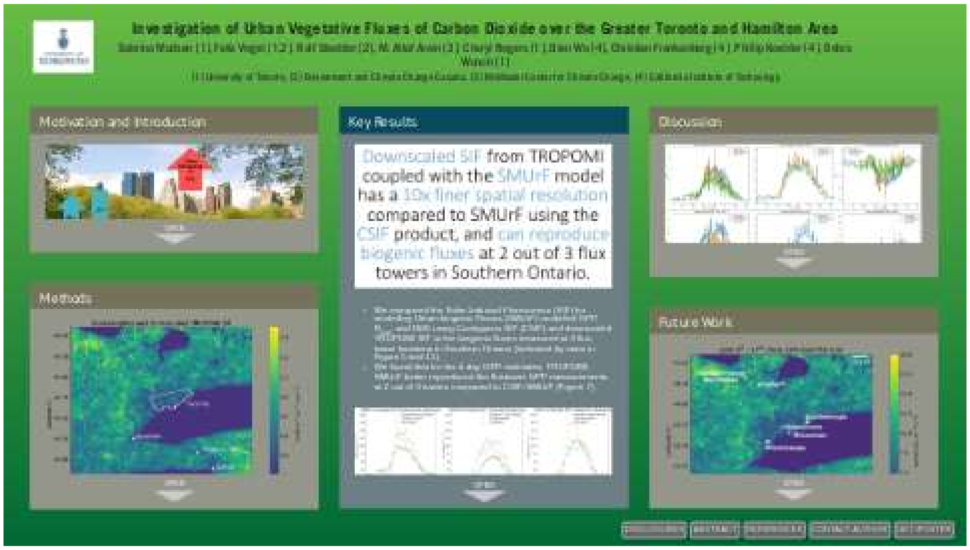
Investigation of Urban Vegetative Fluxes of Carbon Dioxide over the Greater Toronto and Hamilton Area



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PRESENTED AT:

MOTIVATION AND INTRODUCTION

Main Goal: Estimation of the net effect of urban vegetation on the carbon cycle in the Greater Toronto and Hamilton Area

- In order to properly monitor the amount of CO_2 emitted by cities it is important to understand the biogenic fluxes of CO_2 in and arround the area of study.
- Accounting for vegetation will result in better estimates of anthropogenic fluxes which in turn will help cities to monitor and reduce their greenhouse gas emissions **(Newman et al. 2013)**.

- Let's start with some definitions:
  - Net Ecosystem Exchange (NEE): The net amount of CO_2 exchanged between the atmosphere and vegetation
  - Gross Primary Productivity (GPP): Amount of CO_2 sequestered by vegetation via photosynthesis
  - Ecosystem Respiration (R_{eco}): Amount of CO_2 respired by vegetation

NEE = Reco - GPP

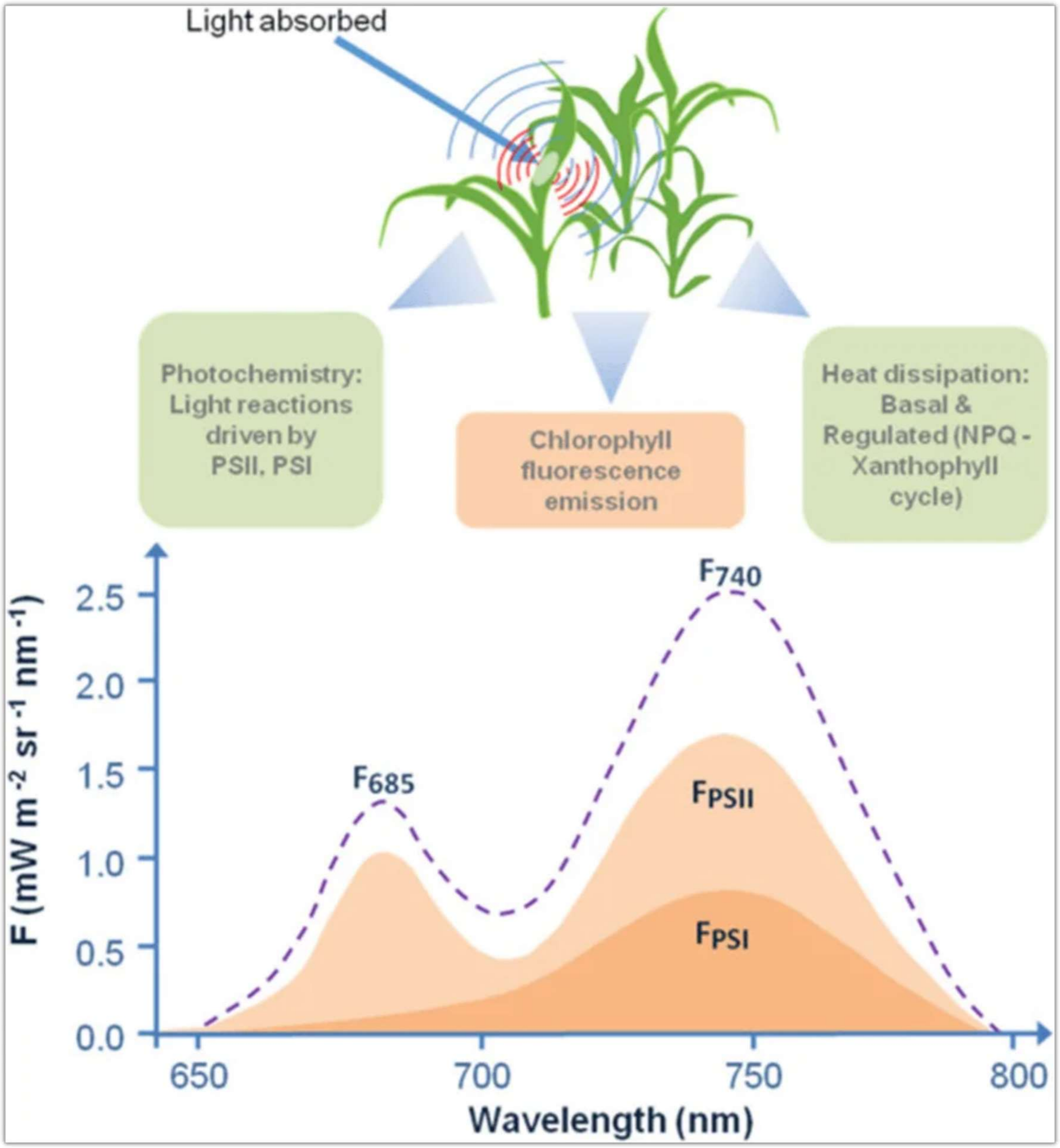

Figure 2: During photosynthesis some energy is re-emitted at a longer wavelength as Solar Induced Fluorescence (SIF), with peaks near 685 nm and 740 nm. Figure from **Mohammed et al. (2019).**

