Technical project proposal description

ICAAP – Increasing Carbon Accumulation in Arctic Peatlands

Principal Investigator: Prof. Angela Gallego Sala

1. Rationale

Peatlands are an important part of the global carbon cycle and store approximately one third of the terrestrial soil carbon (C) pool, with 500 ± 100 Gt C in northern peatlands [1,2], the equivalent to total global vegetation biomass. This vast northern peatland C pool is thought to be vulnerable to the large temperature increases resulting from climate change and increasing rates of decay [3]. The focus of much of the existing work is on the processes for loss of peatland and permafrost carbon [4], changes in thermokarst [e.g. 5], fire [6, 7] and peatland loss in temperate regions [8]. However, increasing temperatures will also drive an increase in plant productivity and an overall increase in the rate of vertical carbon accumulation [9-12], plus warming may also lead to the expansion of peatland extent leading to greater C accumulation in Arctic peatlands overall. The potential for increased high latitude peatland C accumulation is untested and unknown.

Existing work by us and others now shows that during past long-term warming events, there was a larger increase in primary productivity than decomposition that led to an increase of vertical peat accumulation rates from northern peatlands as a whole, based both on observed rates of peat accumulation in palaeo-records [9,10,11] and a global model that includes total peat accumulation [12]. Furthermore, there is also evidence that recent warming may have led to increased peat accumulation for some high latitude northern peatlands [13, 14].

The overall response of the peatland C sink at high northern latitudes will be determined by changes in peatland extent as well as in carbon accumulation rates. Past changes in peatland extent probably played a key role in the past global C balance [15] and such changes have been reported from many regions, e.g. [16], but there has been no attempt to assess whether future changes in Arctic peatland extent could be a significant feedback to climate change. The over-arching aim of the project is to test the hypothesis that changes in the Arctic peatland C pool will help mitigate future warming, taking account of both changes in accumulation rates and changes in the extent of peatlands. Demonstration and quantification of an increasing C sink in arctic peatlands would represent a fundamental shift in our understanding of the role of the arctic terrestrial C store in mediating climate change. The potential increased sink is in the order of 2Tg yr^{-1}, assuming a 1% areal expansion and an increase of 10 $gCm^{-2}yr^{-1}$ in vertical accumulation.

Because carbon flux field data in Arctic peatlands is still limited temporally and spatially, i.e. there are few individual site measurements that go back sufficiently in time, plus the fluxes involved are very small, it is difficult to upscale these direct measurements to estimate the overall response of arctic peatland carbon to warming over decadal to centennial timescales. As an alternative, we propose a novel combination of palaeo-ecological and remote sensing methodologies to test dynamic global vegetation model (DGVM) simulations of peatland extent and accumulation rates over the circum-Arctic region for the last millennium, the last 150 years and the last c.30 years.

2. Objectives

Hypothesis 1 – Arctic peatlands C accumulation rates increased in response to warmer past climates:

- Objective 1a. Establish the relationship between C accumulation rates and climate warming.

We will test the response of Arctic peat accumulation to warming by developing records of apparent C accumulation changes at selected locations in the Northeastern Canadian (CA) and European Arctic (EA). We will focus on two main time periods: i) the last millennium focusing on the contrast between the MCA (Medieval Climate Anomaly) and LIA (Little Ice Age) and ii) the post-LIA warming period, specifically focusing on renewed onset of peat formation.

• Objective 1b. Develop model runs using the 'LPX' DGVM to simulate changes in peat accumulation rates over the pan-Arctic using CMIP5 climate model runs for the last millennium and meteorological and reanalysis data for the instrumental period.

Hypothesis 2 – Arctic peatlands have expanded laterally due to increased temperature since the LIA, including post-industrial warming:

• Objective 2a. Explore the relationship between recent (last 30 yr) climate warming and changes in peatland extent using satellite data to measure changes in the extent of peatland vegetation (moss/sedge cover), especially at northern limits of peatland distribution.

• Objective 2b. Assess longer term (200-300 yr) peatland spread in relation to climate warming using field data for dates of peat initiation (14C, 210Pb) at the margins of existing peatlands.

Hypothesis 3 – Future climate change will result in an increase of the Arctic peatland C store as a result of increased rates of C accumulation and increased potential for new peatland formation.

