VEGETATION COUPLING
The boreal and Arctic zone

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Outline

• Motivation and background

• WRF regional modelling vegetation impacts
  – Northward migration of vegetation in the Boreal and Arctic zones

• NorESM global climate modelling
  – Dynamic global vegetation modelling: CLM4.5 – BGCDV
  – Feedbacks and stability

• Summary and future research
Motivation Arctic vegetation as a tipping element
Motivation  Arctic vegetation as a tipping element

increased water stress, increased peak summer heat stress

increased mortality, vulnerability to disease and subsequent fire, as well as decreased reproduction rates

Continental steppe grasslands will expand at the expense of boreal forest

Lenton et al. 2008
<table>
<thead>
<tr>
<th>Tipping element</th>
<th>Boreal forest</th>
<th>Amazon rainforest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feature (direction) of change</td>
<td>Tree fraction (-)</td>
<td>Tree fraction (-)</td>
</tr>
<tr>
<td>Control parameter</td>
<td>Local $\Delta T_{\text{air}}$</td>
<td>Precipitation, dry season length</td>
</tr>
<tr>
<td>Critical value</td>
<td>$+\sim 7^\circ\text{C}$</td>
<td>$1,100$ mm/yr</td>
</tr>
<tr>
<td>Global warming</td>
<td>$+\sim 3-5^\circ\text{C}$</td>
<td>$+\sim 3-4^\circ\text{C}$</td>
</tr>
<tr>
<td>Transition timescale</td>
<td>$\sim 50$ yr (gradual)</td>
<td>$\sim 50$ yr (gradual)</td>
</tr>
<tr>
<td>Key impacts</td>
<td>Biome switch</td>
<td>Biodiversity loss, decreased rainfall</td>
</tr>
</tbody>
</table>

Lenton et al., PNAS, 2008
Biogeochemical and biogeophysical effects of forests

Bonan, Science, 2008
LATICE: Land ATmosphere Interactions in Cold Environments

- Land-Atmosphere feedbacks and regional climate
- Cold environments (snow, ice, permafrost, vegetation)
- Interdisciplinary group at UiO (met, hyd, cryo, ecology)
- Observation and modelling based approach
- Process understanding yielding improved ESM
Climate modelling

Global: NorESM - CLM

Regional: WRF NOAH -> CLM

Giorgi et al., WMO Bulletin
Magnitude of Arctic trend from 1982 to 2008 (i.e., total trend magnitude over 27 yr) of (a) sea ice concentration at the 50% climatological value, (b) SWI, (c) MaxNDVI, and (d) TI-NDVI. SWI and NDVI trends are shown only for tundra regions (southernmost plot latitude is 558N and color scales are not linear).

Bhatt et al., Earth Interactions, 2010
Arctic vegetation vs sea ice

Autumn sea-ice and temperature trends in the Arctic. Linear trends in tundra mean air-temperature and sea-ice concentration (September and October, 1979 to 2011). Where temperature or sea-ice trends were insignificant (p<0.05), the value was set to zero (white for the ocean, grey for the tundra).

Parmentier et al. 2013, Nature Geosc
Arctic vegetation vs sea ice

Parmentier et al. 2013, Nature Geosc
Detrended time series of sea-ice concentration, SWI and TI-NDVI correlate with each other at a 95% level.

Suggest a connection — through higher temperatures — between sea ice and plant productivity.

Parmentier et al. 2013, Nature Geosc
Climate sensitivity across the tundra biome. The size of the circle shows the strength of the summer temperature sensitivity as indicated by the ΔAIC. The colour of the circles indicates the direction of the relationship with summer temperature variables. Locations with multiple circles indicate study sites where multiple species were sampled.

Myers-Smith et al., Nature Climate Change, 2015
Climate sensitivity: \( \Delta \text{growth/} \Delta T \)

Dendroecological data (treerings), 37 sites, 25 species, 1950-2010

Myers-Smith et al., Nature Climate Change, 2015
Climate sensitivity: $\Delta$growth/$\Delta$T

Dendroecological data (treerings), 37 sites, 25 species, 1950-2010

Myers-Smith et al., Nature Climate Change, 2015
Dendroecological data (tree rings), 37 sites, 25 species, 1950-2010

Myers-Smith et al., Nature Climate Change, 2015
Sensitivity of the regional European boreal climate to changes in surface properties resulting from structural vegetation perturbations

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Investigates atmospheric response to specific, observed and anticipated vegetation changes in the boreal region

Manually imposed land cover perturbations

- Weather Research and Forecasting Model V3.5.1 (WRF)
- NOAH LSM
- 27 km x 27 km resolution
- 10 year simulation
Investigates atmospheric response to specific, observed and anticipated vegetation changes in the boreal region

