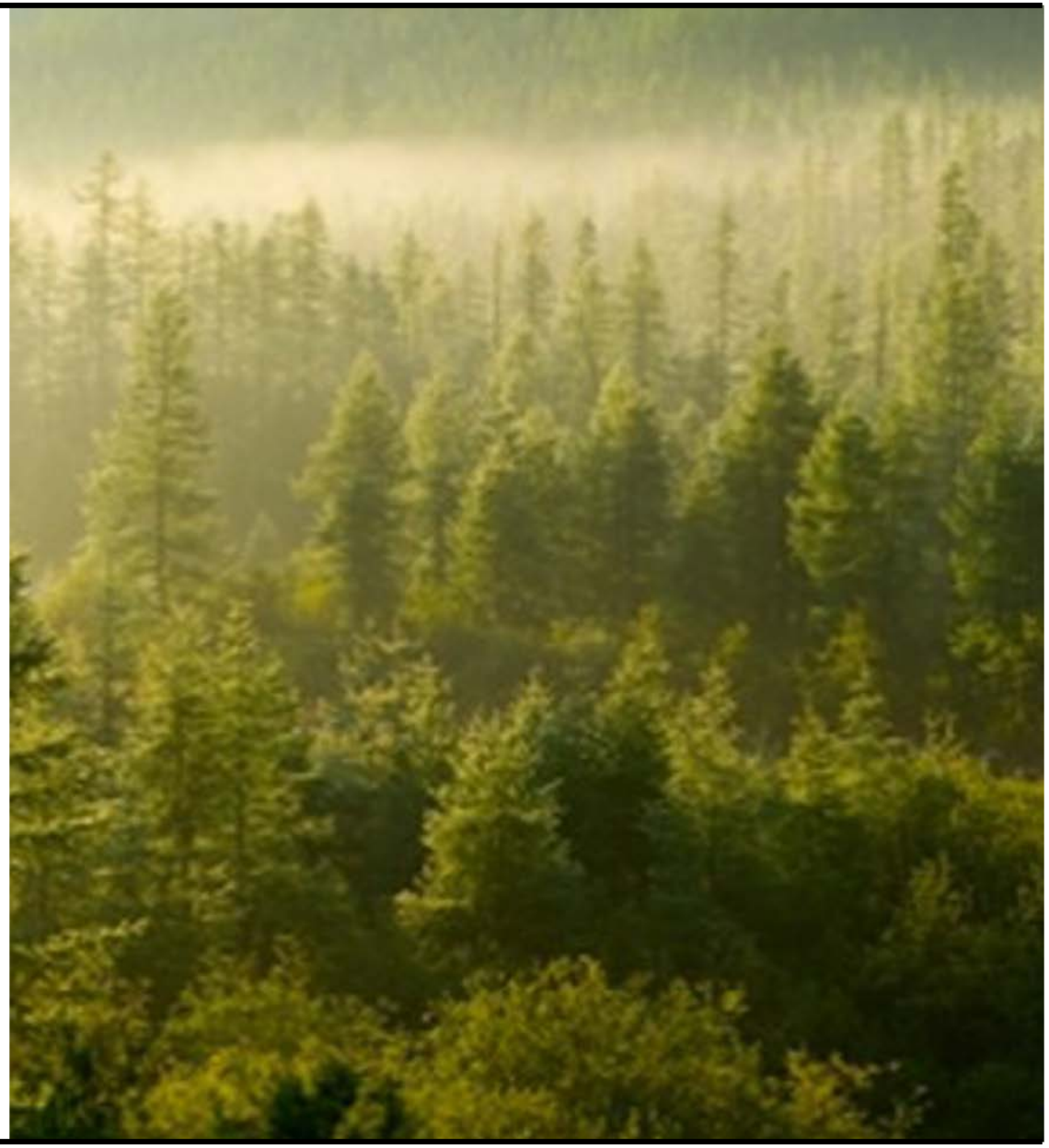
Effets d’un réchauffement artificiel sur la respiration des sols d’une érablière des Laurentides

Par Sharlène Laberge

Projet dirigé par Nicolas Bélanger

Colloque CEF Mai 2023



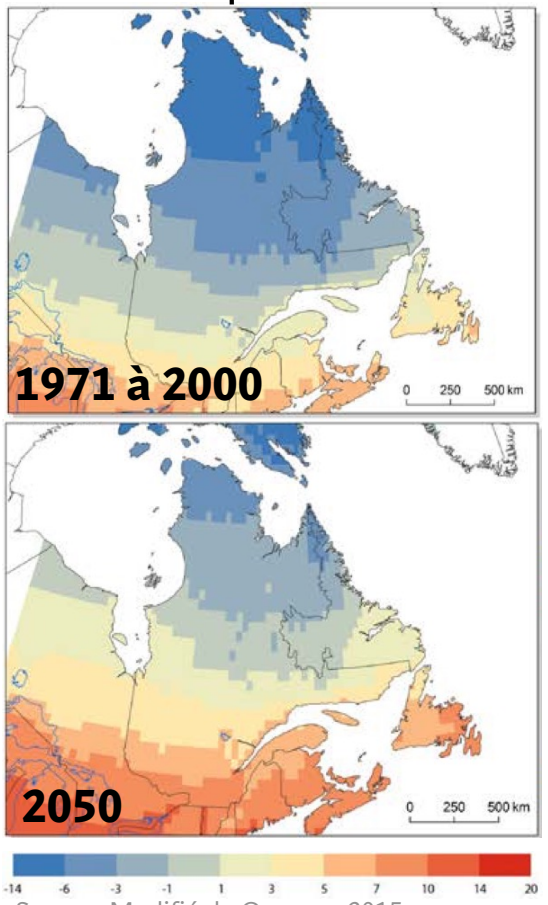
1. Contexte

Projections climatiques

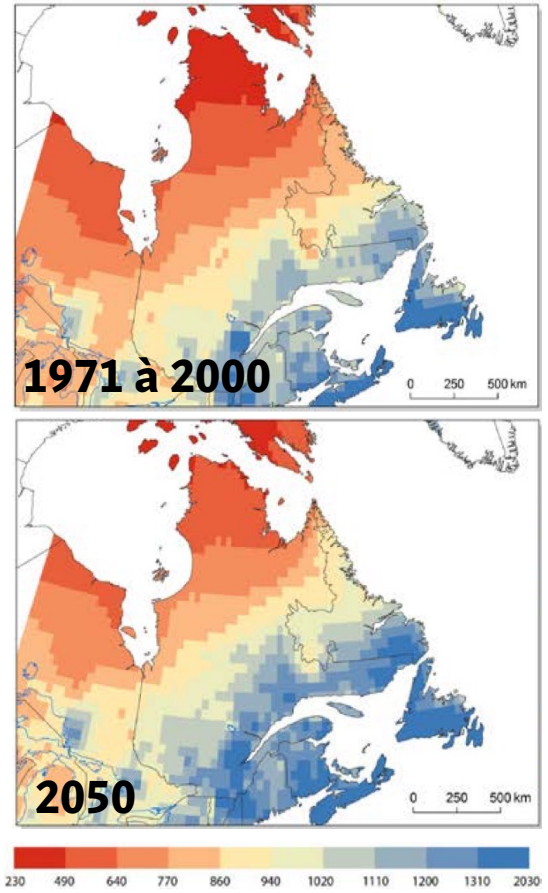
- Augmentation > 1.5°C d'ici la fin du siècle
- Augmentation des précipitations, mais pas assez pour compenser la hausse de l'évapotranspiration
- Déficit hydrique plus marqué qu'aujourd'hui

(Collins et al., 2013; Ouranos 2015; Seneviratne et al., 2012)

Température



Précipitations



Source: Modifié de Ouranos 2015.

1. Contexte

Déclin des écosystèmes forestiers

- Manifestations des changements climatiques par des épidémies d'insectes et des feux de forêt
- Changement dans la composition en espèces des écosystèmes
- Modification de l'aire de répartition pour suivre les conditions de température et d'humidité optimales

(Kramer et al., 2000)

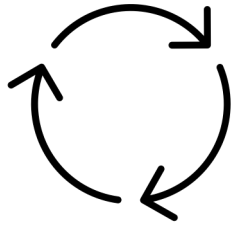
Source: MFFP 2019

Source: MFFP 2020

1. Contexte

Boucle de rétroaction

- Transition du rôle des écosystèmes forestiers de puits à sources de carbone
- Certaines parties de la forêt amazonienne et boréale agissent maintenant comme sources
- Risque de rétroaction positive entre le cycle du carbone terrestre et le système climatique

