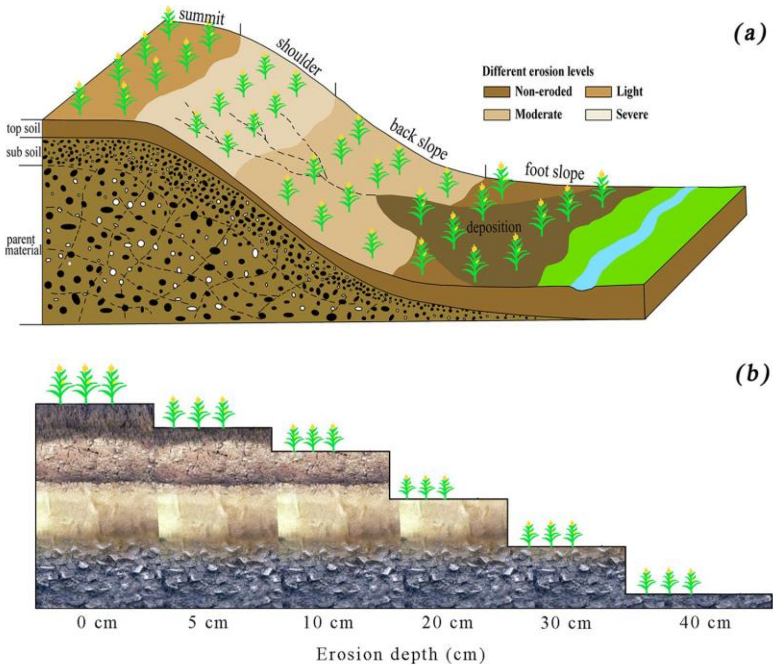
Hilltops
aka: knolls, uplands, crests, summits, plateaus, etc.

- **Highest elevations**
- **Convex slope curvature (runoff key characteristic)**
- **Droughty**
- **Erosion prone: wind, water, tillage**

- **Soils: thin/missing topsoil; low SOM; low SOC/high IC; poor seedbed**
- **Low fertility? (Not necessarily…)**

Problem – How to Track Soil that has gone "missing"???

- Clues:
  - Soil survey info
  - Visual clues (color, etc.)
  - Yield maps



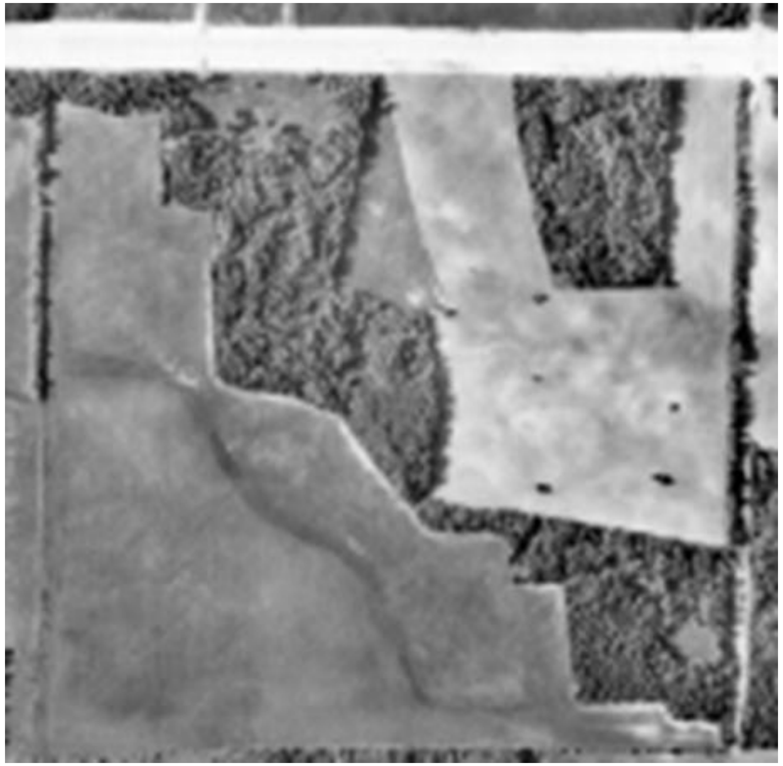
- ^{137}Cs analyses (measure)

- Rule of Thumb (Zhang et al, 2021): erosion concerns if:
  - current thickness of A horizon is < 25 cm; (mixing with subsoil?)
  - "erosion depth" > 5 cm (esp. > 20 cm)

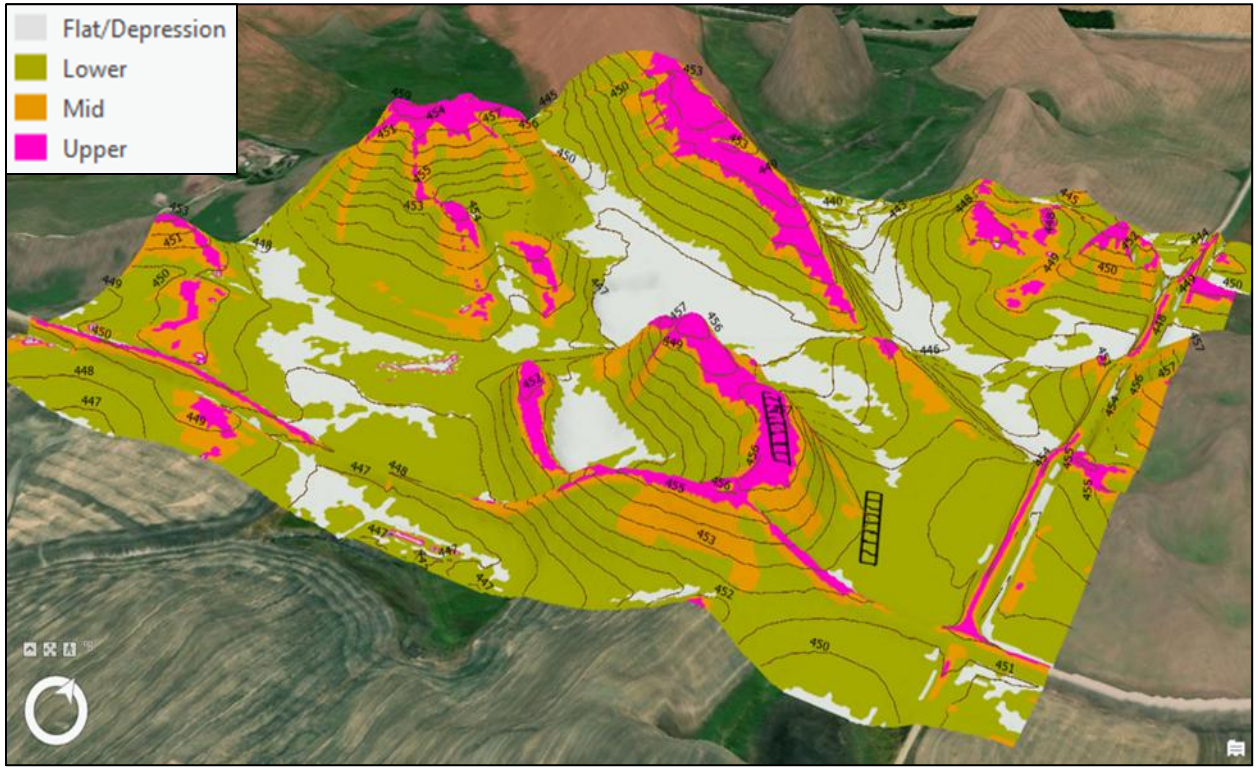
Soil Survey Information (Background)

Site	Altamont		Bruxelles		Manitou	
Position	Upper Slope	Lower Slope	Upper Slope	Lower Slope	Upper Slope	Lower Slope
Soil Series	Poyser (OGL)	Tellier (Gl DGC)	Vandal (ODGC)	Dezwood (ODGC)	Fifere (ODGC)	Guerra (RHG)
Texture	CL	CL / L	L / GrS	CL	L	L / SiCL
Drainage	Well	Imperfect	Rapid	Well	Well	Poor
Ag. Capability	2T	2W	3MT	2X	2T	3W
Water Holding Capacity	Medium	Medium	Low	Medium	Low	Medium
Slope	5 – 9%	0 – 0.5%	9 – 15%	2 – 5%	2 – 5%	0 – 0.5%
% of Landbase	15	12	9	35	10	82
Notes from report (clues)	Moderately eroded		Moderately eroded		Subject to erosion	

What eroded hilltops look like...