• Objective 4a. Evaluate the past model simulations with the field and satellite data on C accumulation rates and changes in peatland extent.

• Objective 4b. Use ensemble model runs of LPX driven by the RCP climate scenarios to estimate future changes in peat accumulation rates and lateral extent, leading to estimates of the changes in the total C store in northern Arctic peatlands. These will include assessment over shorter (2100 AD) and longer term (2300 AD) RCP scenarios.

3. Progress to date

The field-work has been completed in the European sites (in 2019) and a first paper on remote sensing of changes in productivity is about the be submitted. Lab work on the peat cores from European sites is partially completed. This year is our final chance to obtain field data for Canada.

4. Methodology

4.1 Study site locations

Our overall approach is to develop a detailed set of in-situ and satellite data from two broad study regions: Canadian Arctic/Sub-arctic and European Arctic/Sub-Arctic (Fig. 1). We have chosen two different Arctic Regions to cover some of the spatial variability of the Arctic. There will be two study areas in each region: one with more extensive existing peatlands in the sporadic and discontinuous permafrost zone where permafrost was more prevalent in the LIA, and one at a more northerly location where peat development is sporadic, but where recent temperature change should have begun to drive vegetation changes and the early stages of peatland spread if our hypotheses are correct.

Using these two latitudinal transects will allow us to test the effect of an increase in the growing season length on the carbon sink. We have identified suitable field locations in these regions, where peat is bordering a non-peat ecosystem and where substantive local logistical support is available through our research partners.

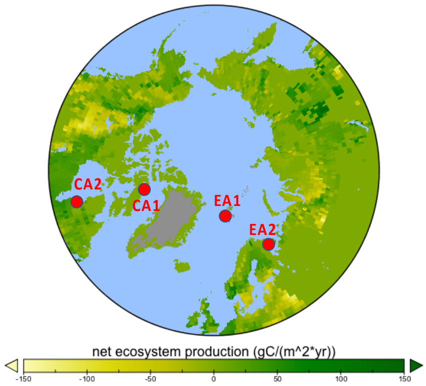

Figure 1: Site locations superposed over a map of millennium (850-1850 AD) NEP LPX using MIROC climate outputs.

4.2 WP1 Peatland accumulation rates and long term lateral spread (Objectives 1a, 2b)

We will sample three + sites in each of the four study areas. Replication within each of the study areas is important for statistical testing of differences between regions and estimation of uncertainty in rates of accumulation and lateral spread. At each site, a central core will be used to estimate changes in peat accumulation rates (i.e. one core at 3 replicate sites in each of 4 regions = 12 cores). Some sites in high Arctic locations may have little appreciable C accumulation over the past millennium or may have a hiatus with a recommencement of peat growth in more recent centuries [9], so replication is essential. Initial coarse chronologies for each core will be established by 2 to 3 ^{14}C dates per core to make sure we target the last millennium. Bulk density, C and nitrogen analyses will be measured in 1cm depth increments. Full chronologies will be determined using ^{14}C dates (approx. total 9-10 dates per core, including 2-4 post bomb spike ages) and ^{210}Pb analyses. These will be used to derive estimates of peat accumulation rates over the past millennium and the last 150 years.

To test for lateral spread of peat at each site, transects from mineral ground to shallow peat at the edges of sites will be sampled by short sections or cores. Transects will be systematically sampled over a depth gradient (e.g. at locations in 3cm depth increments, up to 30cm max depth. Approximately 10 profiles per site will be used across a range of shallow depths. Basal ages will be estimated from a combination of ^{14}C and ^{210}Pb dating. We anticipate having to date the start of recent moss growth using bomb-spike ^{14}C ages at times. Total C accumulated since inception will be measured by bulk density and C content. The rate of lateral spread will be calculated both as age-distance and as age-total C relationships.

To characterise each site for plant communities and topography, we will fly a drone over the study area to create a detailed orthomosaic.