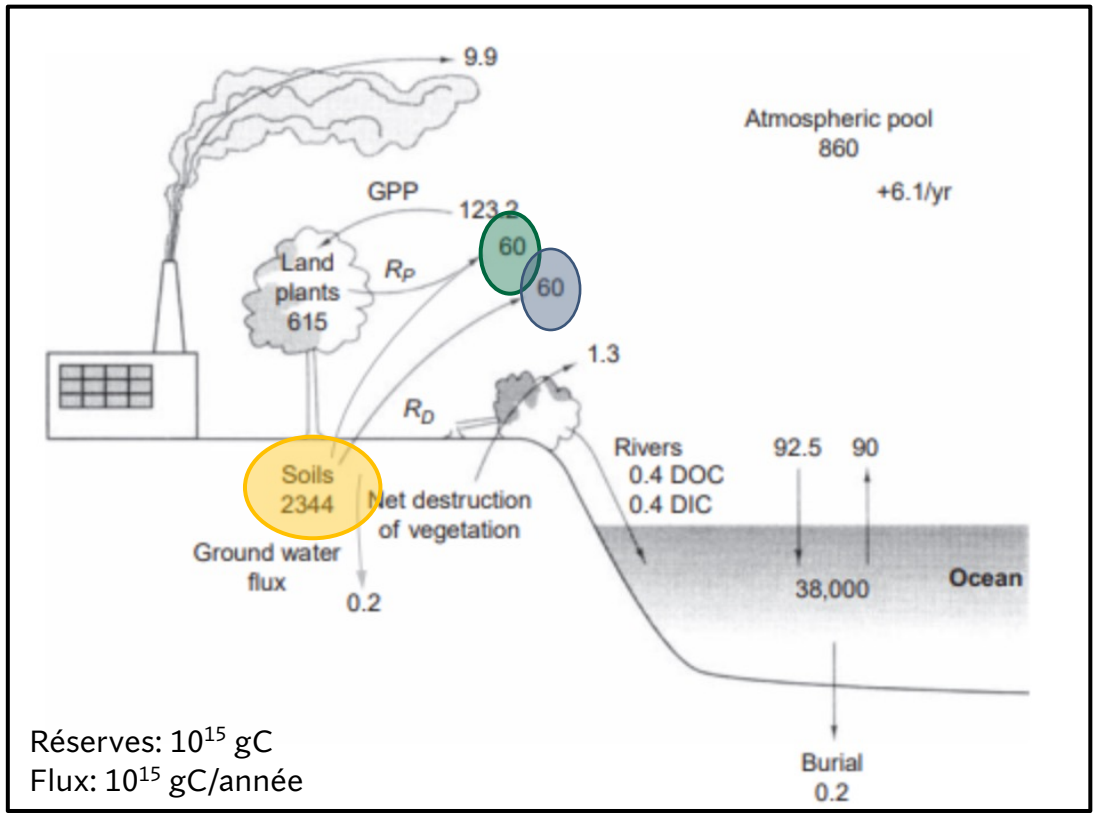


(Gatti et al., 2021; Melillo et al., 2017; Zhao et al., 2021)

Source: Québec Science 2020

1. Contexte

Les sols dans le cycle du carbone global



Source: Schlesinger et Bernhardt, 2020.

Flux de CO_2 du sol

Respiration autotrophe

Respiration hétérotrophe

Système racinaire et rhizosphère

Communautés du sol (faune et microorganismes)

(Hanson et al., 2000)

2. Recension des écrits

Flux de CO_2 du sol

Facteurs primaires

Température du sol

Teneur en eau du sol

Facteurs secondaires

Composition en espèces

Position sur le versant

3. Question de recherche

Quels sont les effets des changements climatiques sur la respiration des sols d'une forêt tempérée décidue à sa limite nordique?

4. Objectifs et hypothèses

Premier objectif: Étudier les effets d'un réchauffement et d'un assèchement artificiel des sols sur le flux de CO_2.

↳ **Hypothèse**: Le réchauffement et l'assèchement artificiels du sol mèneront à une augmentation du flux de CO_2, sauf durant la période la plus chaude de l'été.

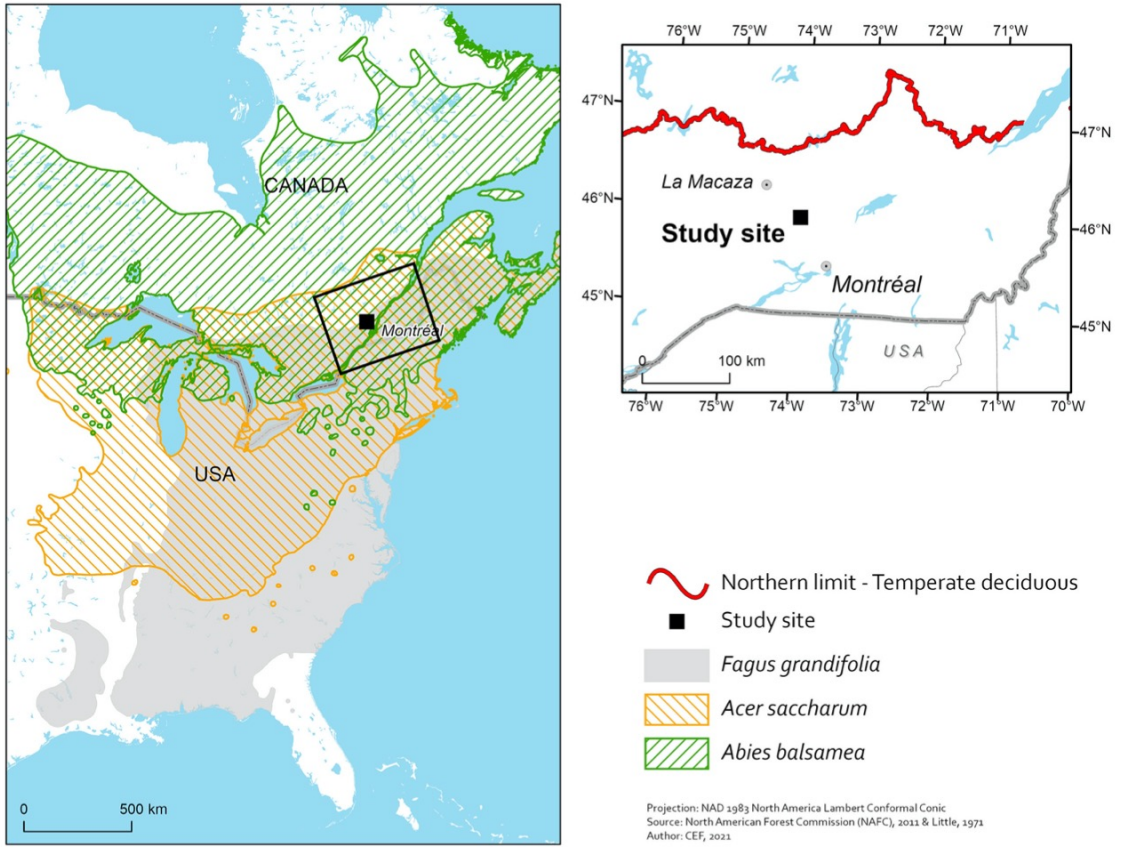
Deuxième objectif: Étudier l'effet du type de couvert forestier sur la réponse des sols à l'assèchement et au réchauffement.

↳ **Hypothèse**: Durant la période la plus chaude de l'été, la respiration sous couvert de conifères sera moindre que sous couvert de feuillus en raison de la litière plus sèche et acide.