Aerial image (1958)



Terrain Maps (Lidar data)

Surface of upland

Soil profile of upland

Upland Soils – Characteristics

- Texture: variable
- Drainage: well/moderately well (dominantly runoff vs infiltration)
- Agriculture Capability limitations: E (eroded)
  M (lack of moisture, droughty)
  T (topography) – slopes
- Weedy: poor crop competition;
  poor herbicide efficacy/breakdown
- What they are NOT: wet, saline, compacted

Topsoil: The Secret Ingredient

- Organic Carbon (OC) (Bullock & Kravchenko) – the “hero”
- versus

Inorganic Carbon (IC) (Schneider et al)

– the “villain”

The Dominant Erosion Pathway: Tillage Erosion

- The Good News:
  - Not the entire field (usually)
  - Little soil has left the field (redistribution)
  - Reversible

Confirm degree of tillage erosion using ^{137}Cs analysis

- The Bad News:

- Many don’t believe it is real!!!
- Tillage is: a necessary evil or a tool that needs enhanced management (or elimination)?
- It’s not so much the *type* of tillage equipment, it’s how you use it...

Restoring Productivity on Eroded Hilltops – Options

1. Increase cropping inputs
2. Increase water supply
3. Redistribute crop residues
4. Add livestock manures/compost
5. Add other organic amendments
6. Plant cover crops
7. Add topsoil from downslope

1. Increase Cropping Inputs

a. Add more fertilizer

- Kapoor & Shaykewich (1987):

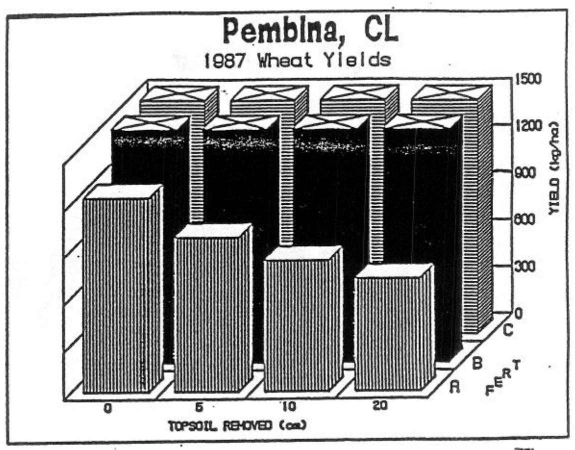


Figure 1. Effect of topsoil removal and fertilizer applications on wheat yields grown on a Pembina clay loam.

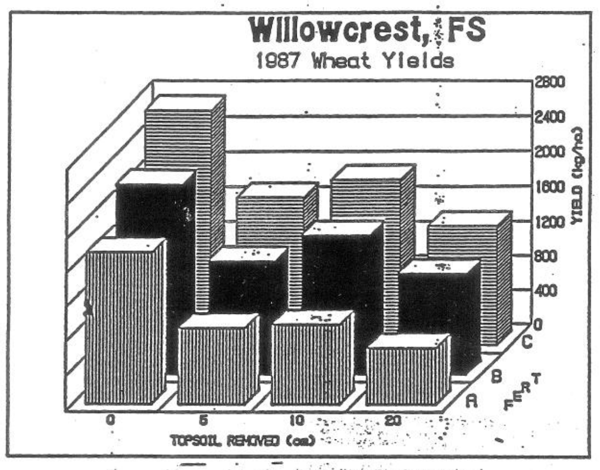


Figure 3. Effect of topsoil removal and fertilizer applications on wheat yields grown on a Willowcrest fine sand.

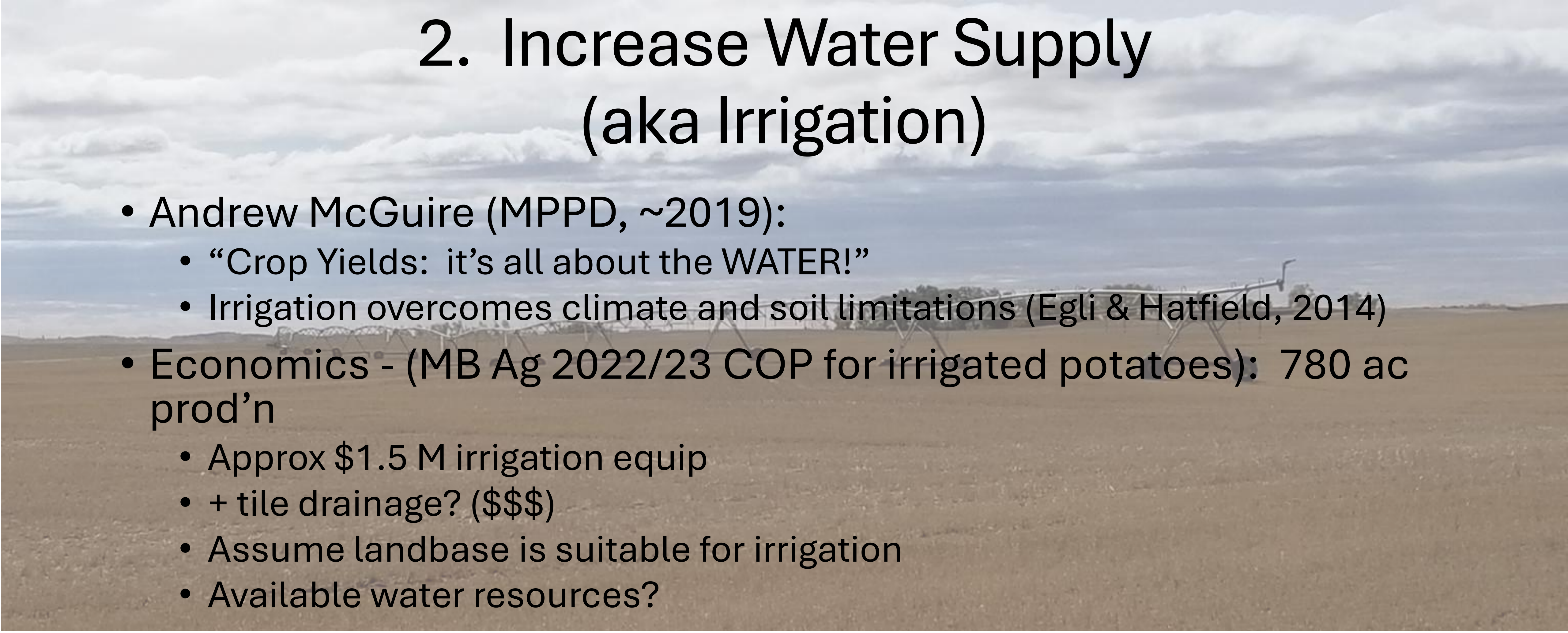
b. Increase seeding rates

- Gyssels et al (Belgium)

- Cavers (2022/23 demos):

Wheat (bu/ac)	Portage (level)	Altamont (eroded knoll)	
Check	70	Check	11
2X seed	55	2X seed	17
2X fert	72	+ topsoil	15
2X seed + fert	49	2X seed+ topsoil	20

c. Strategic Planting ("Crop the Best, Diversify the Rest")



2. Increase Water Supply (aka Irrigation)

- Andrew McGuire (MPPD, ~2019):
  - “Crop Yields: it’s all about the WATER!”
  - Irrigation overcomes climate and soil limitations (Egli & Hatfield, 2014)
- Economics - (MB Ag 2022/23 COP for irrigated potatoes): 780 ac prod’n
  - Approx $1.5 M irrigation equip
  - + tile drainage? ($$$)
  - Assume landbase is suitable for irrigation
  - Available water resources?

- McGuire: Maximize photosynthesis; minimize tillage…

3. Redistribute Crop Residues

- Relatively cheap, easy; available resource (Duane Thompson - SK)
  - Reduce evaporation & runoff, conserve moisture
- Cavers 2023 demo:

Altamont 2023 (eroded knoll)	Wheat yield (bu/ac)
Control	11
Added straw	9
Added topsoil	15
Added topsoil + straw	13

- Chaff >> straw
- Weed management?
- Heavy harrows → tillage… (***not*** no-till, technically) – Dwayne Beck - SD
- Livestock Integration (Bale Grazing)

4. Add Livestock Manure/Compost

- Livestock Integration (Bale Grazing)
- Availability?
- Nutrient over-applications (regulations)
- Odour

- Larney: "legacy effects"
- Lobb/Beauchamp: How long to increase SOM by 1% (10 g kg^{-1}) (using beef manure annually @ P rates)?

