On the influence of shrub height and expansion on boreal climate

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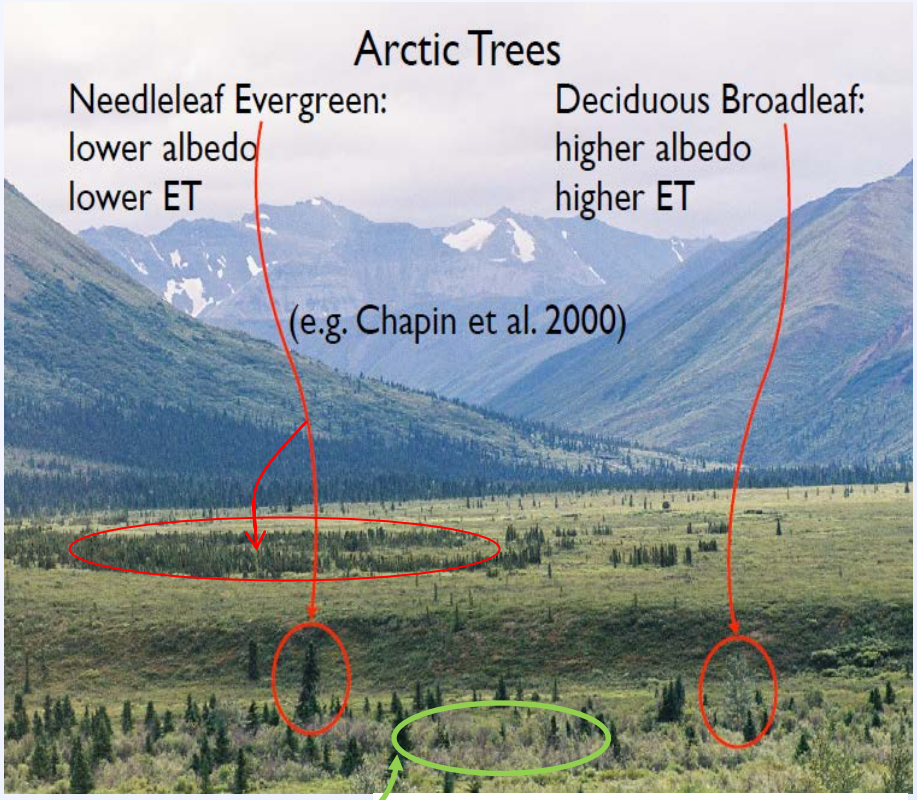
IMPACTs / Boreal team

Rapid changes in arctic vegetation are expected in response to the pronounced warming climate

➡ **Tundra-to-forest conversion**



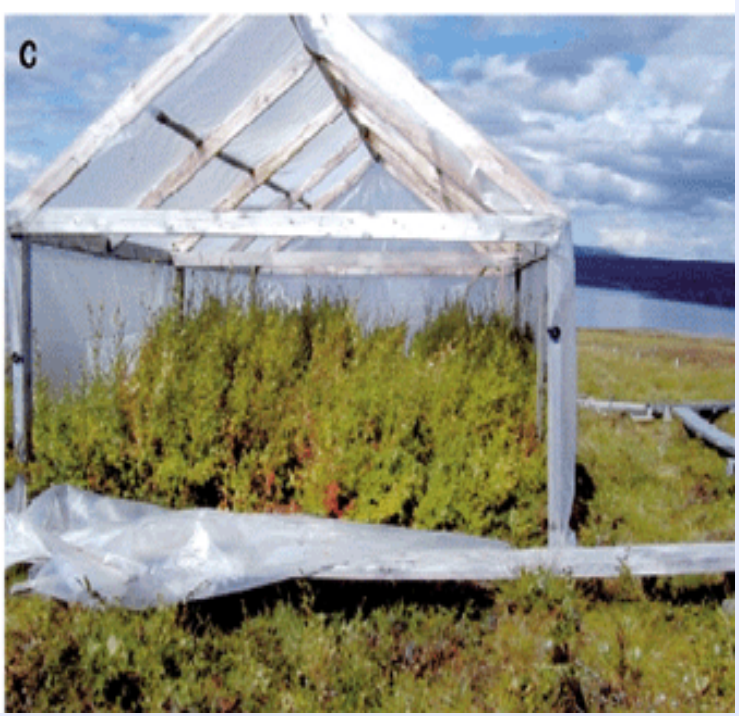
from Swann et al., iLEAPS-GEWEX

- Expanding evergreen forest amplify warming through an albedo feedback (Bonan et al. 1992, Foley et al. 1994, Levis et al. 1999)
- Expanding deciduous forest cause an additional evapotranspiration-induced GHG feedback (Swann et al. 2010)
- Widespread tundra-to-forest conversion mainly predicted by equilibrium vegetation models; unlikely to occur in the current century (Chapin et al. 2005)