5. Dispositif expérimental

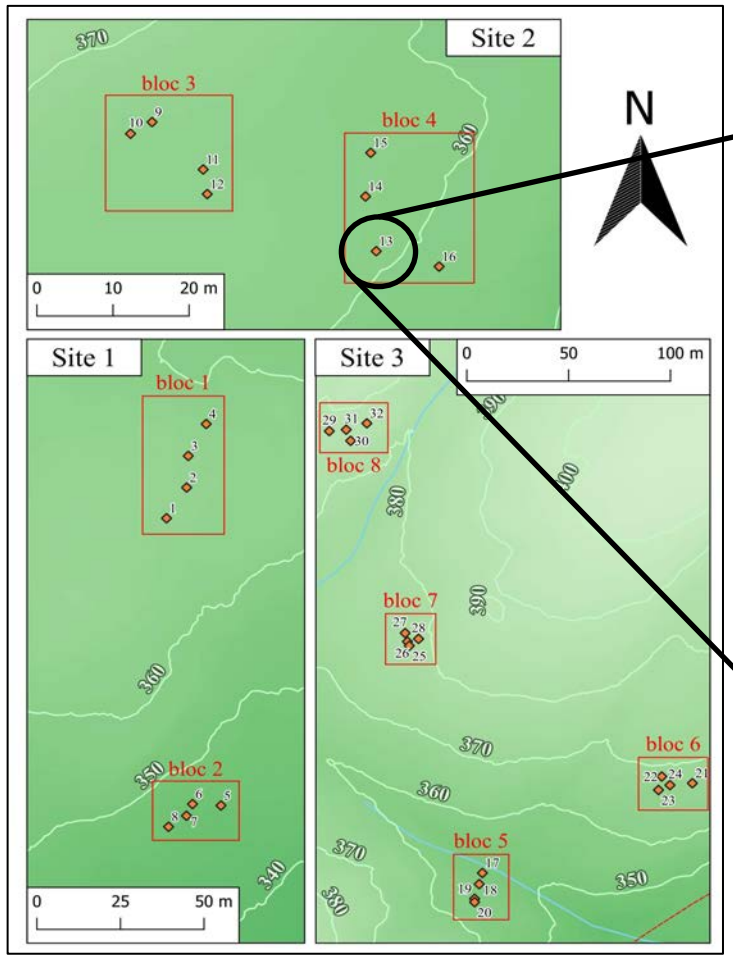
Site d'étude

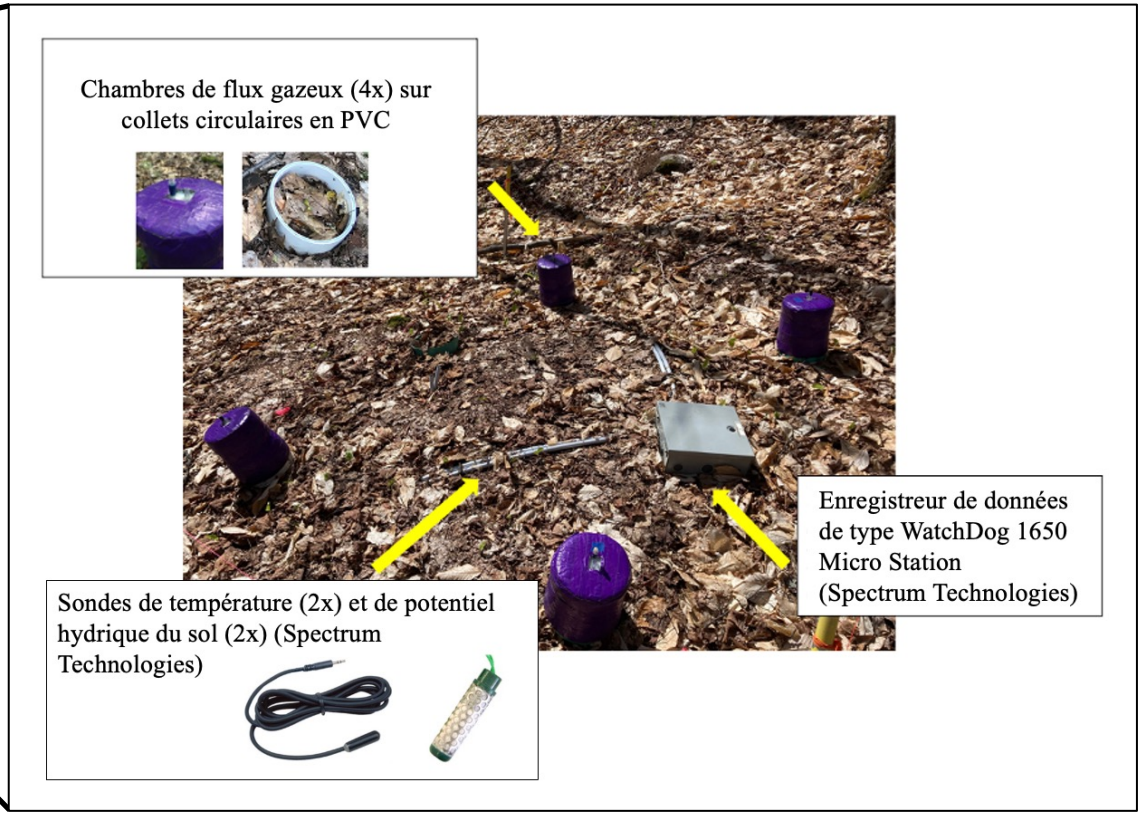
- Station de biologie des Laurentides (SBL).
- Domaine bioclimatique de l'érablière à bouleau jaune.
- À la limite nordique de la forêt tempérée décidue.
- Mélange d'espèces de la forêt tempérée (*Acer saccharum* Marsh) et de la forêt boréale (*Abies balsamea (*L.) Mill).



Source: Bélanger et al., 2021.

5. Dispositif expérimental

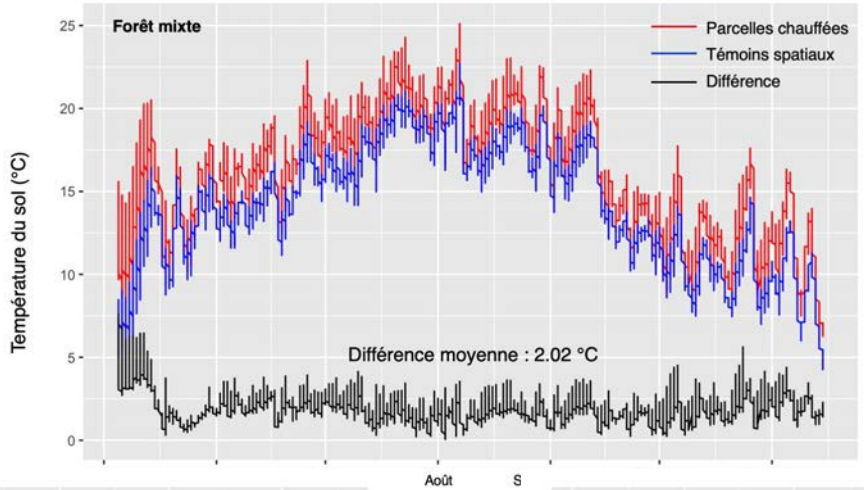


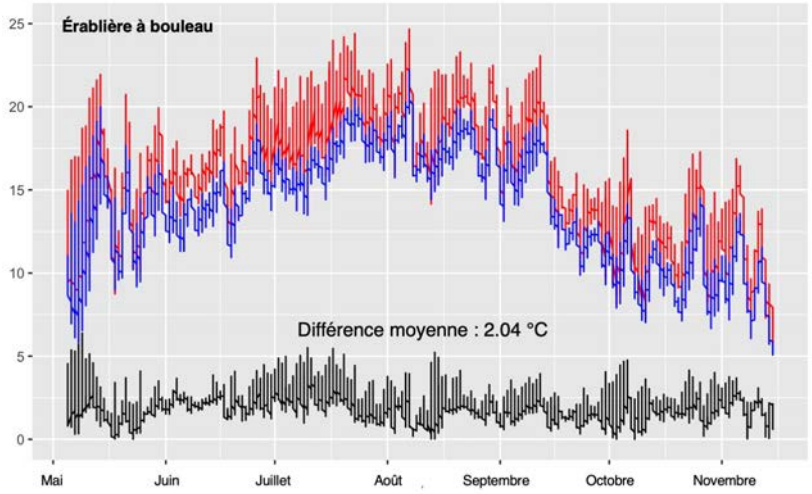


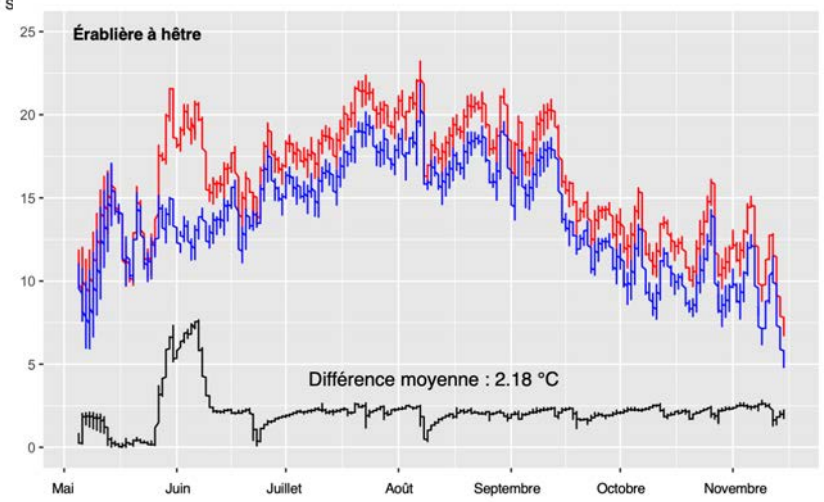
Source: Simon Lebel Desrosiers 2021.