30 years!!!

5. Add (Other) Organic Amendments

- Examples include: biochar, biosolids, paper mill by-products, etc

- Larney and Angers (2012): considerations (like manure mgmt.)
  - readily-decomposable vs. stable (C:N ratio)
  - waste vs resource
  - large single application vs cumulative loading

- Cost? Effectiveness? Buyer beware…

6. Plant Cover Crops

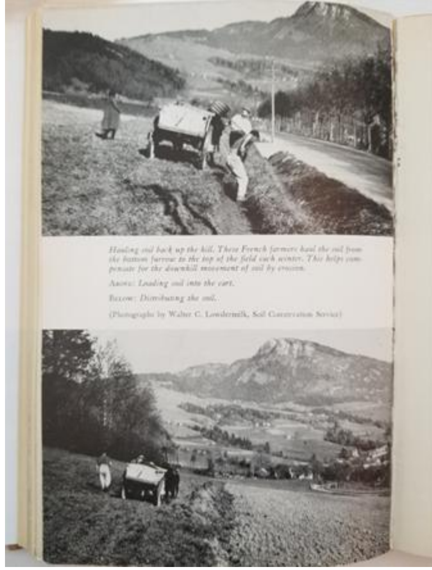
- Lawley, Morrison, etc: numerous benefits, but:

- Difficult to establish on eroded hilltops under dry conditions
  - Less biomass – less C sequestered
  - LT forages better?
  - Economics vs annual cropping…

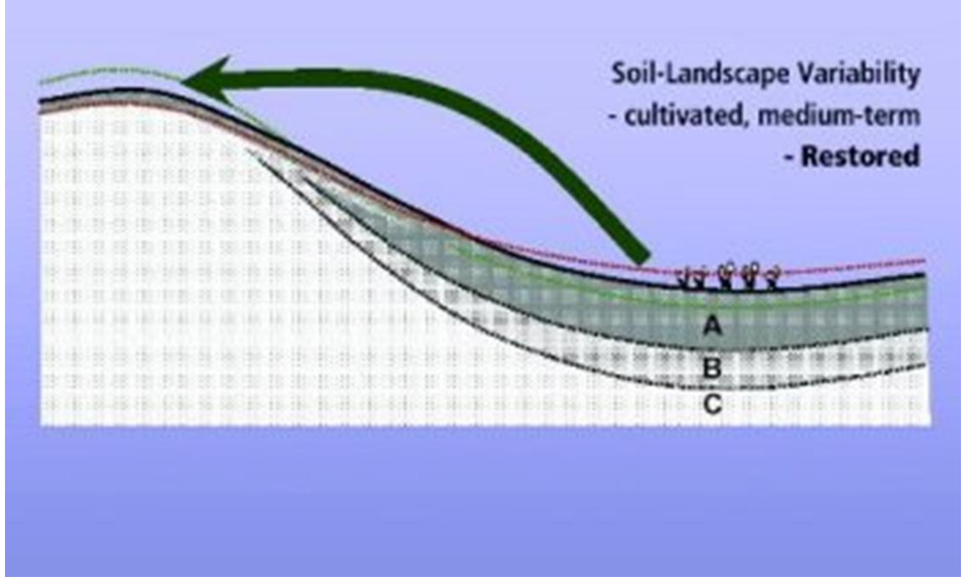
- Cover crops can deplete soil of moisture needed by the upcoming cash crop (a problem if moisture is limiting)

7. Soil Landscape Restoration (SLR)

(Adding Topsoil (back) to Eroded Hilltops from Downslope)



- An immediate increase in SOC
  (not true "sequestration", but sets stage for the future)
  - *"It is important to consider redistributing SOM-rich topsoil rather than trying to increase it in-situ."* (McGuire, 2023)
- "One-time" practice, if done "right"…



Restoring Productivity on Eroded Hilltops - Summary

Management Practice	Pros	Cons
1. Increase seed, fertilizer rates	Easy	Cost; effectiveness (short term)
2. Irrigation	Effective	Cost; availability
3. Re-distribute Crop Residues	Soil/weed mgmt benefits; easy	Additional time, equipment
4. Manure/Compost	Builds SOM, nutrient source	Availability
5. Organic Amendments	Numerous products; claims (?)	Effectiveness
6. Cover Crops	Numerous benefits	Establishment; competition
7. Soil Landscape Restoration	Fast; effective; consistent (?)	Still refining protocols; data...

This study examines the effects of Practice #7 further...

Part 2:
Using Soil Landscape Restoration to Improve Soil Health and Crop Productivity:
quantification of results…

Background Information

- Eroded Hilltops are consistently the lowest-yielding areas of a given field, especially in years of low-normal rainfall – but typically occupy 10-30% of the landscape
- Relative productivity: 30-50% of yields compared to midslope/depression
  - Goal: 80% (F. Zvomuya)
- "Isn't it enough to practice No-Till"? (R. Stevenson & others: No!)
  - <u>2 reasons:</u>

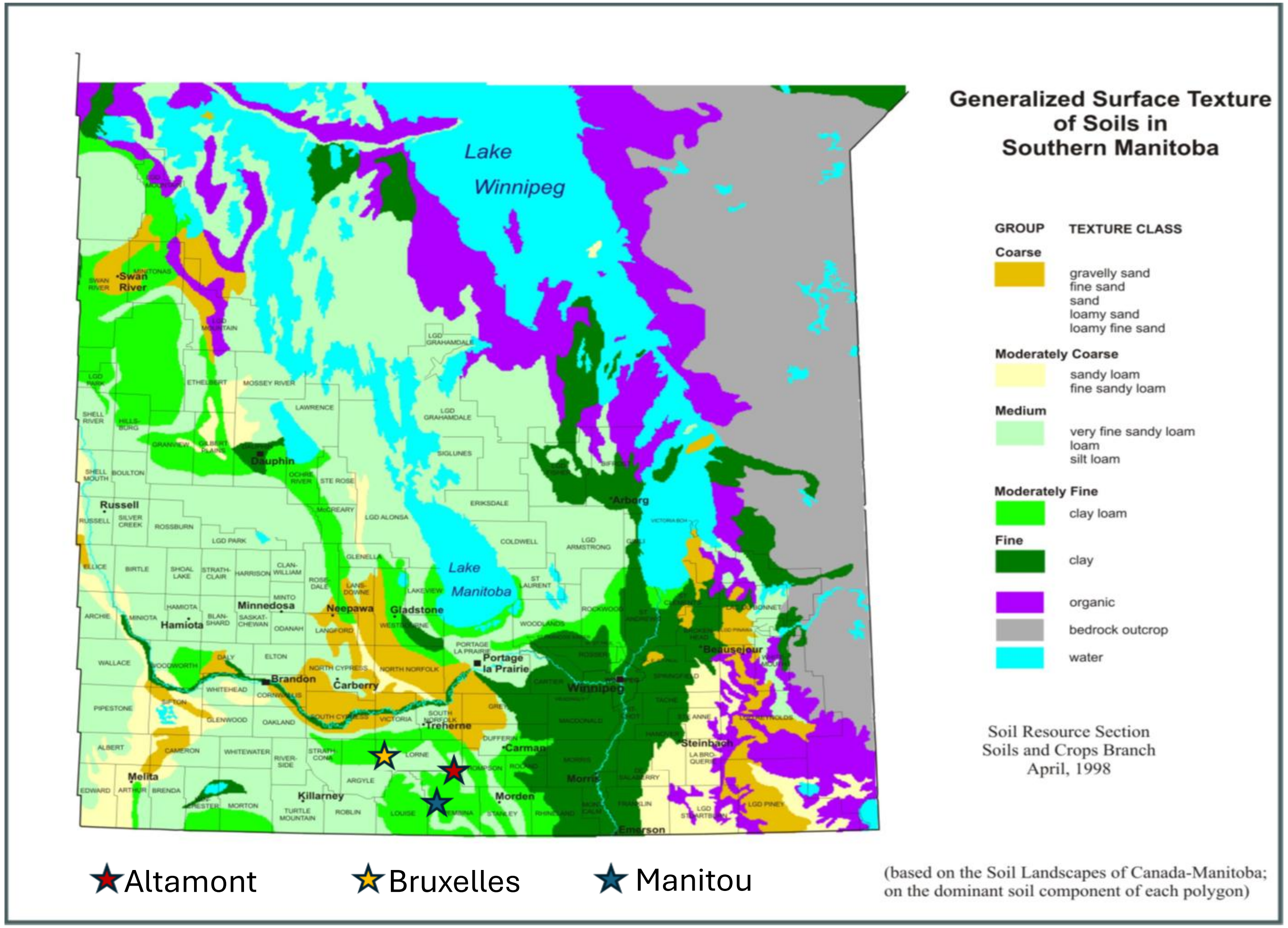
1) SOIL FORMATION IS A VERY SLOW PROCESS, EVEN UNDER NO-TILL… not years – decades/centuries! (Pimentel et al, 1976)