- Solar Induced Fluorescence (SIF), a by-product of photosynthesis, has been shown to be linearly related to GPP on regional scales **(Frankenberg et al., 2011; Magney et al., 2019; Turner et al., 2020; Wood et al., 2017)**.
- SIF has been shown to be a better proxy for photosynthesis than Vegetation Indices which use reflectance to estimate photosynthesis **(Frankenberg et al., 2011)**.
- Therefore SIF can be used to estimate GPP.

METHODS

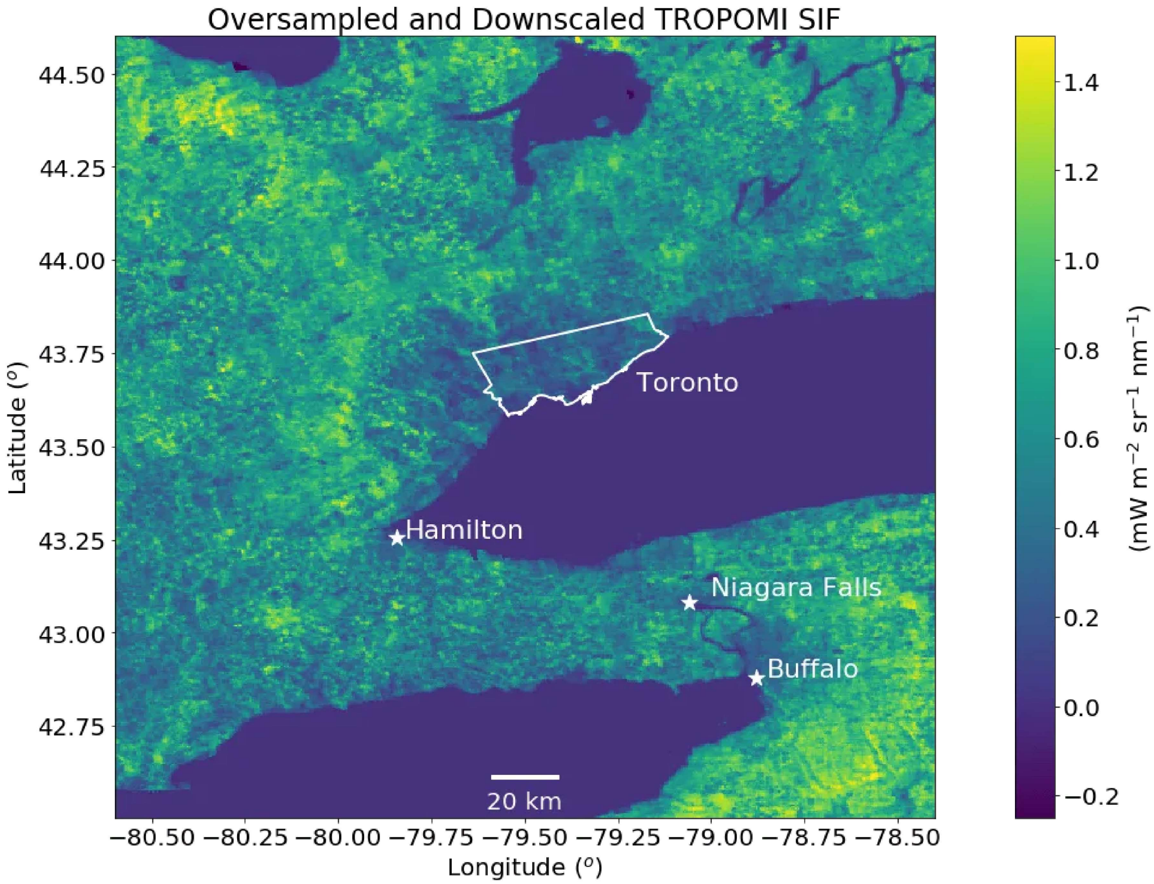

Figure 3: SIF measured from TROPOMI downscaled using NIR_v from MODIS over the Greater Toronto and Hamilton Area averaged over June 4th– 17th, 2018.

- We used SIF from the satellite-borne TROPOspheric Monitoring Instrument (TROPOMI).
- Using the downscaling method outlined in **Turner et al. (2020)** we took overlapping measurements of SIF from TROPOMI and averaged them. This average is weighted by the Near Infrared Reflectance of vegetation index (NIR_v) **(Badgley et al., 2017)** from the MODerate Resolution Imaging Spectroradiometer (MODIS) to allocate the SIF signal to photosynthesizing vegetation.
- We obtained a 500 m x 500 m resolution of SIF over the Greater Toronto and Hamilton Area (Figure 3).