5. Dispositif expérimental

Différentiel de température





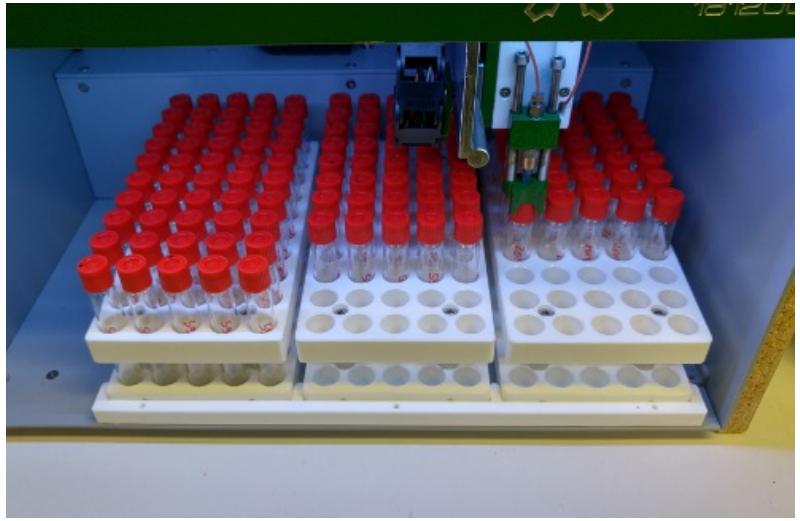


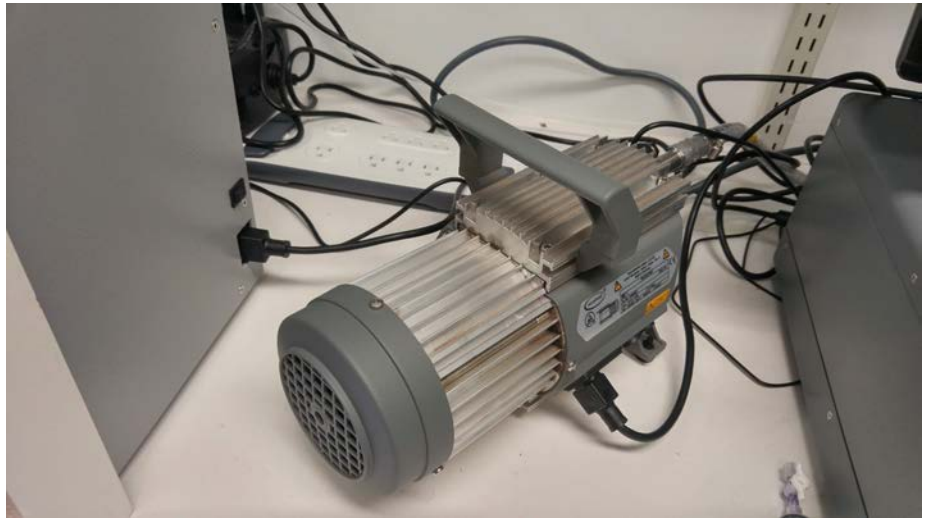
6. Méthodologie

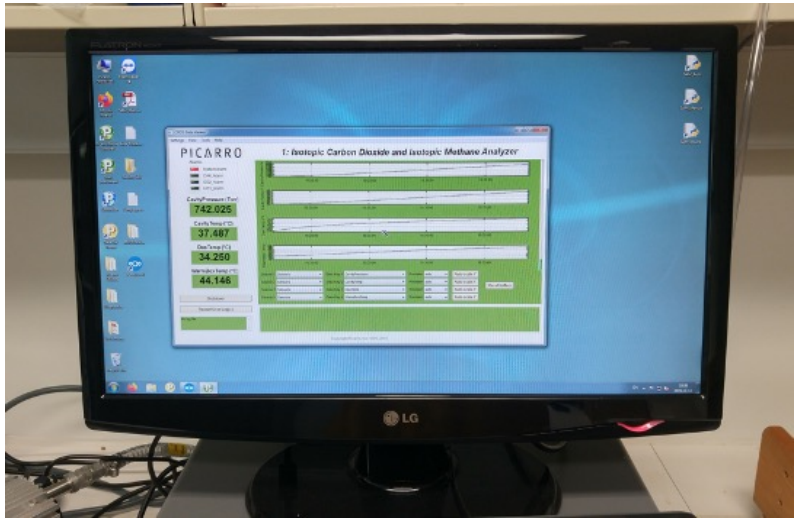
Méthodes de terrain

6. Méthodologie

Méthodes de laboratoire

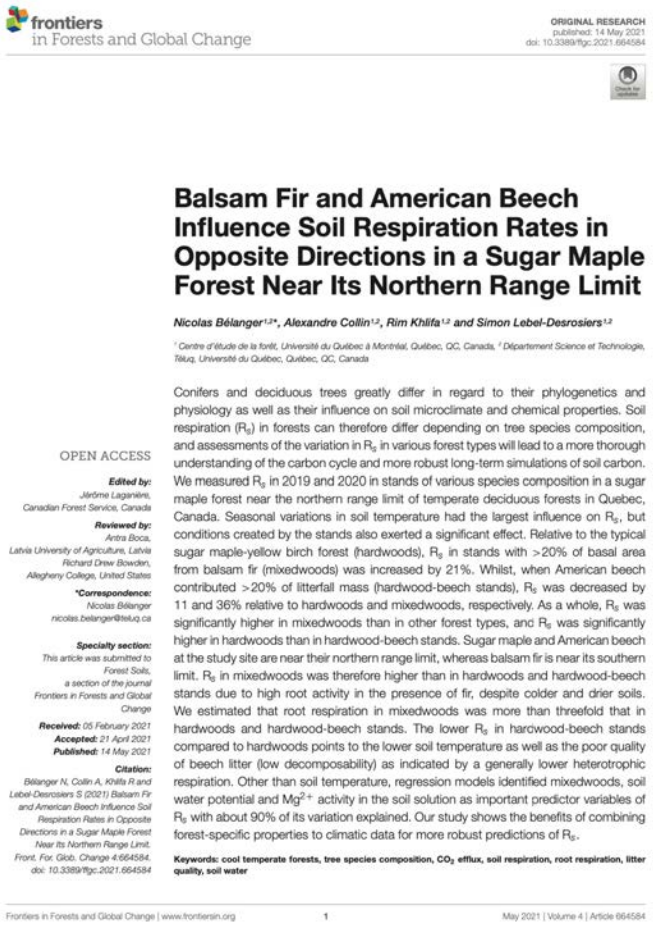






Analyse du contenu des fioles par spectroscopie à cavité optique (Picarro)

7. Résultats et discussion



frontiers in Forests and Global Change

ORIGINAL RESEARCH
published: 14 May 2021
doi: 10.3389/ffgc.2021.664584

Balsam Fir and American Beech Influence Soil Respiration Rates in Opposite Directions in a Sugar Maple Forest Near Its Northern Range Limit

Nicolas Bélanger[1,2], Alexandre Collin[1,2], Rim Khlifa[1,2] and Simon Lebel-Desrosiers[1,2]*

[1] Centre d'étude de la forêt, Université du Québec à Montréal, Québec, QC, Canada, [2] Département Science et Technologie, Téluq, Université du Québec, Québec, QC, Canada

Conifers and deciduous trees greatly differ in regard to their phylogenetics and physiology as well as their influence on soil microclimate and chemical properties. Soil respiration (R_S) in forests can therefore differ depending on tree species composition, and assessments of the variation in R_S in various forest types will lead to a more thorough understanding of the carbon cycle and more robust long-term simulations of soil carbon. We measured R_S in 2019 and 2020 in stands of various species composition in a sugar maple forest near the northern range limit of temperate deciduous forests in Quebec, Canada. Seasonal variations in soil temperature had the largest influence on R_S, but conditions created by the stands also exerted a significant effect. Relative to the typical sugar maple-yellow birch forest (hardwoods), R_S in stands with >20% of basal area from balsam fir (mixedwoods) was increased by 21%. Whilst, when American beech contributed >20% of litterfall mass (hardwood-beech stands), R_S was decreased by 11 and 36% relative to hardwoods and mixedwoods, respectively. As a whole, R_S was significantly higher in mixedwoods than in other forest types, and R_S was significantly higher in hardwoods than in hardwood-beech stands. Sugar maple and American beech at the study site are near their northern range limit, whereas balsam fir is near its southern limit. R_S in mixedwoods was therefore higher than in hardwoods and hardwood-beech stands due to high root activity in the presence of fir, despite colder and drier soils. We estimated that root respiration in mixedwoods was more than threefold that in hardwoods and hardwood-beech stands. The lower R_S in hardwood-beech stands compared to hardwoods points to the lower soil temperature as well as the poor quality of beech litter (low decomposability) as indicated by a generally lower heterotrophic respiration. Other than soil temperature, regression models identified mixedwoods, soil water potential and Mg^{2+} activity in the soil solution as important predictor variables of R_S with about 90% of its variation explained. Our study shows the benefits of combining forest-specific properties to climatic data for more robust predictions of R_S.

Keywords: cool temperate forests, tree species composition, CO_2 efflux, soil respiration, root respiration, litter quality, soil water

OPEN ACCESS

Edited by:
Jérôme Laganière, Canadian Forest Service, Canada

Reviewed by:
Antra Boca, Latvia University of Agriculture, Latvia
Richard Drew Bowden, Allegheny College, United States

****Correspondence:***
Nicolas Bélanger
nicolas.belanger@teluq.ca

Specialty section:
This article was submitted to Forest Soils, a section of the journal Frontiers in Forests and Global Change