2) Tillage Erosion – even from non-primary tillage equipment – is continuing to increase in-field variability and reduce productivity! (Lobb and others)

Objectives

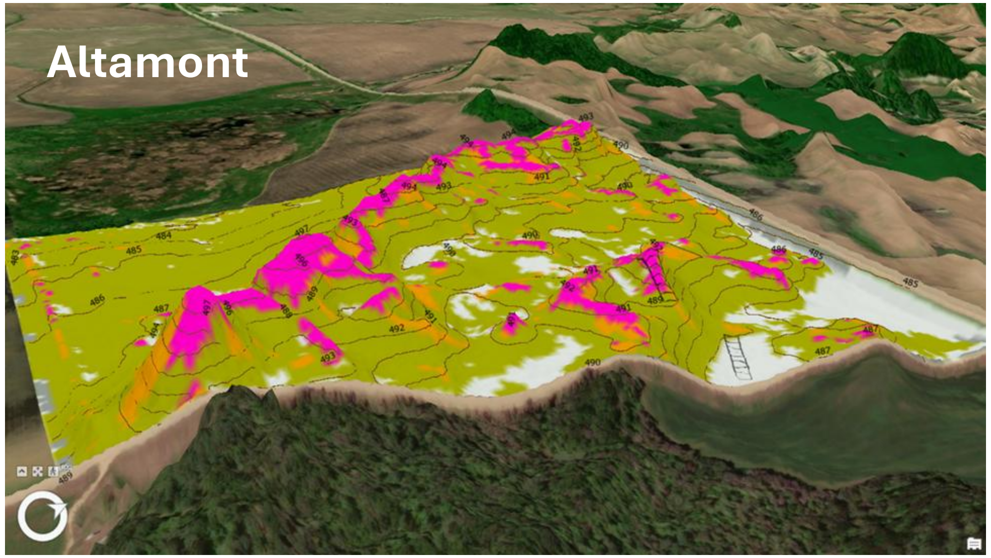
1. Identify areas suitable for soil landscape restoration and document their responses over time
2. Measure changes in soil properties
3. Measure changes in crop growth, performance and productivity

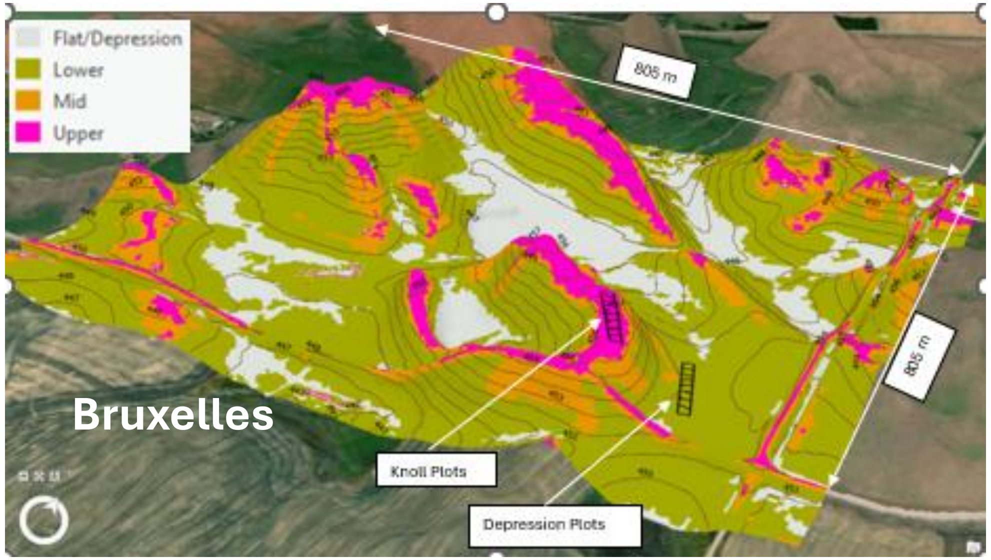
***Is soil landscape restoration a reliable/beneficial practice that should be adopted by producers and scaled up over several agricultural landscapes???