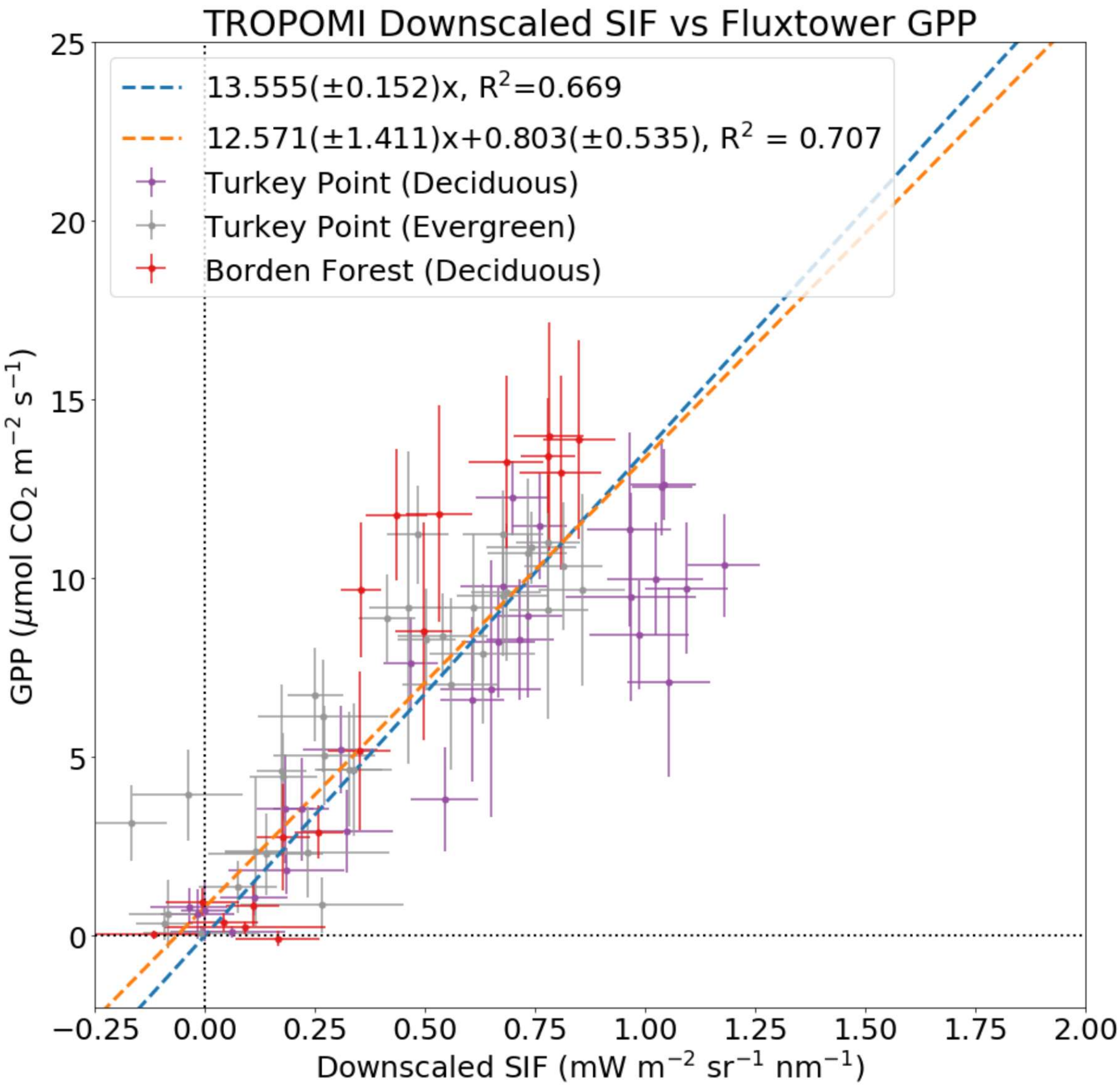

Figure 4: Relationship between downscaled TROPOMI SIF and GPP measured at three flux towers in Southern Ontario.

- We compared the downscaled TROPOMI SIF to GPP measured at three nearby flux towers to obtain a linear relationship between SIF and GPP (Figure 4).
- We used this relationship with the downscaled SIF product to estimate GPP over the Greater Toronto and Hamilton Area at a spatial resolution of 500m x 500m (Figure 5).

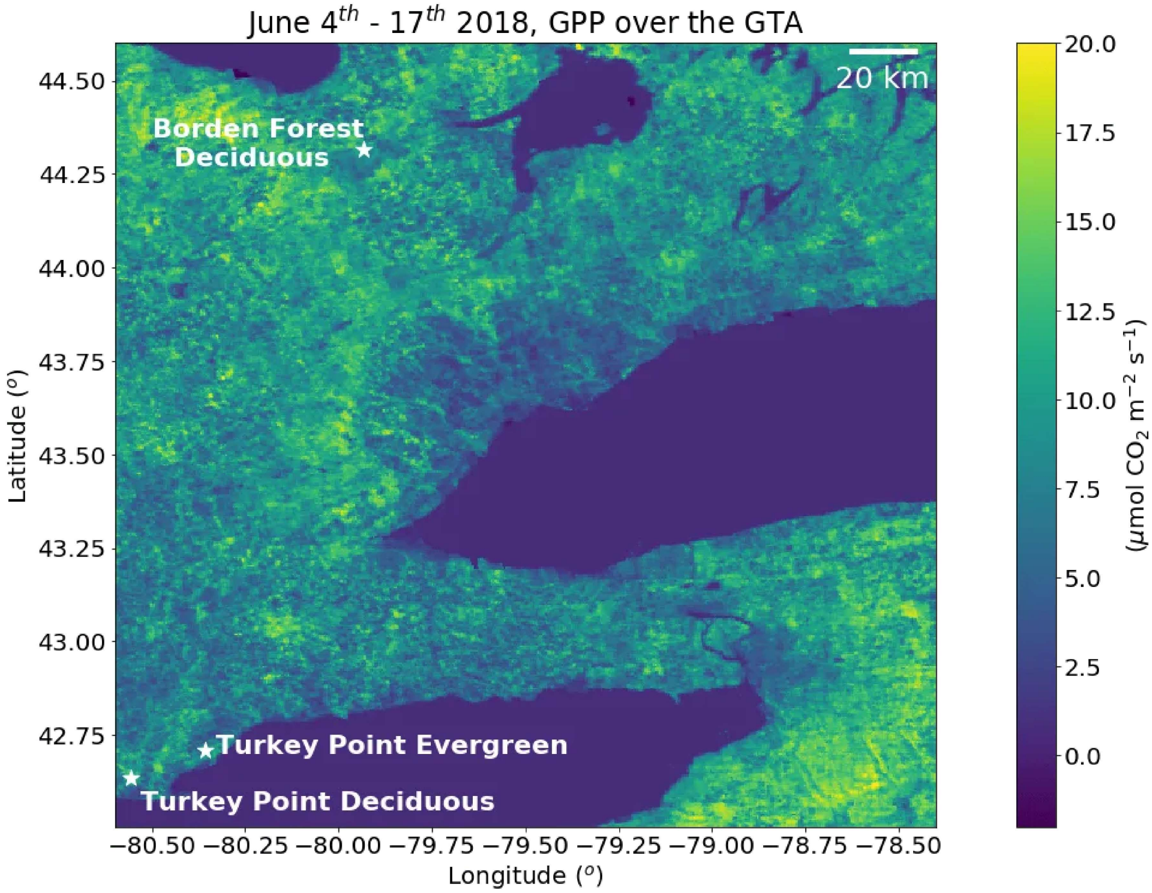

Figure 5: GPP in the Greater Toronto and Hamilton Area from downscaled SIF (Figure 3) scaled by a linear relationship between SIF and GPP (Figure 4). Flux tower locations are indicated by white stars.