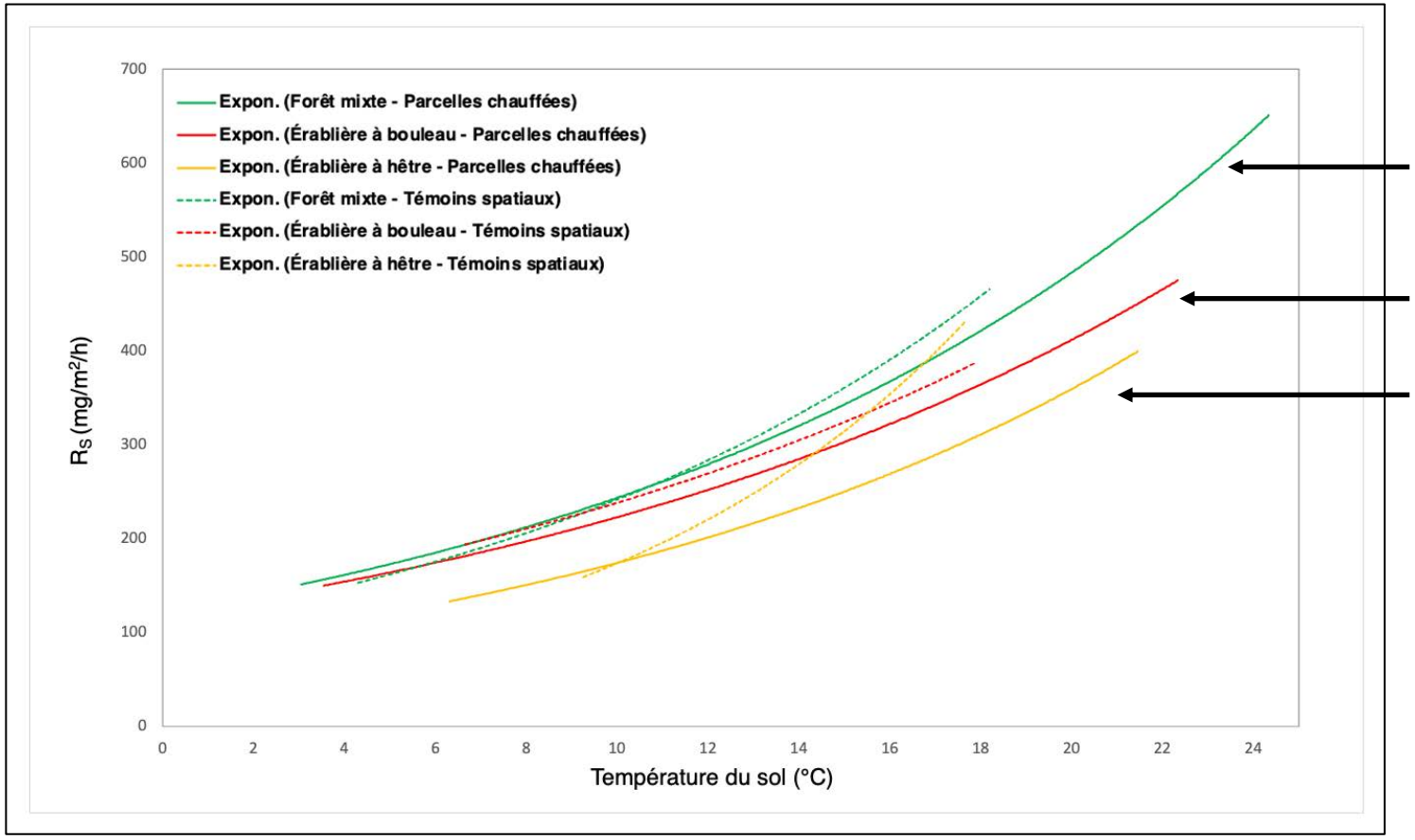
Received: *05 February 2021*
Accepted: *21 April 2021*
Published: *14 May 2021*

Citation:
Bélanger N, Collin A, Khlifa R and Lebel-Desrosiers S (2021) Balsam Fir and American Beech Influence Soil Respiration Rates in Opposite Directions in a Sugar Maple Forest Near Its Northern Range Limit. Front. For. Glob. Change 4:664584. doi: 10.3389/ffgc.2021.664584

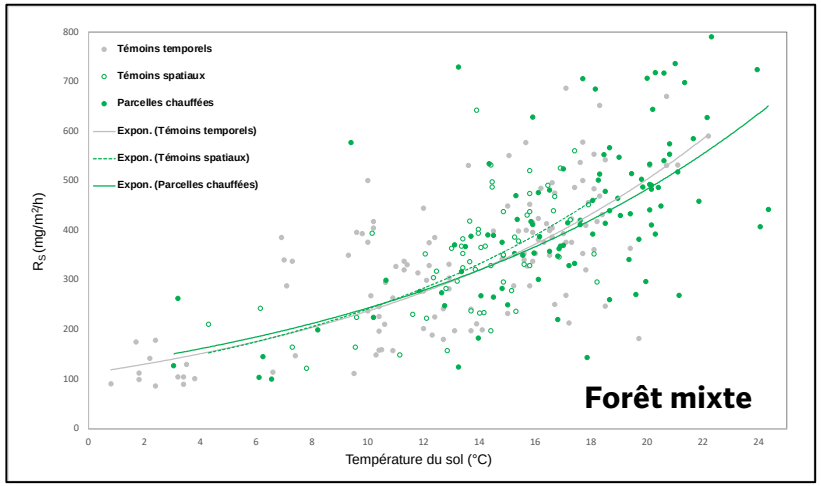
Les **parcelles chauffées** (16) sont comparées à deux types de témoins:

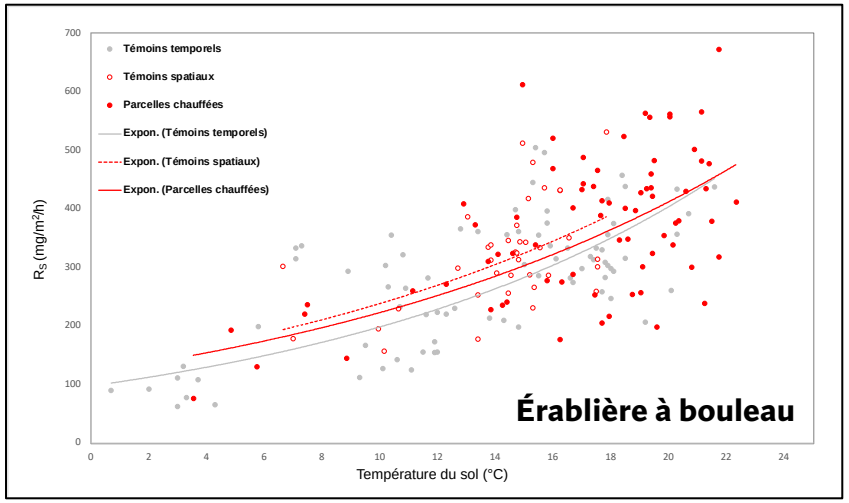
- **Témoins spatiaux** → Parcelles non chauffées (16) après le début du réchauffement en 2021-2022
- **Témoins temporels** → Toutes les parcelles (32) avant le début du réchauffement en 2019-2020 (Bélanger et al., 2021)