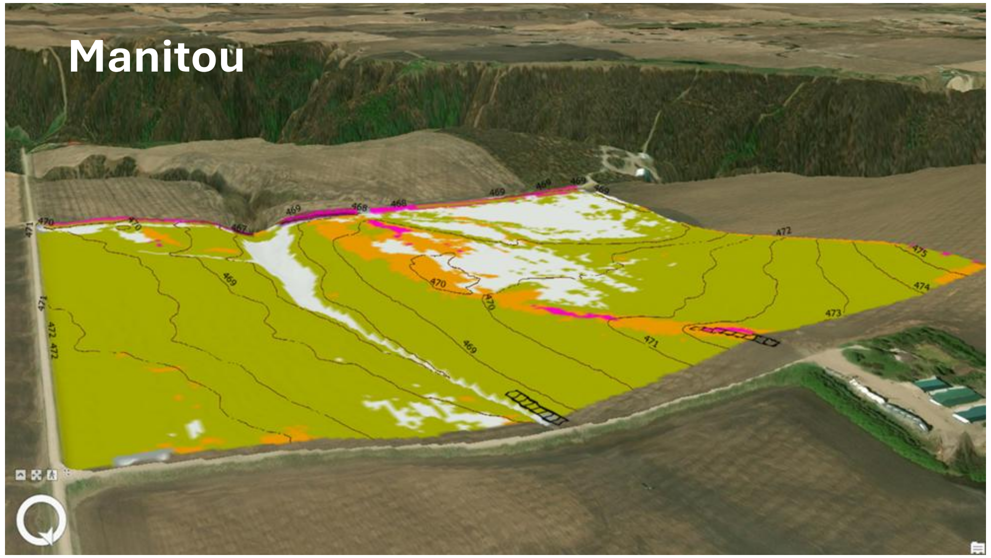


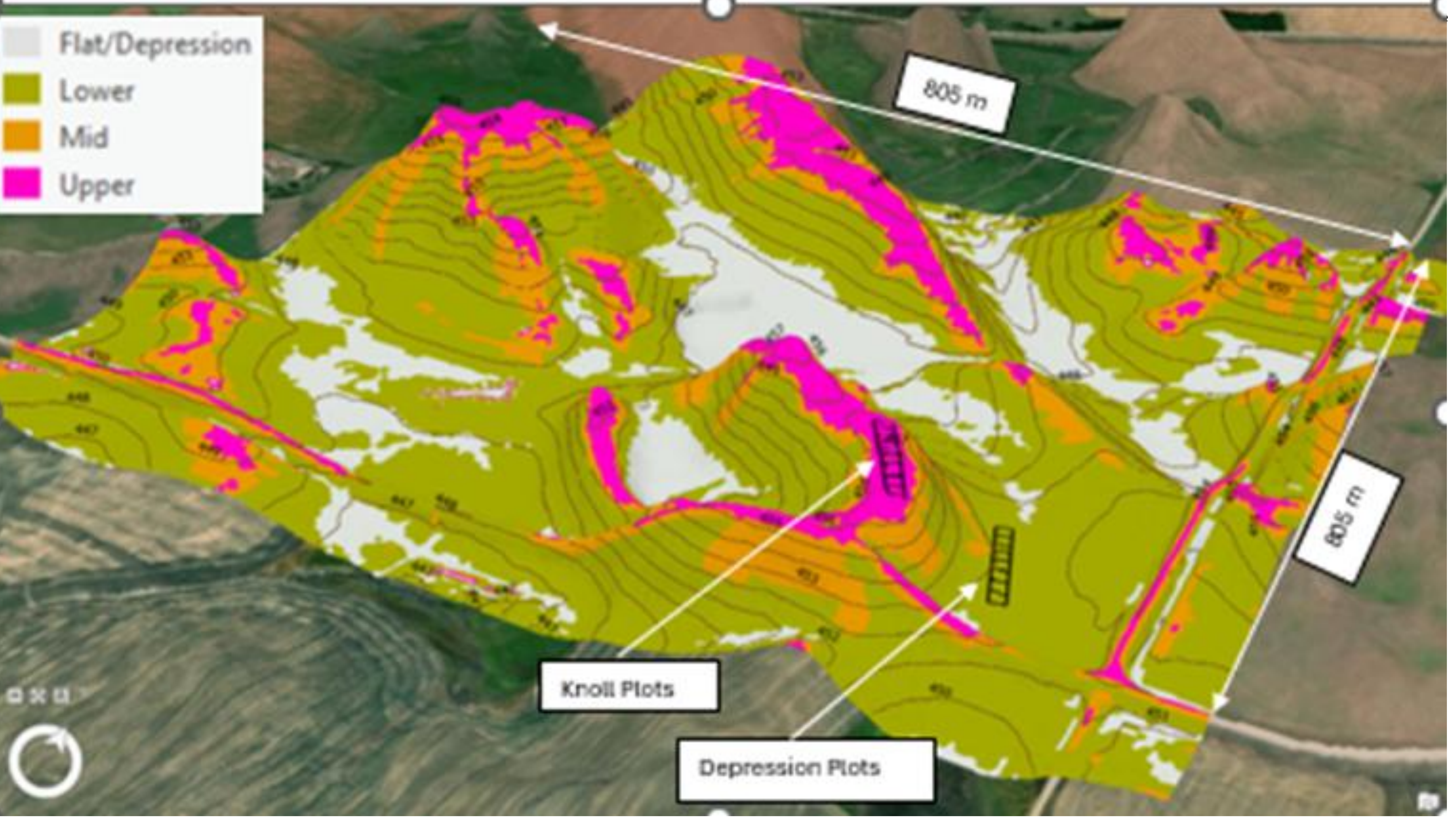
Site Landforms / Plot Locations

- Vertical Exaggeration 10 X
- Upper slopes occupy 9-15% of their respective landscapes
- Note relative location/distance between knoll and depression plots (50 – 150 m)





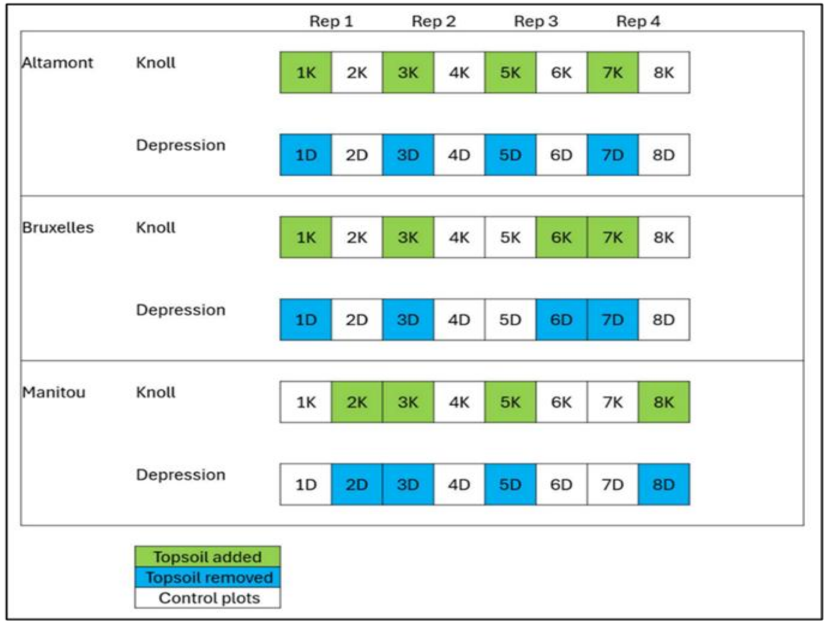




Flat/Depression
Lower
Mid
Upper
805 m
805 m
Knoll Plots
Depression Plots

Experimental design

	Altamont		Bruxelles		Manitou	
Important factors	Knoll	Depression	Knoll	Depression	Knoll	Depression
Texture	CL	CL / L	L / GrS	CL	L	L / SiCL
Water Holding Capacity	Medium	Medium	Low	Medium	Low	Medium
Notes from report	Moderately eroded		Moderately eroded		Subject to erosion	

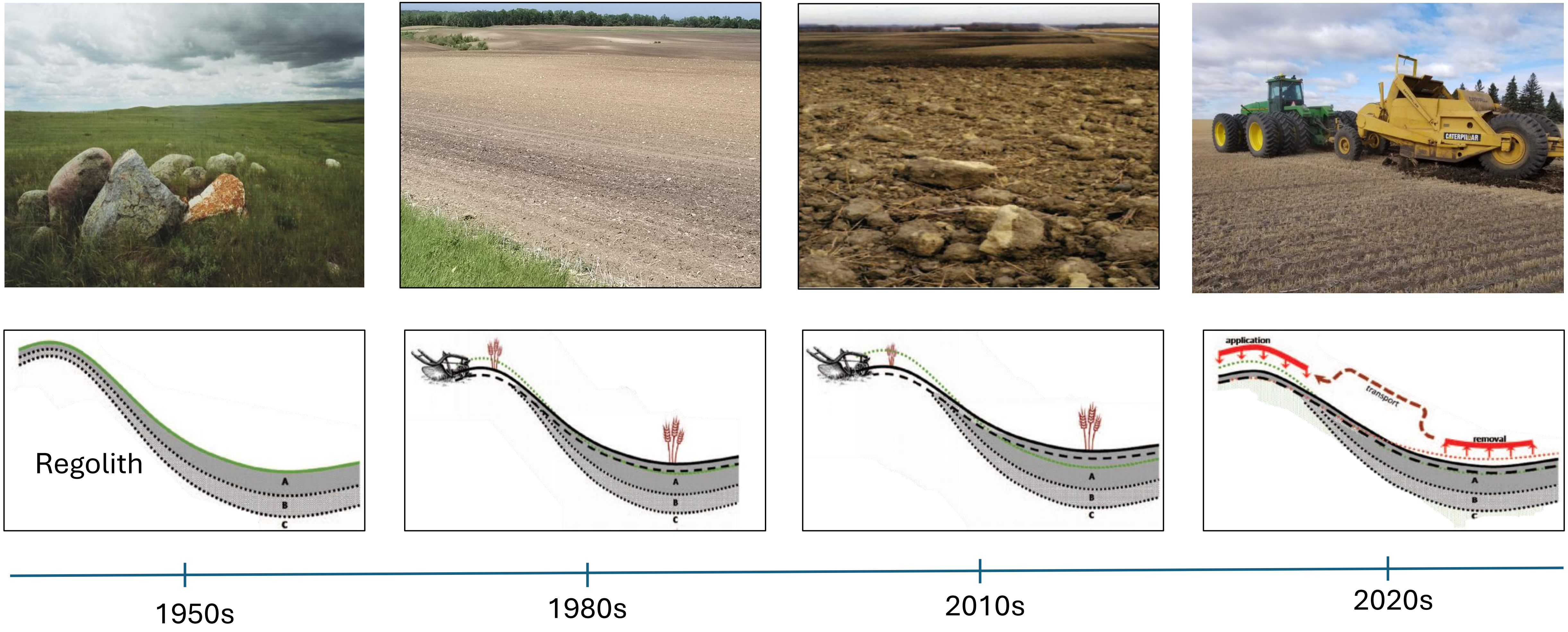


Plot layout of each site

Topsoil removed from depression
(Bruxelles, 2020)

Topsoil added to knoll
(Bruxelles, 2020)