Manually imposed land cover perturbations

Vegetation cover perturbations:

To the north:
Migration of evergreen needleleaf boreal forest and shrub cover increase

From the south:
Mixing broad leaf forest into needle leaf

- Weather Research and Forecasting Model V3.5.1 (WRF)
- NOAA LSM
- 27 km x 27 km resolution
- 10 year simulation
Biophysical changes in surface properties

- Evergreen needleleaf forest taking over for tundra (northern border):
  - Albedo decrease, LAI increase

- Mixed forest taking over for needleleaf forest (southern border):
  - Albedo increase, LAI decrease

10 year annual means. From Rydsaa et al. (2015)
Effect on surface fluxes

**Sensible heat flux**
- Weak decrease along northern border due to increased LH/cloud cover and weaker windspeeds
- Strong decrease along southern border due to increased albedo

**Latent heat flux**
- Strong increase along northern border due to increased LAI and deeper roots
- Strong decrease along southern border due to decreased LAI and increased albedo

10 year annual means. (Only showing significant results at the 95% confidence level). From Rydsaa et al. (2015)
Effect on near surface temperature and humidity

Near surface temperature (2m)
- Increased near surface temperature (2m) along northern border and shrub increase areas
- Decreased along southern border and surroundings

Absolute humidity (2m)
- Increase in areas with increase in evergreen needleleaved forest
- Decrease along southern border due to decreased LH

10 year annual means. (Only showing significant results at the 95% confidence level). From Rydsaa et al. (2015)
MOTIVATION

Investigate the land-atmosphere interactions and feedback mechanisms induced by increased shrub cover

Determine effect of varying shrub cover height and sensitivity to snow cover and temperature on atmospheric response.

METHODOLOGY

- WRF with NOAH-UA land model with high resolution (5.4 km)
- 2 summer seasons: warm, cold
- 2 spring seasons: snow rich, snow poor
- Vegetation zones derived by summer temperatures
- 3 shrub categories with different height
  - Sub alpine >5 m
  - Low alpine (2-5 m)
  - Mid alpine (0.5-2 m)
Change in greenhouse effect ($LW_{\text{surface}} - LW_{\text{TOA}}$)

Change in temperature
Increased shrub cover leads to

- Increased near surface temperatures
- Earlier onset of melting season
- Increased latent heat flux
- More atmospheric water, clouds and precipitation
- Increased greenhouse effect
- Strongest effect in areas with taller shrubs
Dynamic global vegetation model (DGVM) in NorESM

CLM4.5-BGCDV
- CN cycle
- vegetation dynamics
- vertical-layer soil biogeochemistry based on CENTURY model

Oleson et al. 2013
CLM4.5-BGCDV: Sub-Grid Structure

Oleson et al. 2013
### CLM4.5-BGCDV: Plant functional types (PFTs)

<table>
<thead>
<tr>
<th>PFT and PFT number corresponding to the list of PFTs in Table 2.1</th>
<th>Survival $T_{c,\text{min}}$ (°C)</th>
<th>$T_{c,\text{max}}$ (°C)</th>
<th>GDD$_{\text{min}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical broadleaf evergreen tree (BET)</td>
<td>15.5</td>
<td>No limit</td>
<td>0</td>
</tr>
<tr>
<td>Tropical broadleaf deciduous tree (BDT)</td>
<td>15.5</td>
<td>No limit</td>
<td>0</td>
</tr>
<tr>
<td>Temperate needleleaf evergreen tree (NET)</td>
<td>-2.0</td>
<td>22.0</td>
<td>900</td>
</tr>
<tr>
<td>Temperate broadleaf evergreen tree (BET)</td>
<td>3.0</td>
<td>18.8</td>
<td>1200</td>
</tr>
<tr>
<td>Temperate broadleaf deciduous tree (BDT)</td>
<td>-17.0</td>
<td>15.5</td>
<td>1200</td>
</tr>
<tr>
<td>Boreal needleleaf evergreen tree (NET)</td>
<td>-32.5</td>
<td>-2.0</td>
<td>600</td>
</tr>
<tr>
<td>Boreal deciduous tree</td>
<td>No limit</td>
<td>-2.0</td>
<td>350</td>
</tr>
<tr>
<td>Temperate broadleaf deciduous shrub (BDS)</td>
<td>-17.0</td>
<td>No limit</td>
<td>1200</td>
</tr>
<tr>
<td>Boreal broadleaf deciduous shrub (BDS)</td>
<td>No limit</td>
<td>-2.0</td>
<td>350</td>
</tr>
<tr>
<td>C$_4$</td>
<td>15.5</td>
<td>No limit</td>
<td>0</td>
</tr>
<tr>
<td>C$_3$</td>
<td>-17.0</td>
<td>15.5</td>
<td>0</td>
</tr>
<tr>
<td>C$_3$ arctic</td>
<td>No limit</td>
<td>-17.0</td>
<td>0</td>
</tr>
</tbody>
</table>
Present-day runs