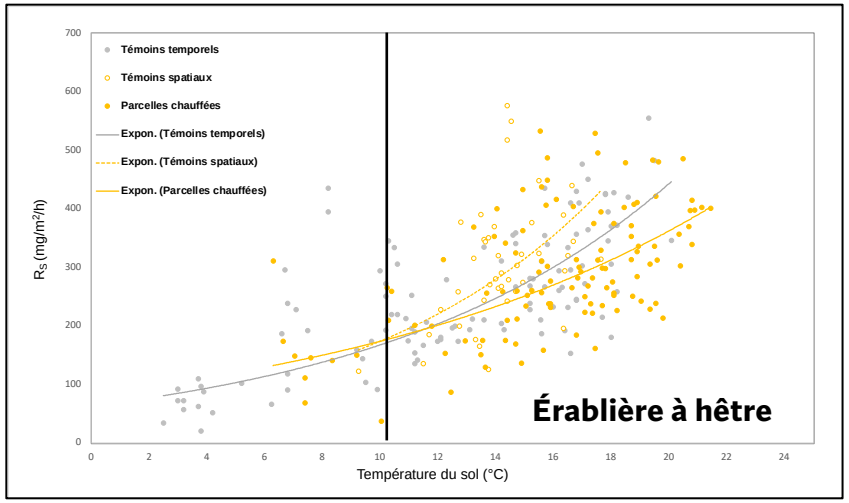
7. Résultats et discussion



7. Résultats et discussion

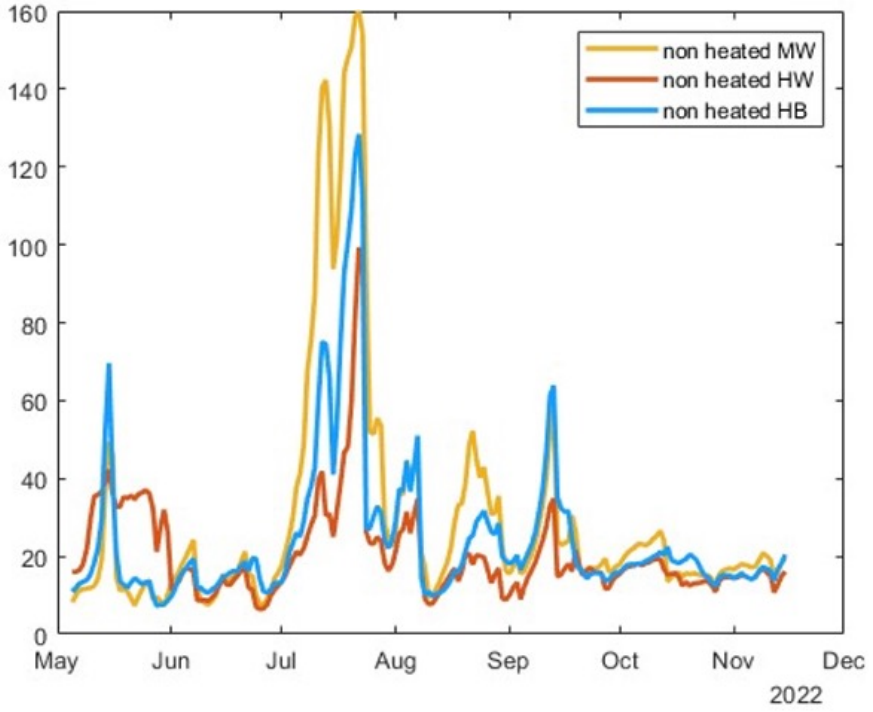




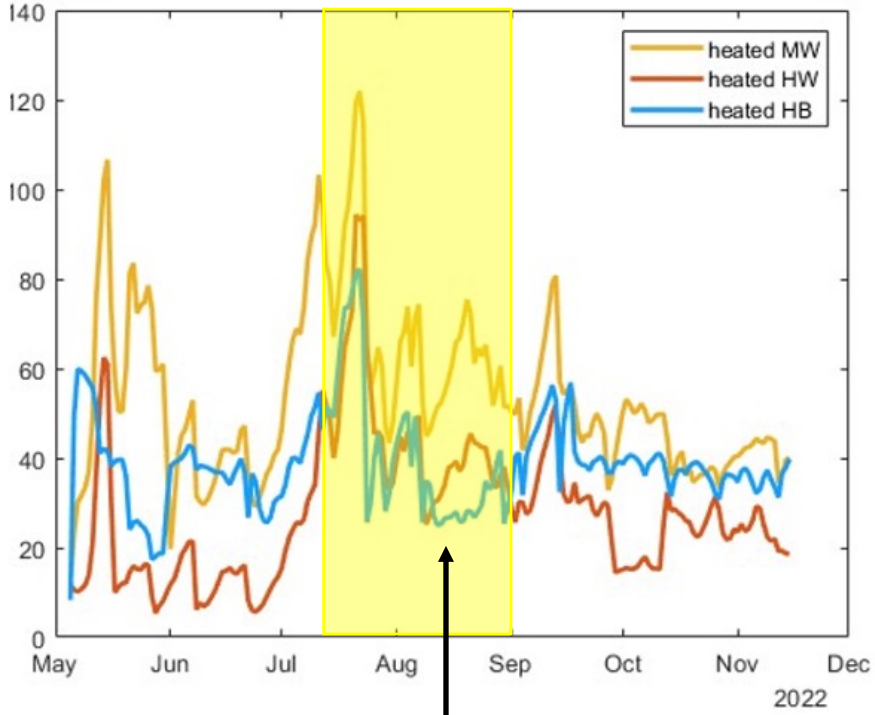


7. Résultats et discussion

Témoins spatiaux de chacun des peuplements



Parcelles chauffées de chacun des peuplements

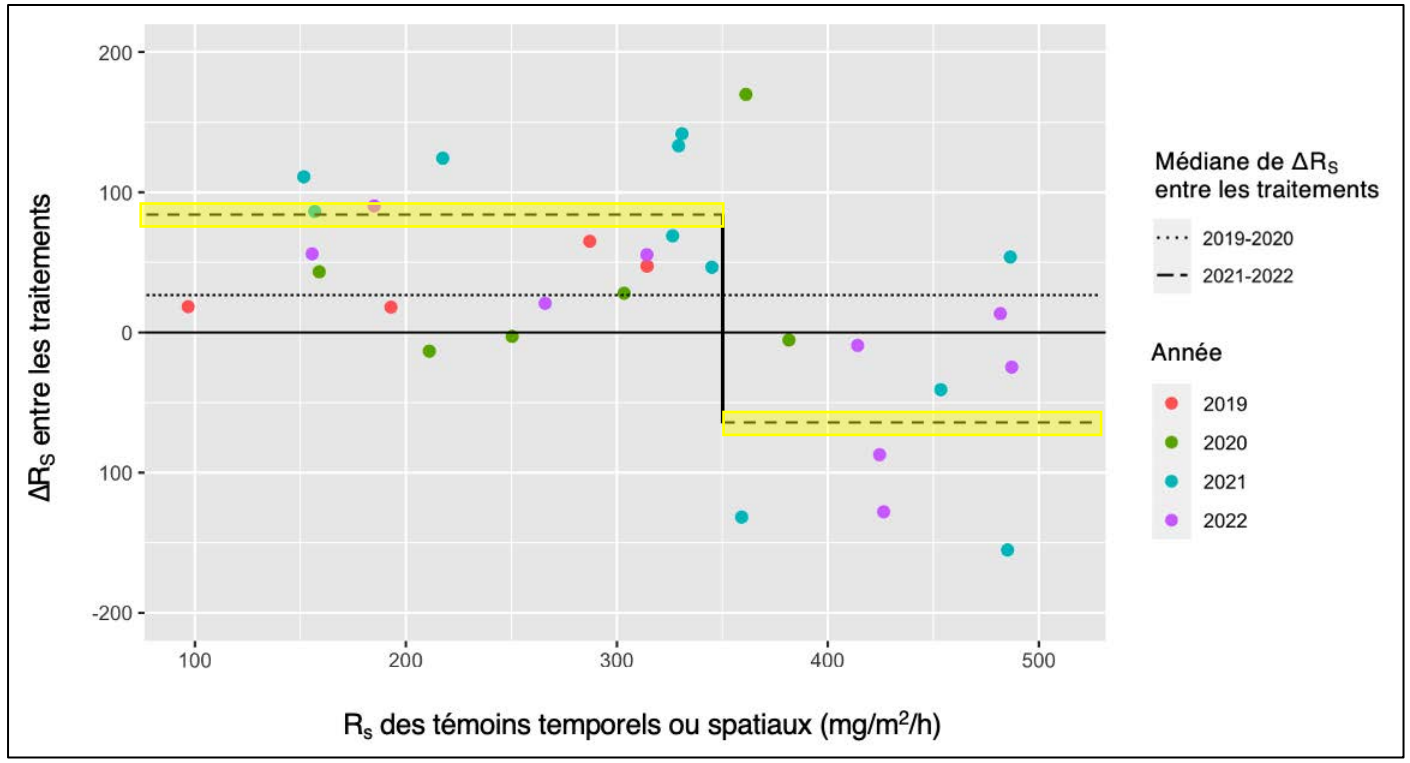


Source: Blandine Courcot 2022.

Érablière à hêtre en bleu

7. Résultats et discussion

Bloc 7 (forêt mixte)



Peuplement	Bloc	Seuil (mg/m^2/h)
Forêt mixte	1	NA
	4	500
	7	350
Érablière à bouleau	2	400
	6	NA
Érablière à hêtre	3	400
	5	300
	8	300

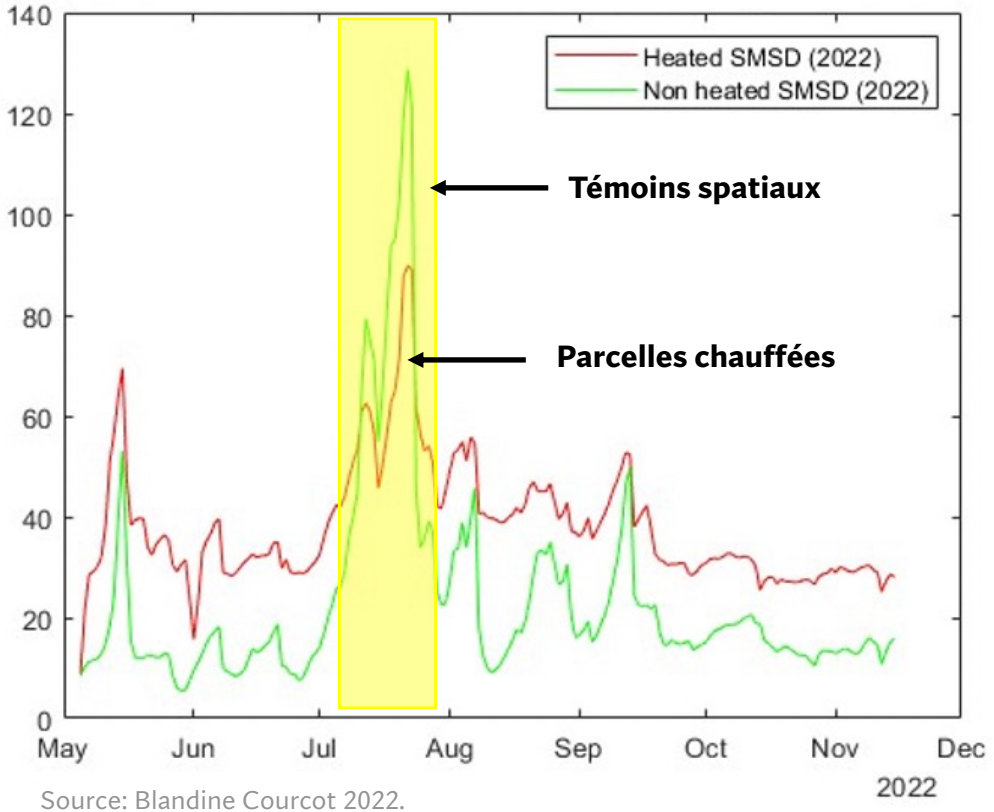
7. Résultats et discussion

Peuplement	Traitement	[0-15]°C			]15-25]°C		
		n	R^2 ajusté	p-value	n	R^2 ajusté	p-value
Forêt mixte	Chauffé	27	0.26	0.004 *	74	0.13	0.0008 *
	Témoin	41	0.29	0.0001 *	20	0.004	0.31
Érablière à bouleau	Chauffé	18	0.62	5.75e-5 *	55	0.04	0.07
	Témoin	22	0.28	0.006 *	16	-0.06	0.75
Érablière à hêtre	Chauffé	36	0.14	0.02 *	76	0.05	0.03 *
	Témoin	32	0.33	0.003 *	10	-0.06	0.52