^{137}Cs technique for evaluation of erosion and deposition rates



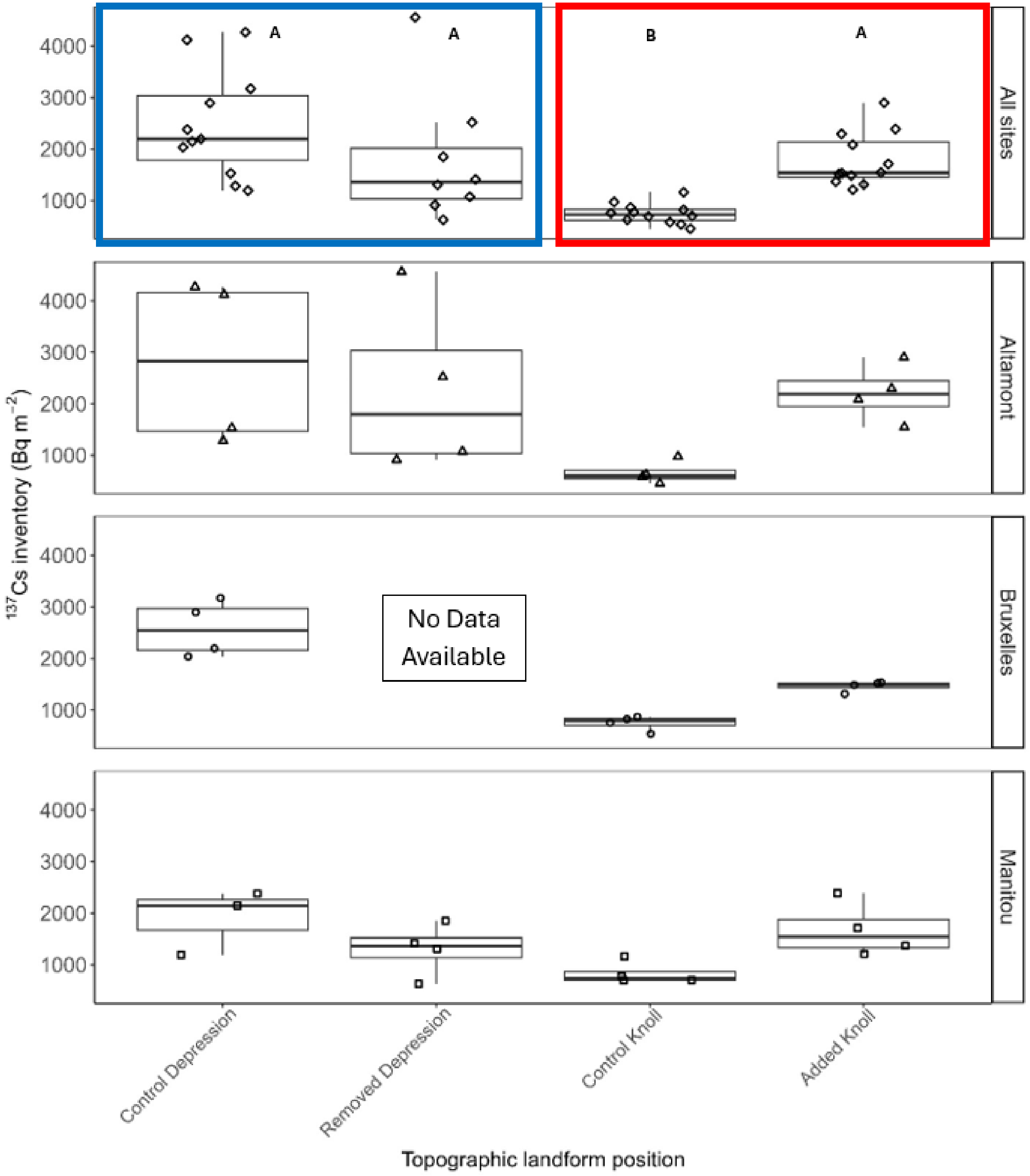
Application of ^{137}Cs in identifying temporal changes of soil loss and accumulation

^{137}Cs Inventories

Treatment effect *P* < 0.0001

- Removing topsoil from depressions did not significantly reduce ^{137}Cs inventories (i.e., did not remove enough topsoil to damage these areas)

- Adding topsoil to knolls increased ^{137}Cs inventories, not significantly different from those found in depressions (i.e., "restored")

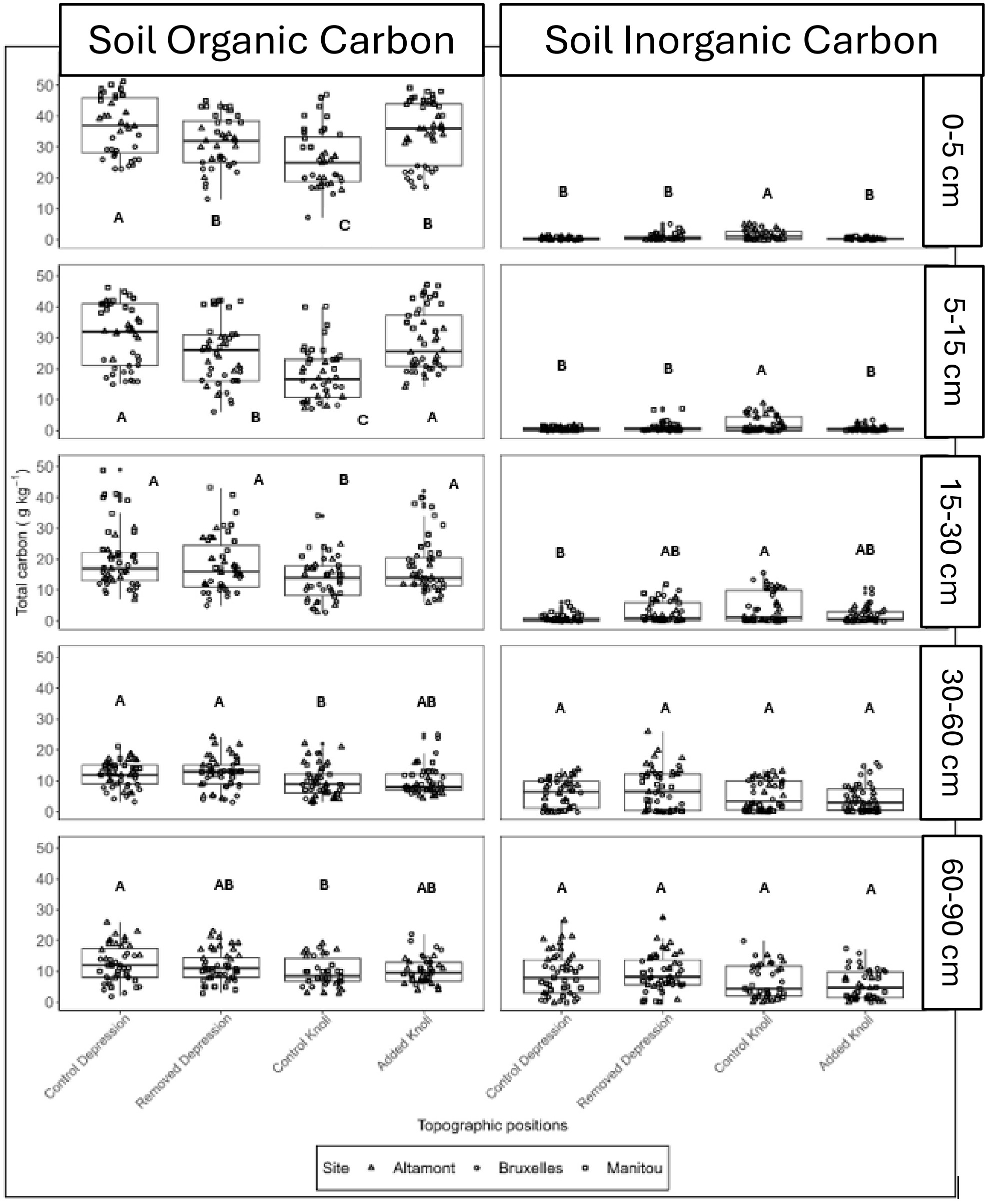


Rates of Soil Erosion (Mass Balance Model-2 and ^{137}Cs data)

- "Moderately eroded" = 11-22 Mg ha^{-1} yr^{-1} (Badreldin and Lobb, 2023)
- Point-based vs area-based erosion estimates
- High erosion rates + higher deposition rates → tillage erosion

Site	Landscape Position	Cs-based soil erosion rates (Mg ha^{-1} yr^{-1}) since approx 1960 (^{137}Cs inventories in parentheses; reference value used = 1500 Bq m^{-2})					
		Transect 1	Transect 2	Transect 3	Transect 4	Mean	Interpretation
Altamont	Hilltop	21.3 (626)	23.1 (583)	29.5 (453)	10.4 (974)	21.1	moderate
	Depression	-66.8 (4269)	3.7 (1283)	-73.2 (4118)	-0.6 (1530)	-34.2	
Bruxelles	Hilltop	13.2 (867)	14.4 (824)	16.6 (756)	25.1 (537)	17.3	moderate
	Depression	-28.8 (2896)	-14.7 (2197)	-11.8 (2036)	-43.3 (3173)	-24.7	
Manitou	Hilltop	6.1 (1162)	18.4 (703)	16.0 (774)	18.6 (696)	14.8	moderate
	Depression	-11.5 (2148)	-20.1 (2379)	5.5 (595)	-9.3 (1907)	-8.9	