- The Solar-Induced Fluorescence for Modeling Urban biogenic Fluxes (SMUrF) model, developed by **Wu et al. (2021)**, uses SIF and meteorological data to model biogenic fluxes, including those in urban areas.
- SMUrF uses the spatially Contiguous SIF (CSIF) data product at a resolution of 0.05^{o} and 4-days and thus the original SMUrF code (CSIF-SMUrF) has a spatial resolution of 0.05^{o} x 0.05^{o} (Figure 6a) **(Zhang et al., 2018; Wu et al., 2021)**.
- We updated SMUrF to use the downscaled TROPOMI SIF product. This new product (TROPOMI-SMUrF) has a resolution of 500 m x 500 m (Figure 6b).

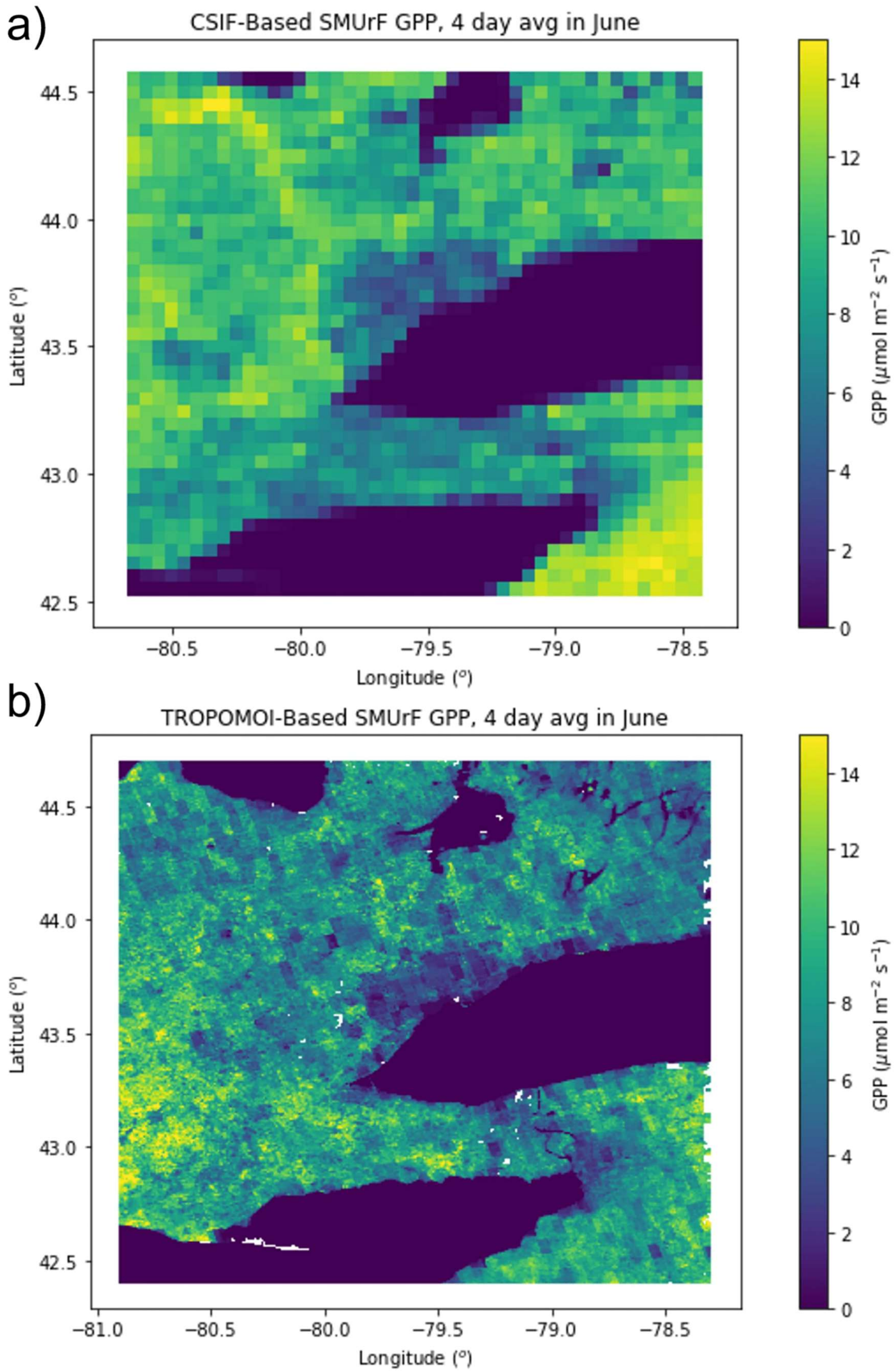

Figure 6: Using downscaled TROPOMI SIF with the SMUrF model (b) obtains a significantly higher spatial resolution compared to SMUrF with CSIF (a).

KEY RESULTS

Downscaled SIF from TROPOMI coupled with the SMUrF model has a 10x finer spatial resolution compared to SMUrF using the CSIF product, and can reproduce biogenic fluxes at 2 out of 3 flux towers in Southern Ontario.

- We compared the Solar-Induced Fluresence (SIF) for modelling Urban biogenic Fluxes (SMUrF) modelled GPP, R_{eco}, and NEE using Contiguous SIF (CSIF) and downscaled TROPOMI SIF to the biogenic fluxes measured at 3 flux tower locations in Southern Ontario (indicated by stars in Figure 5 and 11).
- We found that for the 4-day GPP estimates, TROPOMI-SMUrF better reproduced the fluxtower GPP measurements at 2 out of 3 towers compared to CSIF-SMUrF (Figure 7).