Veg run: spin-up

CLM4.5-BGCDV: 400 yr
Prescribed atmosphere (Qian et al. 2006)

Atm run

CAM5+CLM4.5SP: 10 yr
Prescribed veg. & phenology

AtmVeg run

CAM5+CLM4.5-BGCDV: 30 yr
↓
CLM4.5-BGCDV: 100 yr
↓
CAM5+CLM4.5-BGCDV: 30 yr

Resolution:
CAM5: 1.9x2.5, 30 level
CLM4.5: 1.9x2.5 15 soil levels
Prescribed SST in all experiments
Plant cover fraction (%)

Observation

NET: Needleleaf evergreen temperate tree
NEB: Needleleaf evergreen boreal tree

BDT: Broadleaf deciduous temperate tree
BDB: Broadleaf deciduous boreal tree

C3 grass
C3 Arctic Grass

BDBsh: Broadleaf deciduous boreal shrub
Total: Total plant cover

Veg run

NET
NEB
BDT
BDB
C3 Grass
C3 Arctic
BDBsh
TOTAL
Plant cover fraction (%)
Temperature: Strong cold biases in AtmVeg run

Atm run minus Observation

AtmVeg run minus Observation
Strong positive feedback between T and vegetation

Multiple states of vegetation?

Model of Intermediate Complexity (EMIC)
Planet Simulator (PlasSim)

Dekker et al., 2010
Biomass anomalies between the two states (G-D)

Dekker et al., 2010
Susceptibility factor: \[ S_i = \frac{B_i - B_{0i}}{p} \]

Si >1: The resilience of the system is so low that a change in biomass induced by the perturbation is amplified indicating a net positive vegetation-climate feedback

Dekker et al., 2010
HOWEVER

- The positive feedback between vegetation and temperature may be too strong in coupled models
  - The limitation of nutrients on the growth of plants are often not well represented in models
  - When taken into account may dampen the strong positive feedback
Single cell test runs with modified parameters

Shrub location (63.5 °N, 132.5 °E)

- Light competition
- \textit{fpc\_shrub\_max} increase
- \textit{fpc\_grass\_max} decrease
- N limitation: removed
- Photosynthetic capacity \( V_{c_{\text{max}25}} \) increase
- Water stress resistance increase

Nitrogen Limitation Factor

![Graphs showing plant cover fraction (%)]
Strong climate-vegetation feedbacks can further enhance cooling

**Veg run, JJA**

- Temp. – Photosyn. rate
- Temp. – LAI
- LAI – Albedo

Regression coefficient (standardized)
Albedo is more influenced by SAI in forest:

High SAI -> Low Albedo

High LAI correspond to low SAI in forest zone

Therefore: High LAI -> Low SAI -> High Albedo
Strong snow and cloud feedbacks may also play a role

AtmVeg Run $\textit{minus} \ Atm \ Run$, JJA

Cloud cover fraction

Snow water equivalent

Temperature

-0.4 -0.3 -0.2 -0.1 -0.01  0  0.01 0.1 0.2 0.3 0.4

-1.5 -0.8 -0.4 -0.1  0  0.1 0.4 0.8 1.5

-12 -10 -8 -6 -4 -3 -2 -1  0  1  2  3  4  6  8  10  12
Summary

- WRF uncoupled runs: Increased shrub cover leads to
  - Increased near surface temperatures
  - Earlier onset of melting season
  - Increased latent heat flux
  - More atmospheric water, clouds and precipitation
  - Increased greenhouse effect

- CLM4.5-BGCDV (Veg run) underestimates Arctic shrubs, while overestimates Arctic grass

- The coupled dynamic vegetation-atmosphere run (AtmVeg run) underestimates total Arctic plant cover, leading to strong cold biases in the Arctic

- The positive feedback between vegetation and temperature is particularly strong in Arctic, making the coupled vegetation-atmosphere model highly unstable in this region
Future work

• Decide how to handle cold bias
• Global CC experiments
• Couple WRF with CLM through coupler
  – Use ecosystem data from Norway (NHM/LATICE) to improve CLM parameters and parametrizations
    • Current and additional (e.g. mosses and lichens) PFTs
  – Regional CC and LUC (forest management)
• Chemistry impacts
  – Ozone impacts on vegetation (crops)
  – BVOC impacts on ozone and clouds
Thanks for attending my talk/walk in the Arctic shrublands