7. Résultats et discussion

Peuplement	Bloc	n	Modèle à une variable		Modèle à deux variables	
			R^2 ajusté	p-value	R^2 ajusté	p-value
Forêt mixte	1	47	0.65	$5.83e^{-12}$ *	0.61	$4.83e^{-10}$ *
	4	62	0.41	$1.46e^{-8}$ *	0.44	$1.24e^{-8}$ *
	7	53	0.43	$6.45e^{-8}$ *	0.39	$1.96e^{-6}$ *
Érablière à bouleau	2	61	0.43	$6.60e^{-9}$ *	0.39	$2.63e^{-7}$ *
	6	50	0.36	$2.41e^{-6}$ *	0.32	$4.33e^{-5}$ *
Érablière à hêtre	3	43	0.63	$1.41e^{-10}$ *	0.59	$6.61e^{-9}$ *
	5	57	0.19	0.0005 *	0.14	0.006 *
	8	54	0.20	0.0005 *	0.18	0.003 *

Parcelles chauffées et témoins spatiaux de tous les peuplements confondus



Source: Blandine Courcot 2022.

8. Retombées du projet de recherche

9. Bibliographie

A'Bear, A. D., Jones, T. H., Kandeler, E. et Boddy, L. (2014). Interactive effects of temperature and soil moisture on fungal-mediated wood decomposition and extracellular enzyme activity. *Soil Biology and Biochemistry*, *70*, 151-158. https://doi.org/10.1016/j.soilbio.2013.12.017

Aerts, R. (2006). The freezer defrosting: global warming and litter decomposition rates in cold biomes: *Global warming and litter decomposition*. *Journal of Ecology*, *94*(4), 713-724. https://doi.org/10.1111/j.1365-2745.2006.01142.x

Augusto, L., Ranger, J., Binkley, D. et Rothe, A. (2002). Impact of several common tree species of European temperate forests on soil fertility. *Annals of Forest Science*, *59*(3), 233-253. https://doi.org/10.1051/forest:2002020

Bélanger, N. et Chaput-Richard, C. (2023). Experimental Warming of Typically Acidic and Nutrient-Poor Boreal Soils Does Not Affect Leaf-Litter Decomposition of Temperate Deciduous Tree Species. *Soil Systems*, *7*(1), 14. https://doi.org/10.3390/soilsystems7010014

Bélanger, N., Collin, A., Khlifa, R. et Lebel-Desrosiers, S. (2021). Balsam Fir and American Beech Influence Soil Respiration Rates in Opposite Directions in a Sugar Maple Forest Near Its Northern Range Limit. *Frontiers in Forests and Global Change*, *4*, 664584. https://doi.org/10.3389/ffgc.2021.664584

Bélanger, N., Collin, A., Ricard-Piché, J., Kembel, S. W. et Rivest, D. (2019). Microsite conditions influence leaf litter decomposition in sugar maple bioclimatic domain of Quebec. *Biogeochemistry*, *145*(1-2), 107-126. https://doi.org/10.1007/s10533-019-00594-1

Bélanger, N., Holmden, C., Courchesne, F., Côté, B. et Hendershot, W. H. (2012). Constraining soil mineral weathering 87Sr/86Sr for calcium apportionment studies of a deciduous forest growing on soils developed from granitoid igneous rocks. *Geoderma*, *185-186*, 84-96. https://doi.org/10.1016/j.geoderma.2012.03.024

Ben-Noah, I. et Friedman, S. P. (2018). Review and Evaluation of Root Respiration and of Natural and Agricultural Processes of Soil Aeration. *Vadose Zone Journal*, *17*(1), 170119. https://doi.org/10.2136/vzj2017.06.0119

Binkley, D. (1995). The influence of tree species on forest soils: Processes and patterns. Dans *Proceedings of the trees and soil workshop* (vol. 7).

Binkley, D. et Giardina, C. (1998). Why do tree species affect soils? The Warp and Woof of tree-soil interactions. Dans N. Van Breemen (dir.), *Plant-induced soil changes: Processes and feedbacks* (p. 89-106). Springer Netherlands. https://doi.org/10.1007/978-94-017-2691-7_5

Bolstad, P. V. et Gower, S. T. (1990). Estimation of leaf area index in fourteen southern Wisconsin forest stands using a portable radiometer. *Tree Physiology*, *7*(1-2-3-4), 115-124. https://doi.org/10.1093/treephys/7.1-2-3-4.115

Boone, R. D., Nadelhoffer, K. J., Canary, J. D. et Kaye, J. P. (1998). Roots exert a strong influence on the temperature sensitivityof soil respiration. *Nature*, *396*(6711), 570-572. https://doi.org/10.1038/25119

Borken, W. et Matzner, E. (2009). Reappraisal of drying and wetting effects on C and N mineralization and fluxes in soils. *Global Change Biology*, *15*(4), 808-824. https://doi.org/10.1111/j.1365-2486.2008.01681.x

9. Bibliographie

Borken, W., Savage, K., Davidson, E. A. et Trumbore, S. E. (2006). Effects of experimental drought on soil respiration and radiocarbon efflux from a temperate forest soil: DROUGHT EFFECTS ON SOIL RESPIRATION. *Global Change Biology*, *12*(2), 177-193. https://doi.org/10.1111/j.1365-2486.2005.001058.x

Bradford, M. A., Davies, C. A., Frey, S. D., Maddox, T. R., Melillo, J. M., Mohan, J. E., Reynolds, J. F., Treseder, K. K. et Wallenstein, M. D. (2008). Thermal adaptation of soil microbial respiration to elevated temperature. *Ecology Letters*, *11*(12), 1316-1327. https://doi.org/10.1111/j.1461-0248.2008.01251.x

Soil Classification Working Group (1998). *The Canadian System of Soil Classification, Third edition*. Ottawa: Agriculture and Agri-Food Canada Publication and NRC Research Press.

Canham, C. D., Finzi, A. C., Pacala, S. W. et Burbank, D. H. (1994). Causes and consequences of resource heterogeneity in forests: interspecific variation in light transmission by canopy trees. *Canadian Journal of Forest Research*, *24*(2), 337-349. https://doi.org/10.1139/x94-046

Cisneros-Dozal, L. M., Trumbore, S. E. et Hanson, P. J. (2007). Effect of moisture on leaf litter decomposition and its contribution to soil respiration in a temperate forest. *Journal of Geophysical Research*, *112*(G1), G01013. https://doi.org/10.1029/2006JG000197

Collin, A., Messier, C. et Bélanger, N. (2017). Conifer Presence May Negatively Affect Sugar Maple's Ability to Migrate into the Boreal Forest Through Reduced Foliar Nutritional Status. *Ecosystems*, *20*(4), 701-716. https://doi.org/10.1007/s10021-016-0045-4

Comas, L. H., Becker, S. R., Cruz, V. M. V., Byrne, P. F. et Dierig, D. A. (2013). Root traits contributing to plant productivity under drought. *Frontiers in Plant Science*, *4*. https://doi.org/10.3389/fpls.2013.00442

Coûteaux, M.-M., Bottner, P. et Berg, B. (1995). Litter decomposition, climate and liter quality. *Trends in Ecology & Evolution*, *10*(2), 63-66. https://doi.org/10.1016/S0169-5347(00)88978-8

Curiel Yuste, J., Janssens, I. A., Carrara, A. et Ceulemans, R. (2004). Annual Q10 of soil respiration reflects plant phenological patterns as well as temperature sensitivity. *Global Change Biology*, *10*(2), 161-169. https://doi.org/10.1111/j.1529-8817.2003.00727.x

Davidson, E. A., Belk, E. et Boone, R. D. (1998). Soil water content and temperature as independent or confounded factors controlling soil respiration in a temperate mixed hardwood forest. *Global Change Biology*, *4*(2), 217-227. https://doi.org/10.1046/j.1365-2486.1998.00128.x

D'Orangeville, L., Maxwell, J., Kneeshaw, D., Pederson, N., Duchesne, L., Logan, T., Houle, D., Arseneault, D., Beier, C. M., Bishop, D. A., Druckenbrod, D., Fraver, S., Girard, F., Halman, J., Hansen, C., Hart, J. L., Hartmann, H., Kaye, M., Leblanc, D., … Phillips, R. P. (2018). Drought timing and local climate determine the sensitivity of eastern temperate forests to drought. *Global Change Biology*, *24*(6), 2339-2351. https://doi.org/10.1111/gcb.14096

Epron, D., Farque, L., Lucot, É. et Badot, P.-M. (1999). Soil CO_2 efflux in a beech forest: dependence on soil temperature and soil water content. *ANNALS OF FOREST SCIENCE*, *56*(3), 221-226. https://doi.org/10.1051/forest:19990304