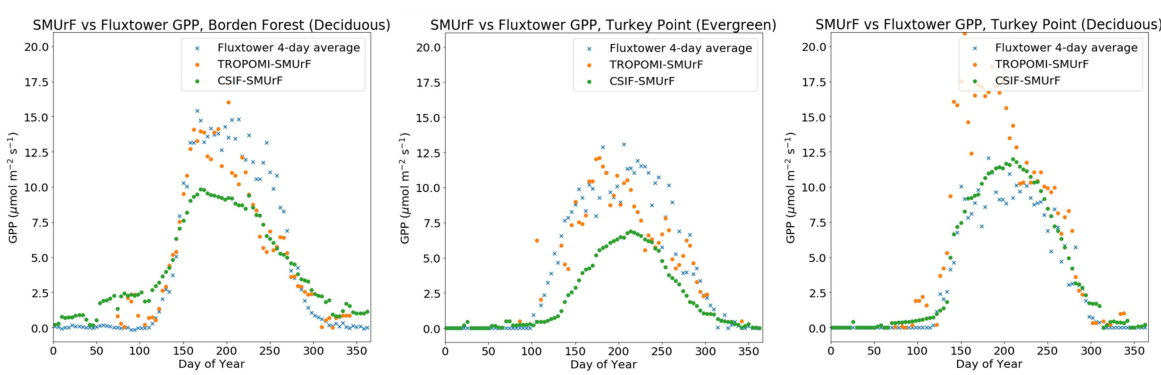

Figure 7: 4-day TROPOMI-SMUrF (orange) GPP agrees better with 4-day averaged flux tower GPP (blue crosses) than does CSIF-SMUrF (green) at 2 out of three flux towers.

- Hourly GPP, R_{eco}, and NEE from TROPOMI-SMUrF and CSIF-SMUrF were compared to estimates from flux towers (Figure 8).
- When using data from all three flux towers, TROPOMI-SMUrF has slightly better 1 to 1 correlation with flux tower data than CSIF-SMUrF.
- R_{eco} is poorly correlated between both TROPOMI-SMUrF and CSIF-SMUrF and fluxtower estimates at hourly scales.

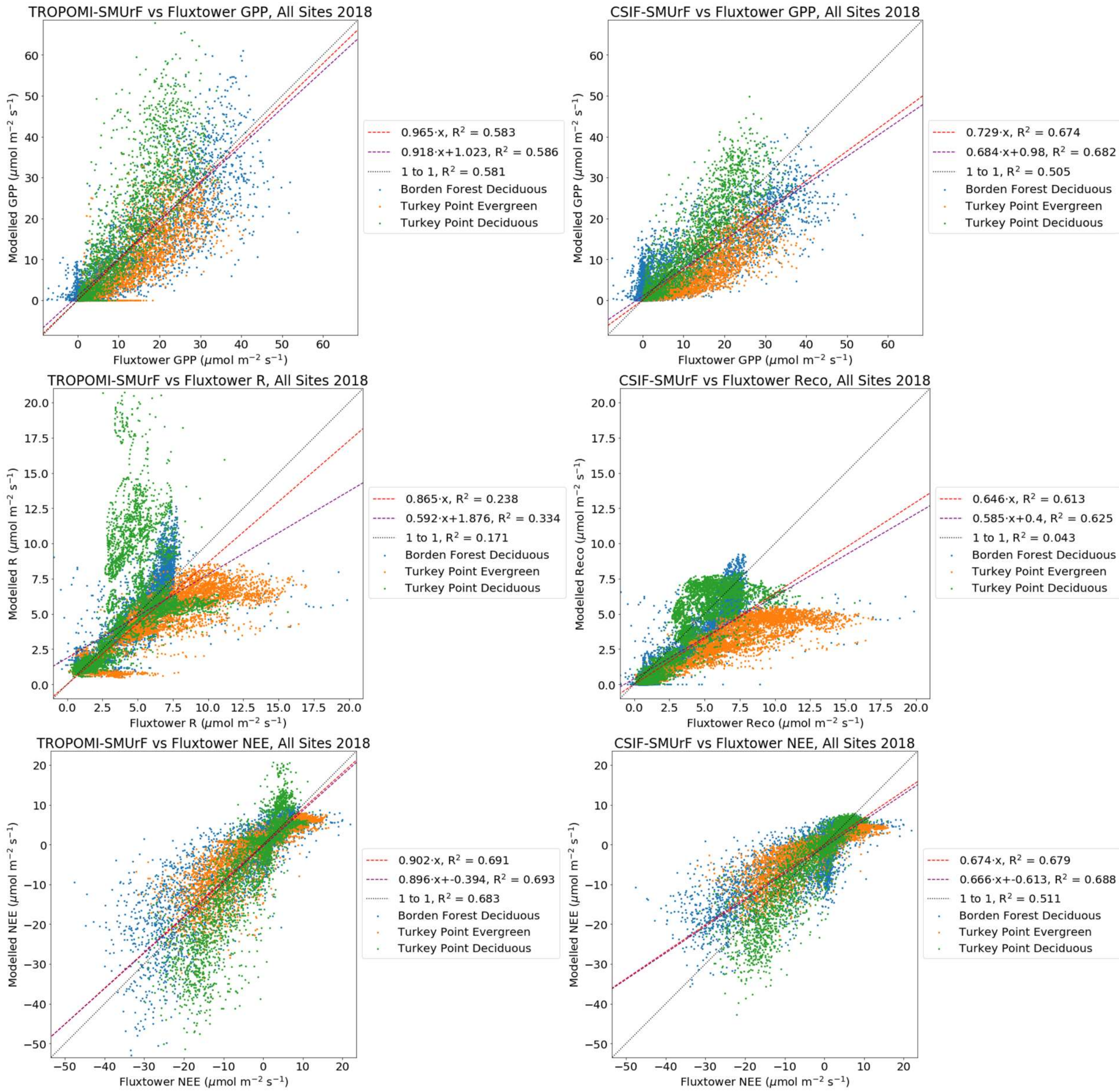

Figure 8: Correlation between hourly TROPOMI-SMUrF (left column) or CSIF-SMUrF (right column) GPP (top row), R_{eco}(middle row) and NEE (bottom row), and flux tower estimates at three flux tower locations in Southern Ontario.