➡ **In contrast, there is no experiment on the possible tundra-to-shrub conversion**

Empirical evidences documenting the increase in deciduous shrub abundance and size

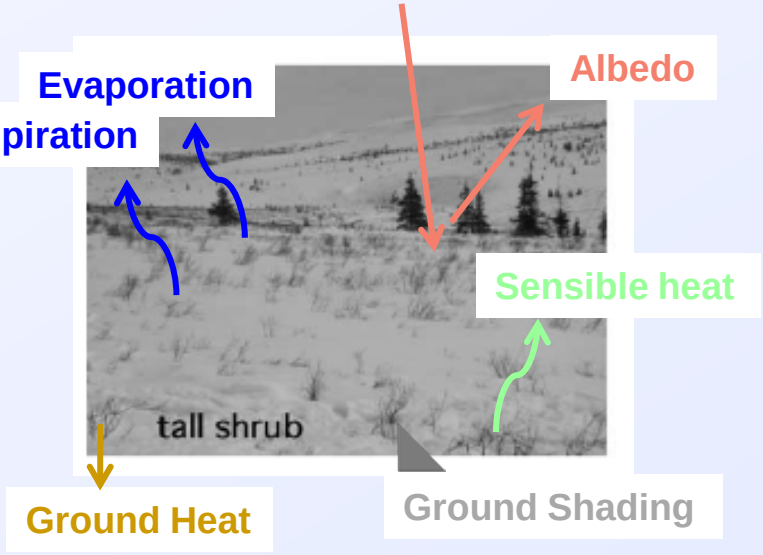
- photographs, transect studies, satellite indices, and local testimonies, etc…
- Up to 1.2% decade^{-1} since 1950 in Northern Alaska (Sturm et al. 2001)
- Already present in most tundra areas, ready to grow under more favorable conditions (field studies, warming treatments, past climate)
- Promote their own development by favoring snow accumulation and soil microbial activity (Sturm et al. 2005)
- Tall shrub predicted in low shrub region by plant dynamics model under a 2°C warming (Epstein et al. 2007)



Dominance of *Betula nana* inside the fertilized greenhouse (Bret-Harte et al 2002)

Expected feedbacks

- Feedbacks: albedo; ET
- Shrub height can affect their timing



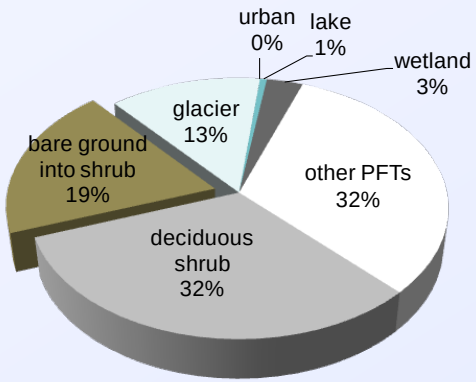
Questions

- What are the biophysically-induced effects of shrub expansion on boreal climate?
- Are they sensitive to the height of shrubs?
- What are the effects on permafrost?

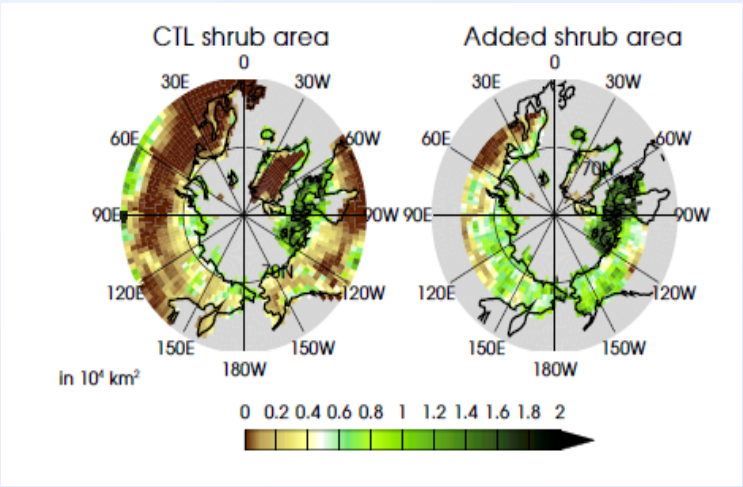
Sturm and Douglas, 2003

Experimental design with CESM1 (1.9°x2.5°)

	short shrubs replace bare ground (**S**)	tall shrubs replace bare ground (**T**)	Objective
1xCO_2 fixed ocean (FO)	$(S\text{-}CTL)^{FO}$	$(T\text{-}CTL)^{FO}$	Effect of adding shrubs
1xCO_2 interactive ocean (IO)	$(S\text{-}CTL)^{IO}$	$(T\text{-}CTL)^{IO}$	Added effect from indirect ocean / sea-ice feedbacks
2xCO_2 interactive ocean (IO)	$(S_{2xCO2}\text{-}CTL)^{IO}$	$(T_{2xCO2}\text{-}CTL)^{IO}$	Added effect from 2xCO_2