Carbon Concentrations by Depth

Site × Treatment			Treatment effect
$P = 0.0069$		0-2”	$P < 0.0001$
$P = 0.0062$		2-6”	$P < 0.0001$
$P = 0.3201$*		6-12”	$P = 0.0295$
$P = 0.0050$		12-24”	$P = 0.0301$
$P < 0.0001$		24-36”	$P = 0.1890$

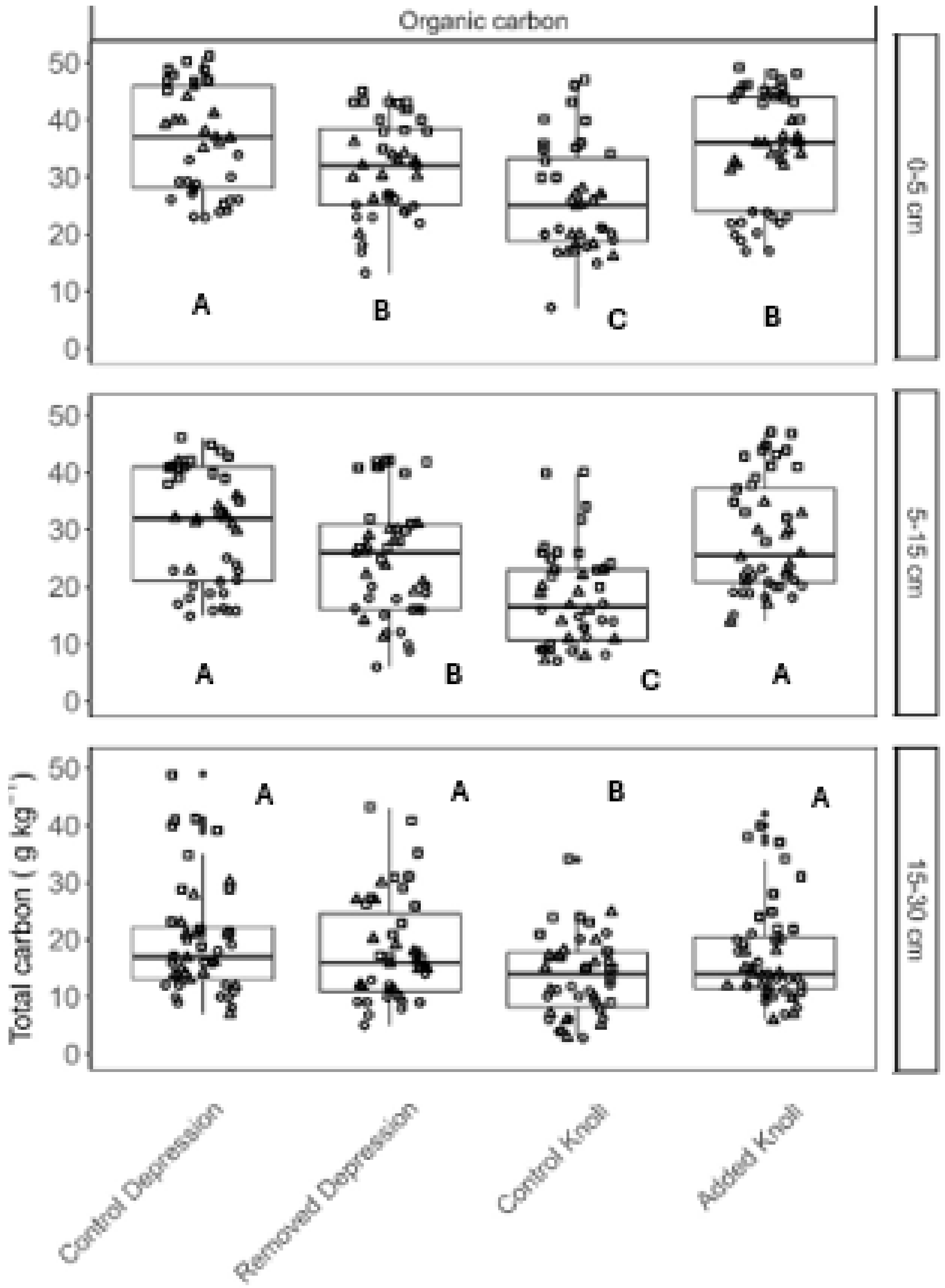
*Treatment effects and site effects significant at all depths

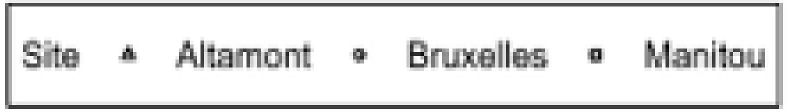
Soil Organic Carbon

- Significant site effect ($P < 0.0001$):
  Manitou > Altamont > Bruxelles

- Significant treatment effect ($P < 0.0001$) at all three depths

  - The distribution of SOC concentrations throughout the soil profile may influence stocks once soil landscape restoration has occurred



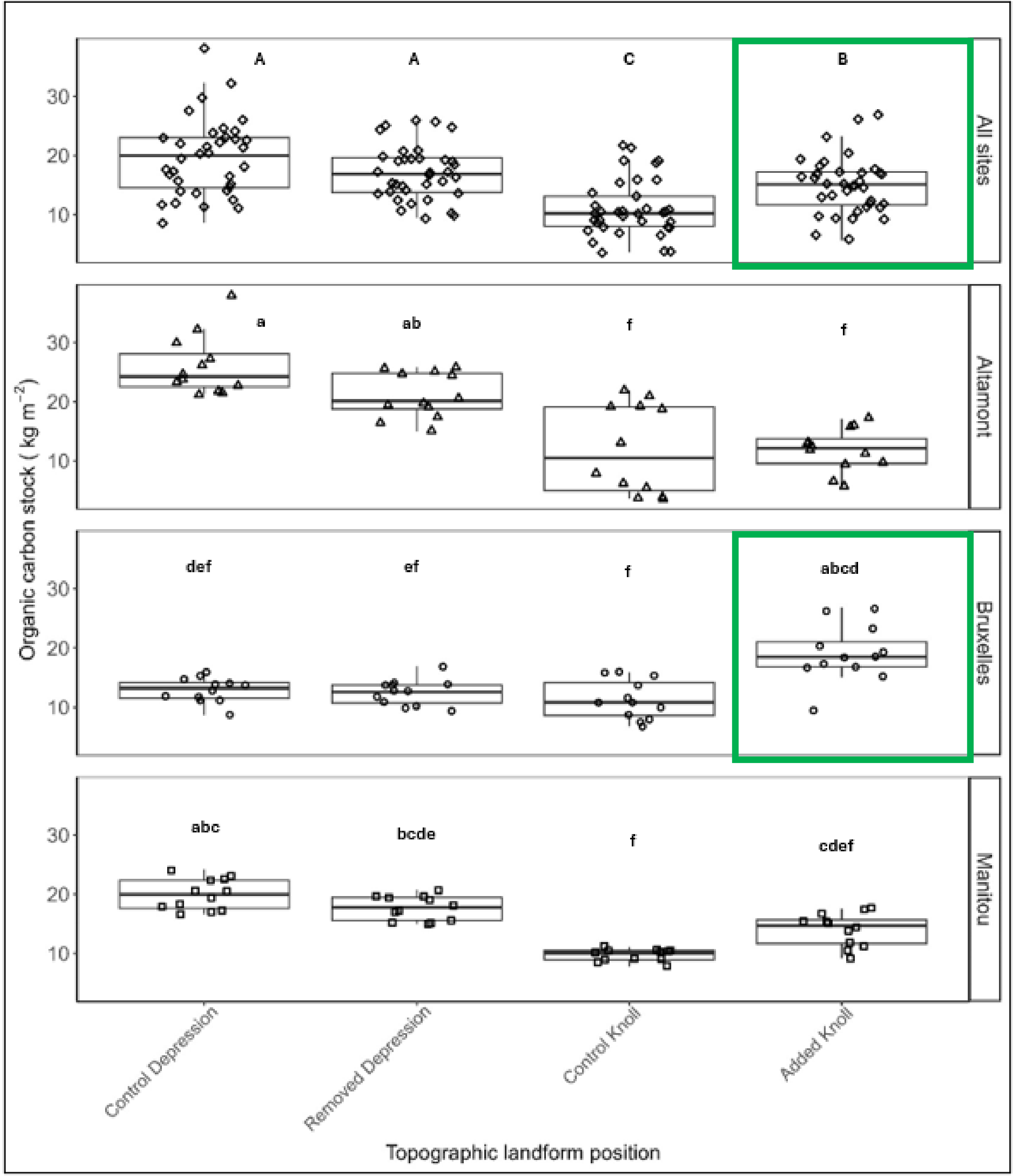


SOC Stocks

Site effect	$P = 0.0370$
Treatment effect	$P < 0.0001$
Site × Treatment	$P < 0.0001$

Soil Carbon Stock (kg C m^{-2})
= Soil Carbon Concentration (g C kg^{-1}) ×
Bulk Density (g cm^{-3}) × Soil Layer Thickness
(cm) × 10

1 Mg ha^{-1} = 0.1 kg m^{-2}



Comparing changes in C status...