DISCUSSION

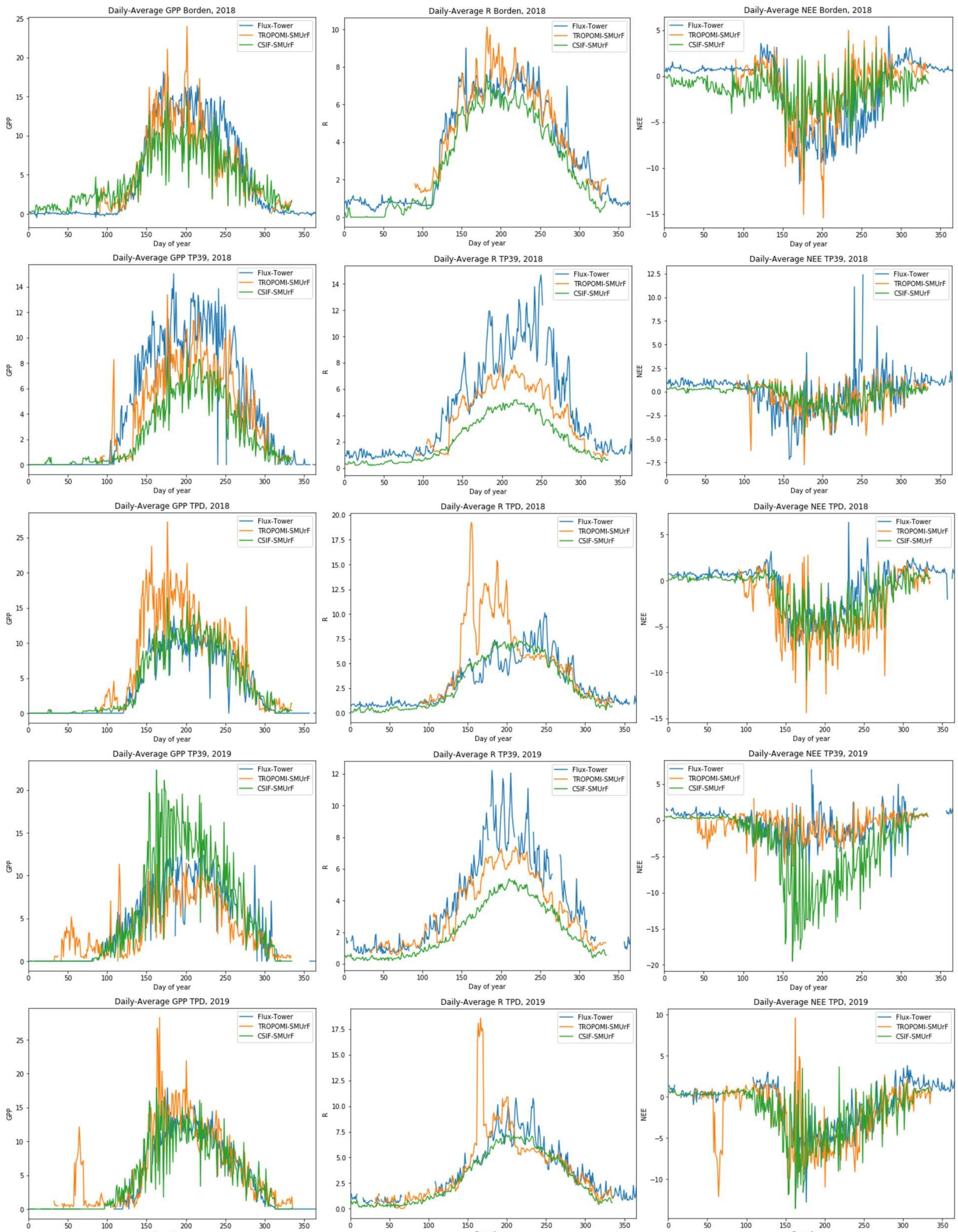

Figure 9: Daily averaged GPP (column 1), R_{eco} (column 2), and NEE (column 3) modelled by SMUrF using downscaled TROPOMI SIF (orange), and CSIF (green) compared to fluxtower estimates (blue) at three fluxtowers during 2018 and 2019.

- Although the overall TROPOMI-SMUrF agrees fairly well with the flux tower measurements, compared to CSIF-SMUrF, there is a significant disagreement in GPP and R_{eco} at the Turkey Point Deciduous plot during late spring and early summer in 2018 and late spring in 2019.
- One potential reason for the disagreement is that the NIRv values over the Turkey Point Deciduous site are significantly higher than the surroundings in spring and early summer while they are comparable to the surroundings in late summer (Figure 10).

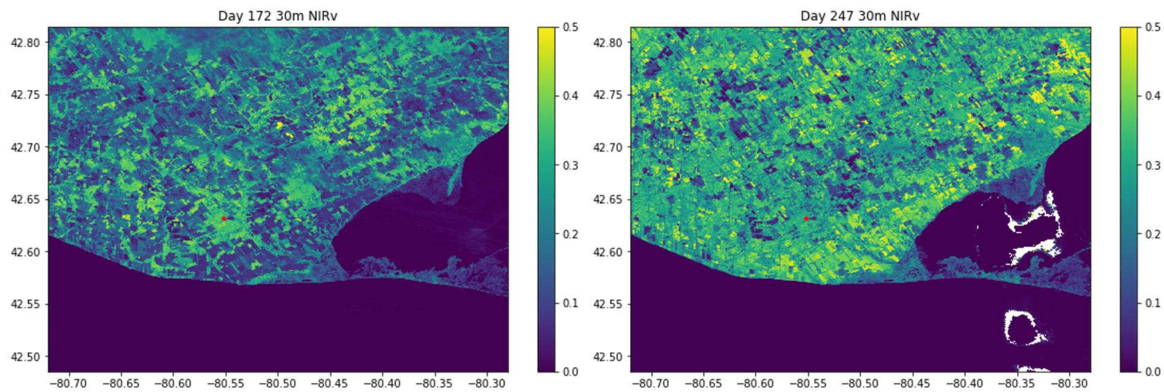

Figure 10: NIRv, from the Harmonized Landsat Sentinel-2 surface reflectance dataset **(Claverie et al., 2018)** over the Turkey Point Deciduous flux tower (red dot) in early summer (left) and late summer (right) 2018.