4.3. WP2 Pan-Arctic changes in lateral extent of peatland vegetation over the past 30 years using remote sensing (Objective 2a)

During the satellite era (~40 years), significant changes have been observed in high latitude temperatures [17] and satellite time-series analysis (typically focused on analyses of the normalized difference vegetation index (NDVI); and including, but not limited to Landsat data) have been used to demonstrate vegetation responses in the Arctic region [18-20].

a. Map greenness change: Using data from the Landsat 5 to 8 time series (1984-present) we will extend NDVI (productivity) datasets to new regions Arctic-wide. To achieve this, we will exploit Google Earth Engine (GEE)’s cloud processing capability which will expedite access to the petabytes of satellite data (including the full Landsat archive) contained in the catalogue [21]. Two products will be generated: (i) a spatial map of areal changes in greenness (binary vegetation vs. non-vegetation); (ii) a product reporting changes in greenness (increased vs. decreased NDVI). We will experiment with integrating older Landsat data (missions 1-4) providing up to c.45 years of data, requiring careful handling of radiometric transitions. Providing a direct link to 3.2 (peatland lateral extent from field measurements) we will create timeseries classifications of the field sites for greenness. We will compare the Landsat-predicted “new” peat locations with measured field data for vegetation cover and peat age.

b. Plant type mapping: A second step will seek to refine the existing circum-Arctic vegetation map (CAVM) vegetation classification using a novel scheme that is focused on peatland functional types [22]. We will exploit a peatland classification approach developed by KC and KA that in UK peatlands could discriminate peatland vegetation types based on spatial patterns in the radiometric data arising from structural differences in the vegetation canopies. This has not been attempted previously in Arctic systems so will need investment to adapt it to the Arctic, informed and validated by in situ and drone-based data from WP1.

c. Scaling up: The regularity of cloud-free Landsat measurements is unpredictable. We will explore the use of other global-extent satellite datasets (e.g. MODIS products) with coarser spatial resolution (250m to 1km) but finer temporal resolution.

4.4. WP3 Modelling past changes in peat accumulation and extent (Objectives 1b, 2c)

Understanding past changes in long-term peat accumulation requires projections for future changes made using process-based models. Only a few DGVMs are beginning to incorporate peatland dynamics including peat accumulation and permafrost; LPX is the most advanced in this sense [11].

We will use LPX-Bern to calculate changes in C accumulation as well as peatland extent for each gridcell corresponding to the collection sites for the last millennium using the transient climate simulation outputs performed for the 5th Assessment of IPCC [CMIP5 simulations, 23]. The methodology for 21st century simulations of peatland C dynamics is similar except for the climate forcing that will come from the CMIP5 21st century simulations [RCP scenarios, 23]. The model output for each gridcell will be a temporally resolved dataset over the last millennium of both peatland percentage coverage and changes in accumulation rates that can be aggregated over the same time resolution as the observations.

4.5. WP4 Data-model comparisons (Objective 3a)

The model output will be tested against a series of data sets:

i) Peatland extent changes over the past millennium; the model will simulate changes in peatland vegetation (mosses and flood tolerant graminoids) and peatland extent (the percentage of the gridcell that is actively accumulating C). This output will be tested against lateral spread rates over the past millennium calculated from the trends shown by the shallow core basal dates.

ii) Spatial patterns of last millennium C accumulation; we will choose the appropriate half-degree gridcells to represent each of the four study regions in order to estimate spatial differences in modelled C accumulation which can be compared to spatial differences in the measured C accumulation rates from the extracted cores. We anticipate that the lower latitude regions will accumulate C faster than the high latitude regions; both the relative observed difference and absolute measured rates will be compared to model output.

iii) Temporal trends in C accumulation with particular emphasis on the switch-on of C accumulation after the LIA in the northern locations; The model will produce annually resolved data for C accumulation that can be aggregated in time to produce decadal average C accumulation. The C accumulation changes over the cooling from the MWP-LIA and the warming since the LIA will be compared to the measured C accumulation rates in each of the four study regions.

iv) Changes in coverage of peatland vegetation since the mid-1980s; we will compare the observed changes in extent of peatland vegetation over the past c.30 years derived from remote sensing with model output data. The comparison will be undertaken both in individual study areas and for the whole Arctic, comparing the directional trends across very large areas.

v) Model calibration; The model-data comparison will allow for further calibration of model parameters such as N (number of months during which an area must be inundated in the last 31 years to reach the required inundation persistency for peatland development), λ (a parameter used in calculating effective soil depth) and the parameters for peatland expansion conditions: C*peat (a threshold of minimum total accumulated C) and dC*peat/dt (a threshold of minimum peat C accumulation rate) set to >50 kg C m-2 and >10 g C m-2 yr-1 respectively [24]. The model-data comparison will allow for testing the validity of model outputs on the Arctic, where model estimations of hydrological process and C balance remain uncertain [25].