- Comparing research on the effect of *adding* C by re-distributing topsoil (not *sequestering* C...)
- More severely eroded sites likely to respond faster (limited tracking in short term studies)
- Yield responses may/may not be impressive when compared with actual values...

Research	Increase in SOC concentration @ 0-15 cm depth	Increase in SOC stocks - % (sequestration rate)	Increase in Crop Yield
SLR - Schneider et al (2021) – MN (one site X 6 years)	**2.8 ×** From 12 to 35 g kg^{-1}		Corn: 21-53% Soybean: 12-59%
SLR - Smith and Lobb (2008) – MB (4 sites X 2 years)	**2.1 ×** From 13 to 27 g kg^{-1}		Various sites and crops: 10-133%
SLR – Cavers et al (2026) - MB (3 sites X 4 years) - 4/12 crop response	**1.9 ×** From 19 to 29 g kg^{-1}	**36%** From 110,000 to 150,000 kg C ha^{-1}	Canola: 21-47% Oat: 50% Wheat: 58%

Comparisons...where possible

Research	Increase in SOM concentration (%) @ 0-6" depth	Increase in SOC stocks - % (sequestration rate)	Increase in Crop Yield
SLR - Schneider et al (2021) – MN (one site X 6 years)	**112%** From 29 to 62 g kg^{-1}		Corn: 21-53% Soybean: 12-59%
SLR - Smith and Lobb (2008) – MB (4 sites X 2 years)	**108%** From 22 to 46 g kg^{-1}		Various sites and crops: 10-133%
SLR – Cavers et al (2025) - MB **(3 sites X 4 years) - 4/12 response**	**53%** From 33 to 50 g kg^{-1}	**36%** From 110,000 to 150,000 kg C ha^{-1}	Canola: 21-47% Oat: 50% Wheat: 58%
LSR – Erb and Lobb (2005) – MB (one site X 2 years)	**31%** From 58 to 76 g kg^{-1}		Flax: 18% Pea: 67%
No-Till for 21 years - SK (Schoenau* and Hangs, 2020)	**25%**	220-454 kg C ha^{-1} yr^{-1}	
Multiple beef manure app's (Larney and Olson, 2018) - AB	**19%** From 25 to 30 g kg^{-1}		
Cover crops for > 5 years (Peng et al, 2023) - N. America	**8%**	**7%** 240 kg C ha^{-1} yr^{-1}	
Permanent grass seed-down for 8 years (Nelson et al*, 2008) - SK		1400 – 2900 kg C ha^{-1} yr^{-1}	N/A

Other Soil Factors

A. Bulk Density (2023 samples):

- Higher BD on hilltops than depression (2 sites); BD increases with depth

B. Wet Aggregate Stability:

- Site effect (Altamont); treatment effect (% WSA reduced with topsoil removal)

C. Saturated Hydraulic Conductivity:

- No significant effects (variability too high for sample size)

D. Soil pH:

- Site, Site × Treatment effects at all depths (lower pH at Manitou)

E. Soil Electrical Conductivity:

- All sites and treatments non-saline except few outliers in Manitou depression

Available Water Holding Capacity (AWHC)

From field plots (Study #2, 2021):

Site (0-5 cm)	Knoll	Depression
Altamont	14.9%	16.4%
Bruxelles	12.9%	15.9%
Manitou	16.5%	16.3%

From soil columns (Study #3, 2024):

Site (0-30 cm)	Knoll	Depression
Altamont	63.9 mm	64.3 mm
Bruxelles	33.0 mm	50.1 mm
Manitou	44.4 mm	50.2 mm

Site-specific outcomes from moving topsoil from depression to knoll:

Altamont/Manitou: little to no change in AWHC

Bruxelles: larger increase in AWHC

Total Biomass (crop + weeds), kg ha^{-1}

Site Year	Crop	Control Depression (CD)	Removed Depression (RD)	% Change	Control Knoll (CK)	Added Knoll (AK)	% Change	CK÷CD %	AK÷RD %
				Altamont					
2021	Wheat	4400	2400	- 45*	7700	9400	+22*	175	392
2022	Canola	11600	10900	-6	8700	9100	+5	75	83
2023	Wheat	3900	4600	+18	3000	2900	-3	77	63
2024	Canola	4500	2500	-44*	5100	4000	-22	113	160
				Bruxelles					
2021	Wheat	6200	6300	+2	2900	4200	+45	47	67
2022	Oat	6800	7500	+10	4000	3900	-3	59	52
2023	Canola	8600	6500	-24	3700	3600	-3	43	55
2024	Wheat	12700	11000	-13	7100	10100	+42*	56	92
				Manitou					
2021	Canola	9200	8900	-3	1300	1000	-23	14	11
2022	Soybean	6700	6300	-6	1800	2100	+17	27	33
2023	Wheat	6300	5900	-6	2400	2400	0	38	41
2024	Canola	7700	8000	+4	7100	7200	+1	92	90

**P* (site × treatment × year) = 0.0001

Crop Yields (bu ac^{-1}) by site and treatment. (* = significant at α = 0.05)

Altamont		A	B		C	D		Relative Yield	
Year	Crop	Control Depression	Removed Depression	% Change	Control Knoll	Added Knoll	% Change	C/A %	D/B %
2021	Wheat	54	35	- 35*	13	12	-8	24	34
2022	Canola	11	1	-90*	28	34	+21*	255	340
2023	Wheat	22	19	-14	13	15	+15	59	79
2024	Canola	20	5	-75*	21	22	+5	105	440

Bruxelles									
2021	Wheat	55	39	-29*	24	17	-29	44	44
2022	Oat	116	102	-12	64	96	+50*	55	94
2023	Canola	36	35	-3	19	28	+47*	53	80
2024	Wheat	83	70	-16	40	63	+58*	48	90

Manitou									
2021	Canola	20	26	+30	0.7	0.7	0	0	0
2022	Soybean	59	58	-2	14	17	+21	24	29
2023	Wheat	49	44	-10	15	18	+20	31	41
2024	Canola	45	42	-7	35	33	-6	78	79

Overall Conclusions

- Study #1: ***SOC stocks increase*** due to SLR: none at Altamont, slight at Manitou, significant at Bruxelles
- Study #2: ***crop yield increase*** due to SLR: none at Manitou, variable at Altamont, significant at Bruxelles
- Study #3: ***AWHC increases*** due to SLR: none/slight at Altamont and Manitou, larger at Bruxelles

- **Therefore, SLR is an effective practice at *responsive* sites; additional management practices may be required to induce positive responses at *other* sites…**

Future Strategies

1. ***Take soil samples, check records to determine if you are dealing with a responsive site!***
2. ***<u>Borrow</u> topsoil from where you can spare it; put it where where it is needed most!***
3. ***Minimize future tillage erosion via No-Till or very strategic tillage (type, speed, direction, frequency) – "4R Tillage" - ???***

- "Fix the foundation before you re-model the house…!"

4. Build topsoil long-term through minimizing tillage; maximizing crop residue returns; moisture conservation; other recommended practices such as:

4R Nutrient Mgmt, diverse/intense crop rotations, IPM, etc…

Acknowledgements

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- Stephen Crittenden, Sharon Schneider, Rob Gulden, Alan Moulin
- Cooperating producer/landowners
- Marla Riekman, Kim Brown-Livingston, John Heard, Rejean Picard
- AAFC-Portage staff:

Leonard Arnal, Danny Bouchard, Scott Jackson, Abby Davidson, Dipo Banjoko, Simon Bergeron, Ashley Rosendaal, Zisheng Xing

- My wife, Denise and daughters, Grace and Hope

Questions?