- Since downscaled SIF is weighted by NIRv, a higher NIRv signal will allocate more SIF to that location than surrounding locations. Since SIF and NIRv are not perfectly correlated (**Turner et al., 2020)** this could be causing a high bias in the downscaled SIF (and therefore TROPOMI-SMUrF GPP) during early summer.
- Another potential reason for the disagreement may be that the flux tower is measuring fluxes from areas outside of the forest plot thus altering the fluxes observed at the tower. This may also affect the relationship between the TROPOMI-SMUrF GPP and the Turkey Point Deciduous flux tower values.
- Further investigation is required to determine the root cause of the disagreement between the modelled TROPOMI-SMUrF fluxes and those determined from this particular flux tower.

FUTURE WORK

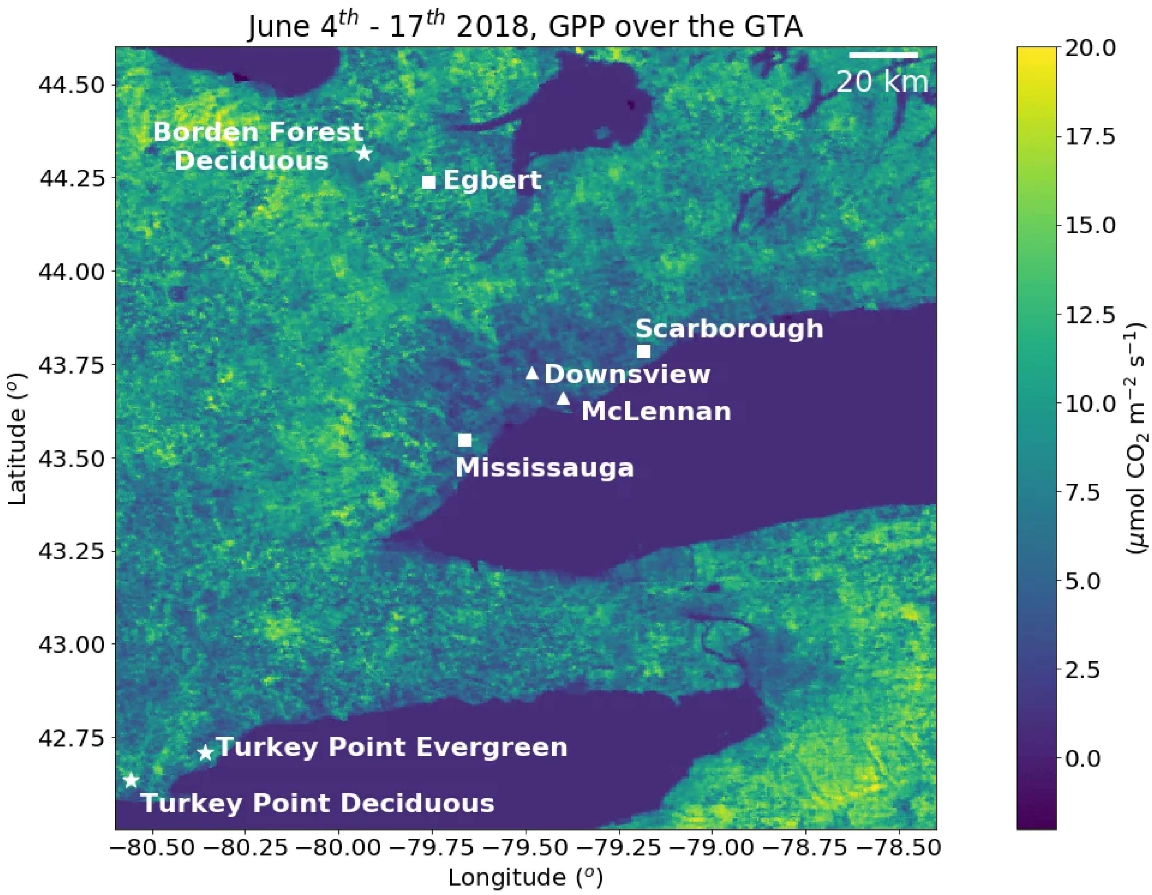

Figure 11: Locations of currently automated (triangles) and future or non-automated (squares) EM 27/Sun instruments which will be used to measure total column CO_2 and the estimated biogenic fluxes to try to asses the contribution of fluxes from vegetation to the measurement. Fluxtowers are indicated by white stars.

Future work includes:

- Further investigation of the disagreement between TROPOMI-SMUrF fluxes and those estimated at the Turkey Point Deciduous flux tower.
  - Running TROPOMI-SMUrF without weighting TROPOMI-SIF by NIRv
  - Investigation of the effect of wind speed and direction on fluxes at theTurkey Point Deciduous flux tower.
- Running and comparing the Urban Vegetation Photosynthesis and Respiration Model (UrbanVPRM) to SMUrF and fluxtower estimates of GPP, R_{eco}, and NEE **(Hardiman et al., 2017).**
- Using downscaled SIF, SMUrF, and/or UrbanVPRM to estimate vegetative fluxes of CO_2 in the Greater Toronto and Hamilton Area.
- Combining column CO_2 measurements, from ground-based EM27/Sun instruments located throughout the GTA and the Orbiting Carbon Observatory versions -2 and -3, with vegetative fluxes to better constrain anthropogenic CO_2 emissions.

- Applying this method to Canada's 4 largest cities to better estimate the role of vegetation on the urban carbon cycle.

DISCLOSURES

TROPOMI SIF data are available online at ftp://fluo.gps.caltech.edu/data/tropomi/ (fluo.gps.caltech.edu/data/tropomi/)

MODIS NBAR (MCD43A4.006) and landcover (MCD12Q1.006) data are available via NASA's Land Processes DirtributedActive Archive Center (LP DAAC) at https://e4ftl01.cr.usgs.gov/MOTA/ (https://e4ftl01.cr.usgs.gov/MOTA/)

GPP data was obtained from Environment and Climate Change Canada for the Borden Forest site and from McMaster Centerfor Climate Change for the Turkey Point sites.