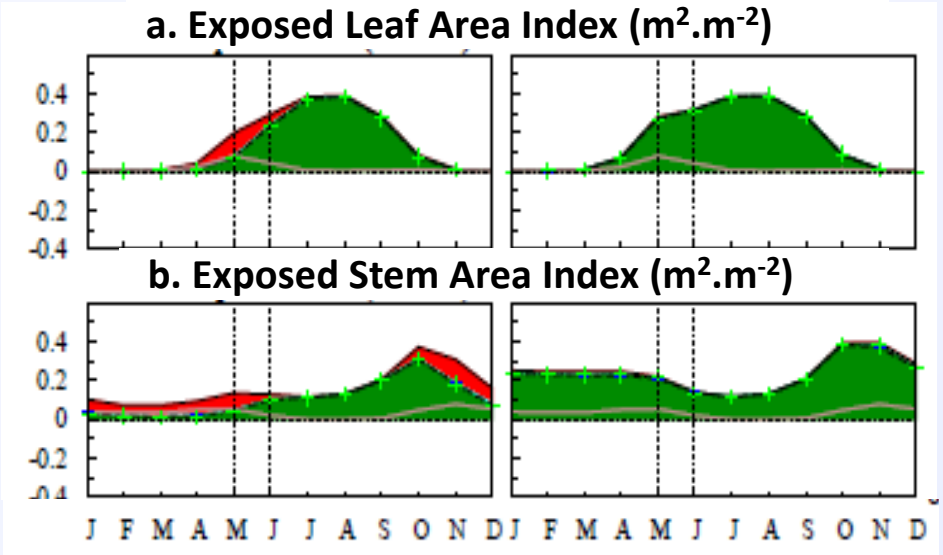


Composition of the land north of 60°N



Changes occur north of 60°N

Seasonal evolution of the vegetation protruding above the snow (calculated over land; N of 60°N)



Short shrub case

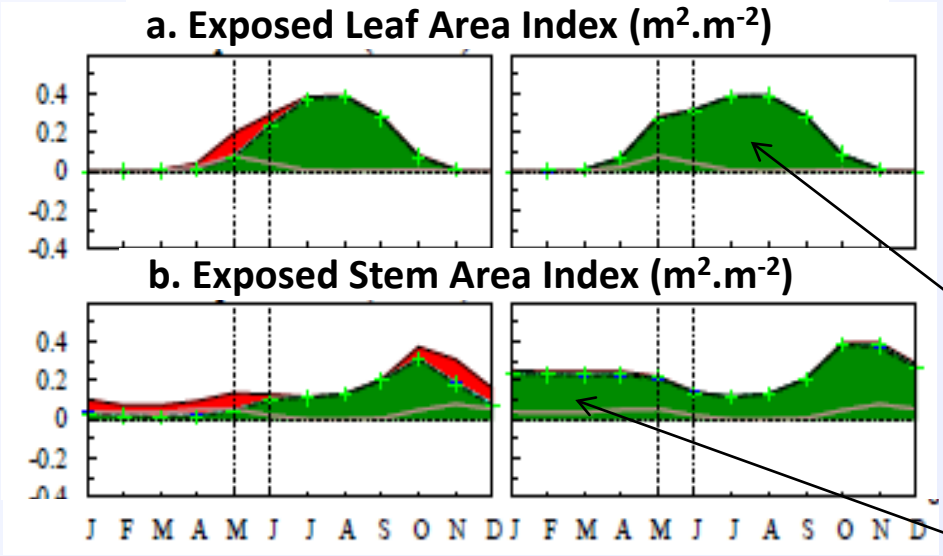
Tall shrub case

Effect of adding shrubs (FO)

Added effect from IO

Added effect from 2xCO2

Seasonal evolution of the vegetation protruding above the snow (calculated over land; N of 60°N)



Short shrub case **Tall shrub case**

Effect of adding shrubs (FO)