4.6. WP5 Simulations of future changes in the peatland C sink (Objective 3b)

The LPX-Bern model framework will be used to simulate changes in the Arctic peatland C sink, specifically transient changes in both rates of C accumulation and peatland extent. We will drive the model with climate model outputs using the CMIP5 database of 20 different models that is available to the community in the context of the IPCC AR5. We will estimate the changes in peatland extent and the associated changes in C stocks under a low (RCP2.6) and high (RCP 8.5) climate change scenario in order to bracket the possible future of peatland dynamics. We will focus on both shorter term (to 2100 AD) and multi-centennial (2300 AD) timescales. The model also estimates methane flux and we will use this to provide an additional first order estimate of overall global warming potential (GWP) change, although testing of the methane element of the model is beyond the scope of this project.

5. **Data management (plan, where and when data will be stored)**

All data will be made available for use by the wider community, but with embargo period (from date of collection) to allow publication of the results beforehand. On publication, the data will be available. Peat core data will be deposited to NGDC (National Geoscience Data Centre, UK), and remote sensing data and datasets derived from satellite data to the NGDC or to the CEDA (Centre for Environmental Data Analysis).

6. **Research outputs**

Publications:

Climate drivers of recent changes in productivity and extent in Arctic peatlands
Climate drivers of changes in productivity and extent since the MWP/LIA
Comparison of model predicted and data measured changes in carbon accumulation and extent since the MWP/LIA
Microtopographic characteristics of a series of Arctic peatlands

Datasets:

Peat core data: Bulk density, C:N data, lead-210, radiocarbon, age-depth model, accumulation rate
Recent changes in peatland productivity and extent from Landsat data at all study sites
Drone orthomosaic and points clouds characterising all study sites
LPX model outputs for carbon accumulation and peatland extent corresponding to our study sites

References

[1] Ciais (2013) in *Climate Change 2013:* Stocker, eds. **[2]** Yu (2010) *Geophys. Res. Letters* 37 **[3]** IPCC (2013) in *Climate Change 2013:* Stocker., eds. **[4]** Schuur *(2015) Nature* 520 :171. **[5]** Anthony (2014) *Nature* 511 :452 **[6]** Turetsky (2011) *Nature Comm.* 2 **[7]** Turetsky (2015) *Nature Geosc.* 8 :11 **[8]** Gallego-Sala & Prentice (2013) *Nature Clim. Change* 3 :152 **[9]** Charman (2013) *Biogeosc.* 10:929 **[10]** Loisel (2014) *The Holocene* 24, 1028 **[11]** Gallego-Sala and Charman et al. Nature Clim. Change, submitted (2017) **[12]** Spahni et al., *Clim. of the Past* 9, 1287-1308 (2013). **[13]** Klein, et al., *Palaeogeog. Palaeoclim. Palaeoecol.* 392, 186-195 (2013). **[14]** Loisel & Yu, *J. of Geophys. Res.-Biogeosc.* 118, 41-53 (2013). **[15]** Korhola *et al.*, *Quat. Sci. Rev.* 29, 611-617 (2010). **[16]** Zhao *et al.*, *The Holocene* 24, 1137-1145 (2014). **[17]** Cunliffe et al. Remote Sens. of Environm. 183, 129-143 (2016) **[18]** Myneni, et al. Nature 386, 698-702 (1997). **[19]** Epstein *et al.*, *Environ. Res. Letters* 7, (2012). **[20]** Xu *et al.*, *Nature Clim. Change* 3, 581-586 (2013). **[21]** Gorelick et al., Remote Sens. of Environm. In Press (2017). **[22]** Crichton et al., *Ecohydrol.* 8, 493-503 (2015). **[23]** Taylor, et al. World Clim. Res. Prog. http://cmip-pcmdi.llnl.gov/cmip5/, (2009). **[24]** Stocker et al., *Geosci. Model Dev.* 7, 3089-3110 (2014). **[25]** McGuire (2012) *Biogeosci.,* 9, 3185-3204 (2012).