Harmonized Landsat and Sentinel-2 surface reflectance data are available online at Harmonized Landsat Sentinel-2 (nasa.gov) (https://hls.gsfc.nasa.gov/)

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Natural Sciences and Engineering Research Council of Canada Conseil de recherches en sciences naturelles et en génie du Canada

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ABSTRACT

Terrestrial vegetation is known to be an important sink for carbon dioxide (CO_2). However, fluxes to and from vegetation are often not accounted for when studying anthropogenic CO_2 emissions in urban areas. This project seeks to quantify urban biogenic fluxes in the Greater Toronto and Hamilton Area located in Southern Ontario, Canada. Toronto is Canada's most populated city but also has a large amount of green-space, covering approximately 13 % of the city. In addition, vegetation is not evenly distributed throughout the region. We therefore expect biogenic fluxes to play an important role in the spatial patterns of CO_2 concentrations and the overall local carbon budget. In order to fully understand biogenic fluxes they can be partitioned into the amount of CO_2 sequestered via photosynthesis, gross primary productivity (GPP), and the amount respired by vegetation, ecosystem respiration (R_{eco}). Solar induced chlorophyll fluorescence (SIF) measured from space has been shown to be a valuable proxy for photosynthesis and thus can be used to estimate GPP. Vegetation models, including the Urban Vegetation Photosynthesis and Respiration Model (UrbanVPRM) and the SIF for Modelling Urban biogenic Fluxes (SMUrF) model, have also been used to estimate both GPP and R_{eco}. In this study we compare modelled and SIF-derived biogenic CO_2 fluxes at a 500 m by 500 m resolution, to ground-based flux tower measurements in Southern Ontario to determine which method best estimates biogenic CO_2 fluxes. These fluxes will also be compared to local measurements of total column CO_2. This study works towards determining the importance of biogenic fluxes in the Greater Toronto and Hamilton Area. Furthermore, the results of this work may inform policy makers and city planners on how urban vegetation affects CO_2 concentrations and patterns within cities.

REFERENCES

Badgley, G., Field, C. B., and Berry, J. A.: Canopy near-infrared reflectance and terrestrial photosynthesis, Science Advances, 3(3), e1602244–e1602244, https://doi.org/10.1126/sciadv.1602244 (https://doi.org/10.1126/sciadv.1602244), 2017.

Claverie, M., Ju, J., Masek, J. G., Dungan, J. L., Vermote, E. F., Roger, J.-C., Skakun, S. V., & Justice, C.: The Harmonized Landsat and Sentinel-2 surface reflectance data set, Remote Sensing of Environment, 219, 145–161, https://doi.org/10.1016/j.rse.2018.09.002 (https://doi.org/10.1016/j.rse.2018.09.002), 2018.

Frankenberg, C., Fisher, J. B., Worden, J., Badgley, G., Saatchi, S. S., Lee, J.-E., Toon, G. C., Butz, A., Jung, M., Kuze, A., and Yokota, T.: New global observations of the terrestrial carbon cycle from GOSAT: Patterns of plant fluorescence with gross primary productivity, Geophysical Research Letters, 38(17), L17706, https://doi.org/10.1029/2011GL048738 (https://doi.org/10.1029/2011GL048738), 2011.

Hardiman, B., Wang, J., Hutyra, L., Gately, C., Getson, J., Friedl, M.: Accounting for urban biogenic fluxes in regional carbon budgets, Science of The Total Environment, 592, 366-372, https://doi.org/10.1016/j.scitotenv.2017.03.028 (https://doi.org/10.1016/j.scitotenv.2017.03.028), 2017.

Magney, T. S., Bowling, D. R., Logan, B. A., Grossmann, K., Stutz, J., Blanken, P. D., Burns, S. P., Cheng, R., Garcia, M. A., Köhler, P., Lopez, S., Parazoo, N. C., Raczka, B., Schimel, D., and Frankenberg, C.: Mechanistic evidence for tracking the seasonality of photosynthesis with solar-induced fluorescence, Proceedings of the National Academy of Sciences - PNAS, 116(24), 11640–11645. https://doi.org/10.1073/pnas.1900278116 (https://doi.org/10.1073/pnas.1900278116), 2019.

Mohammed, G. H., Colombo, R., Middleton, E. M., Rascher, U., van der Tol, C., Nedbal, L.,Goulas, Y., Pérez-Priego, O., Damm, A., Meroni, M., Joiner, J., Cogliati, S., Verhoef, W., Malenovský, Z., Gastellu-Etchegorry, J.-P., Miller, J. R., Guanter, L., Moreno, J., Moya, I., Berry, J. A., Frankenberg, C., and Zarco-Tejada, P. J.: Remote sensing of solar-induced chlorophyll fluorescence (SIF) in vegetation: 50 years of progress, Remote Sensing of Environment, 231, 111177, https://doi.org/10.1016/j.rse.2019.04.030 (http://https://doi.org/10.1016/j.rse.2019.04.030), 2019.

Turner, A. J., Köhler, P., Magney, T. S., Frankenberg, C., Fung, I., and Cohen, R. C.: A double peak in the seasonality of California's photosynthesis as observed from space, Biogeosciences, 17, 405–422, https://doi.org/10.5194/bg-17-405-2020 (https://doi.org/10.5194/bg-17-405-2020), 2020.

Wood, J. D., Griffis, T. J., Baker, J. M., Frankenberg, C., Verma, M., and Yuen, K.: Multiscale analyses of solar-induced florescence and gross primary production, Geophysical Research Letters, 44(1), 533 - 541, https://doi.org/10.1002/2016GL070775 (https://doi.org/10.1002/2016GL070775), 2017.

Wu, D., Lin, J. C., Duarte, H. F., Yadav, V., Parazoo, N. C., Oda, T., and Kort, E. A.: A model for urban biogenic CO2 fluxes: Solar-Induced Fluorescence for Modeling Urban biogenic Fluxes (SMUrF v1), Geosci. Model Dev., 14, 3633–3661, https://doi.org/10.5194/gmd-14-3633-2021 (https://doi.org/10.5194/gmd-14-3633-2021), 2021.

Zhang, Y., Joiner, J., Alemohammad, S. H., Zhou, S., and Gentine, P.: A global spatially contiguous solar-induced fluorescence (CSIF) dataset using neural networks, Biogeosciences, 15, 5779-5800, https://doi.org/10.5194/bg-15-5779-2018 (https://doi.org/10.5194/bg-15-5779-2018), 2018.