9. Bibliographie

Gatti, L. V., Basso, L. S., Miller, J. B., Gloor, M., Gatti Domingues, L., Cassol, H. L. G., Tejada, G., Aragão, L. E. O. C., Nobre, C., Peters, W., Marani, L., Arai, E., Sanches, A. H., Corrêa, S. M., Anderson, L., Von Randow, C., Correia, C. S. C., Crispim, S. P. et Neves, R. A. L. (2021). Amazonia as a carbon source linked to deforestation and climate change. *Nature*, *595*(7867), 388-393. https://doi.org/10.1038/s41586-021-03629-6

Hanson, P. J., Edwards, N. T., Garten, C. T. et Andrews, J. A. (2000). Separating root mais soil microbial contributions to soil respiration: A review of methods and observations. *Biogeochemistry*, *48*(1), 115-146. https://doi.org/10.1023/A:1006244819642

Hendrick, R. L. et Pregitzer, K. S. (1996). Temporal and Depth-Related Patterns of Fine Root Dynamics in Northern Hardwood Forests. *The Journal of Ecology*, *84*(2), 167. https://doi.org/10.2307/2261352

Joly, F., Milcu, A., Scherer-Lorenzen, M., Jean, L., Bussotti, F., Dawud, S. M., Müller, S., Pollastrini, M., Raulund-Rasmussen, K., Vesterdal, L. et Hättenschwiler, S. (2017). Tree species diversity affects decomposition through modified micro-environmental conditions across European forests. *New Phytologist*, *214*(3), 1281-1293. https://doi.org/10.1111/nph.14452

Kirschbaum, M. U. F. (2004). Soil respiration under prolonged soil warming: are rate reductions caused by acclimation or substrate loss?: TEMPERATURE RESPONSE OF SOIL RESPIRATION. *Global Change Biology*, *10*(11), 1870-1877. https://doi.org/10.1111/j.1365-2486.2004.00852.x

Knorr, W., Prentice, I. C., House, J. I. et Holland, E. A. (2005). Long-term sensitivity of soil carbon turnover to warming. *Nature*, *433*(7023), 298-301. https://doi.org/10.1038/nature03226

Kramer, K., Leinonen, I. et Loustau, D. (2000). The importance of phenology for the evaluation of impact of climate change on growth of boreal, temperate and Mediterranean forests ecosystems: an overview. *International Journal of Biometeorology*, *44*(2), 67-75. https://doi.org/10.1007/s004840000066

Liu, L., Wang, X., Lajeunesse, M. J., Miao, G., Piao, S., Wan, S., Wu, Y., Wang, Z., Yang, S., Li, P. et Deng, M. (2016). A cross-biome synthesis of soil respiration and its determinants under simulated precipitation changes. *Global Change Biology*, *22*(4), 1394-1405. https://doi.org/10.1111/gcb.13156
Lu, M., Zhou, X., Yang, Q., Li, H., Luo, Y., Fang, C., Chen, J., Yang, X. et Li, B. (2013). Responses of ecosystem carbon cycle to experimental warming: a meta-analysis. *Ecology*, *94*(3), 726-738. https://doi.org/10.1890/12-0279.1

Melillo, J. M., Steudler, P. A., Aber, J. D., Newkirk, K., Lux, H., Bowles, F. P., Catricala, C., Magill, A., Ahrens, T. et Morrisseau, S. (2002). Soil Warming and Carbon-Cycle Feedbacks to the Climate System. *Science*, *298*(5601), 2173-2176. https://doi.org/10.1126/science.1074153

Melillo, J. M., Frey, S. D., DeAngelis, K. M., Werner, W. J., Bernard, M. J., Bowles, F. P., Pold, G., Knorr, M. A. et Grandy, A. S. (2017). Long-term pattern and magnitude of soil carbon feedback to the climate system in a warming world. *Science*, *358*(6359), 101-105. https://doi.org/10.1126/science.aan2874

Meng, C., Tian, D., Zeng, H., Li, Z., Chen, H. Y. H. et Niu, S. (2020). Global meta-analysis on the responses of soil extracellular enzyme activities to warming. *Science of The Total Environment*, *705*, 135992. https://doi.org/10.1016/j.scitotenv.2019.135992

Mohan, J. E., Cowden, C. C., Baas, P., Dawadi, A., Frankson, P. T., Helmick, K., Hughes, E., Khan, S., Lang, A., Machmuller, M., Taylor, M. et Witt, C. A. (2014). Mycorrhizal fungi mediation of terrestrial ecosystem responses to global change: mini-review. *Fungal Ecology*, *10*, 3-19. https://doi.org/10.1016/j.funeco.2014.01.005

9. Bibliographie

Morneau, C., Couillard, P.-L., Laflamme, J. et Major, M. (2021). *Classification écologique du territoire québécois* (2e édition). Direction des inventaires forestiers.

Ouranos. (2015). *Vers l'adaptation. Synthèse des connaissances sur les changements climatiques au Québec. Partie 1: Évolution climatique au Québec.*

Phillips, R. P., Ibáñez, I., D'Orangeville, L., Hanson, P. J., Ryan, M. G. et McDowell, N. G. (2016). A belowground perspective on the drought sensitivity of forests: Towards improved understanding and simulation. *Forest Ecology and Management*, *380*, 309-320. https://doi.org/10.1016/j.foreco.2016.08.043

Raich, J. W. et Schlesinger, W. H. (1992). The global carbon dioxide flux in soil respiration and its relationship to vegetation and climate. *Tellus B: Chemical and Physical Meteorology*, *44*(2), 81-99. https://doi.org/10.3402/tellusb.v44i2.15428

Raich, James W. et Tufekciogul, A. (2000). Vegetation and soil respiration: Correlations and controls. *Biogeochemistry*, *48*(1), 71-90. https://doi.org/10.1023/A:1006112000616

Rossi, S., Deslauriers, A., Anfodillo, T., Morin, H., Saracino, A., Motta, R. et Borghetti, M. (2006). Conifers in cold environments synchronize maximum growth rate of tree-ring formation with day length. *New Phytologist*, *170*(2), 301-310. https://doi.org/10.1111/j.1469-8137.2006.01660.x

Savage, C. (2001). *Recolonisation Forestière Dans les Basses Laurentides au Sud du Domaine Climacique de L'érablière à Bouleau Jaune*. [thèse de maitrise]. Montréal, QC: Universite´ de Montréal.

Schlesinger, W. H. (2020). *Biogeochemistry: an analysis of global change* (4e éd.). Elsevier.

Schlesinger, W. H. et Andrews, J. A. (2000). Soil respiration and the global carbon cycle. *Biogeochemistry*, *48*(1), 7-20. https://doi.org/10.1023/A:1006247623877
Seneviratne, S., Nicholls, N., Easterling, D., Goodess, C., Kanae, S., Kossin, J., Luo, Y., Marengo, J., McInnes, K., Rahimi, M., Reichstein, M., Sorteberg, A., Vera, C., Zhang, X., Alexander, L. V., Allen, S., Benito, G., Cavazos, T., Clague, J., … Zwiers, F. W. (2012). Changes in climate extremes and their impacts on the natural physical environment. https://doi.org/10.7916/D8-6NBT-S431

Smith, S. E. et Read, D. J. (2008). *Mycorrhizal symbiosis* (3rd ed). Academic Press.

Collins, M., Knutti, R., Arblaster, J., Dufresne, J. L., Fichefet, T., Friedlingstein, P., … & Booth, B. B. (2013). Long-term climate change: projections, commitments and irreversibility. In *Climate Change 2013-The Physical Science Basis: Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 1029-1136). Cambridge University Press.

Strömgren, M. (2001). *Soil-surface CO2 flux und growth in a boreal Norway spruce stand: effects of soil warming and nutrition*. Swedisch University of Agricultural Sciences.

Subke, J.-A. et Bahn, M. (2010). On the 'temperature sensitivity' of soil respiration: Can we use the immeasurable to predict the unknown? *Soil Biology and Biochemistry*, *42*(9), 1653-1656. https://doi.org/10.1016/j.soilbio.2010.05.026

9. Bibliographie

Swift, M. J., Heal, O. W. et Anderson, J. M. (1979). *Decomposition in terrestrial ecosystems*. University of California Press.

Wang, X., Liu, L., Piao, S., Janssens, I. A., Tang, J., Liu, W., Chi, Y., Wang, J. et Xu, S. (2014). Soil respiration under climate warming: differential response of heterotrophic and autotrophic respiration. *Global Change Biology*, *20*(10), 3229-3237. https://doi.org/10.1111/gcb.12620

Wang, Y., Song, C., Liu, H., Wang, S., Zeng, H., Luo, C. et He, J.-S. (2021). Precipitation determines the magnitude and direction of interannual responses of soil respiration to experimental warming. *Plant and Soil*, *458*(1-2), 75-91. https://doi.org/10.1007/s11104-020-04438-y

Zhao, B., Zhuang, Q., Shurpali, N., Köster, K., Berninger, F. et Pumpanen, J. (2021). North American boreal forests are a large carbon source due to wildfires from 1986 to 2016. *Scientific Reports*, *11*(1), 7723. https://doi.org/10.1038/s41598-021-87343-3