Added effect from IO

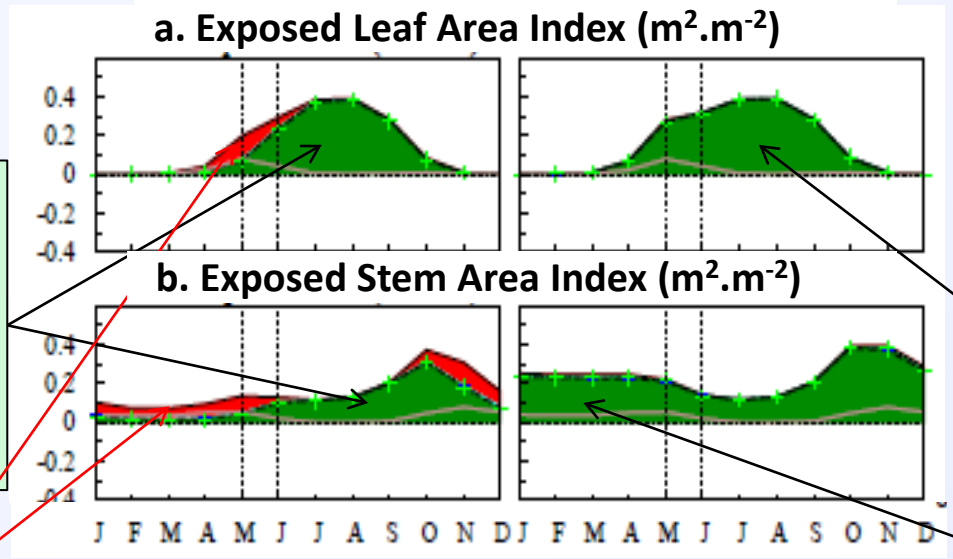
Added effect from 2xCO2

Leaves exposed from Apr to Nov

Branches exposed all year long

No additional effects by IO or 2xCO_2

Seasonal evolution of the vegetation protruding above the snow (calculated over land; N of 60°N)



Short shrub case **Tall shrub case**

Effect of adding shrubs (FO)

Added effect from IO

Added effect from 2xCO2

Leaves/ branches only exposed from May to Nov/Dec

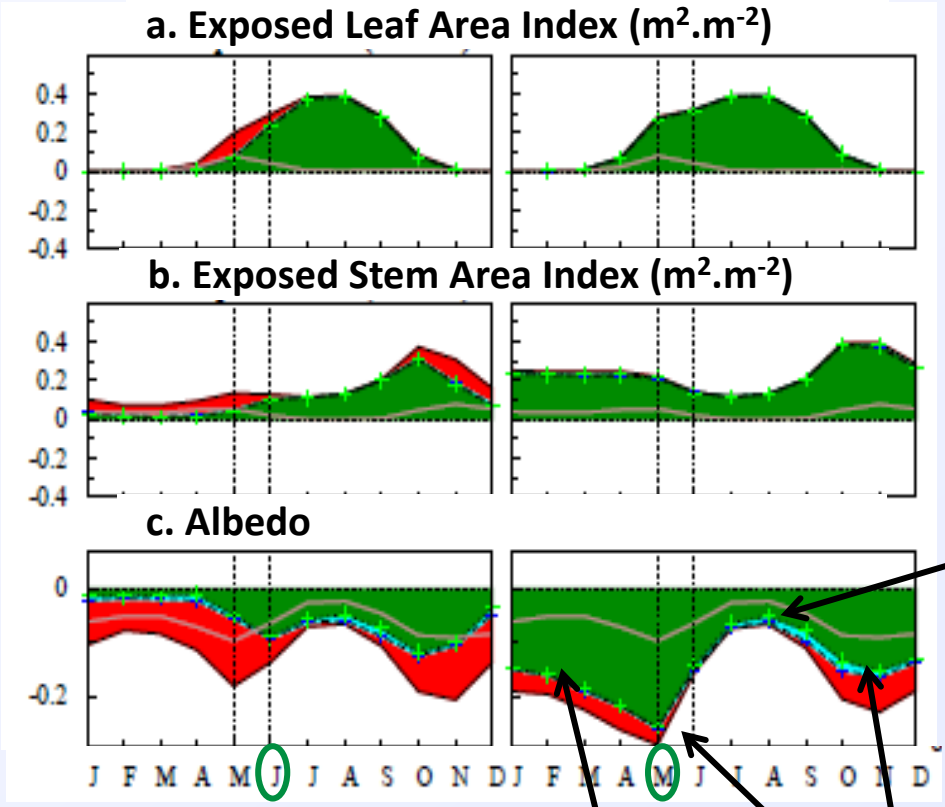
Leaves exposed from Apr to Nov

Branches exposed all year long

Longer exposition if 2xCO_2

No additional effects by IO or 2xCO_2

Exposed vegetation impacts the seasonal evolution of albedo



Effect of adding shrubs (FO)

Added effect from IO

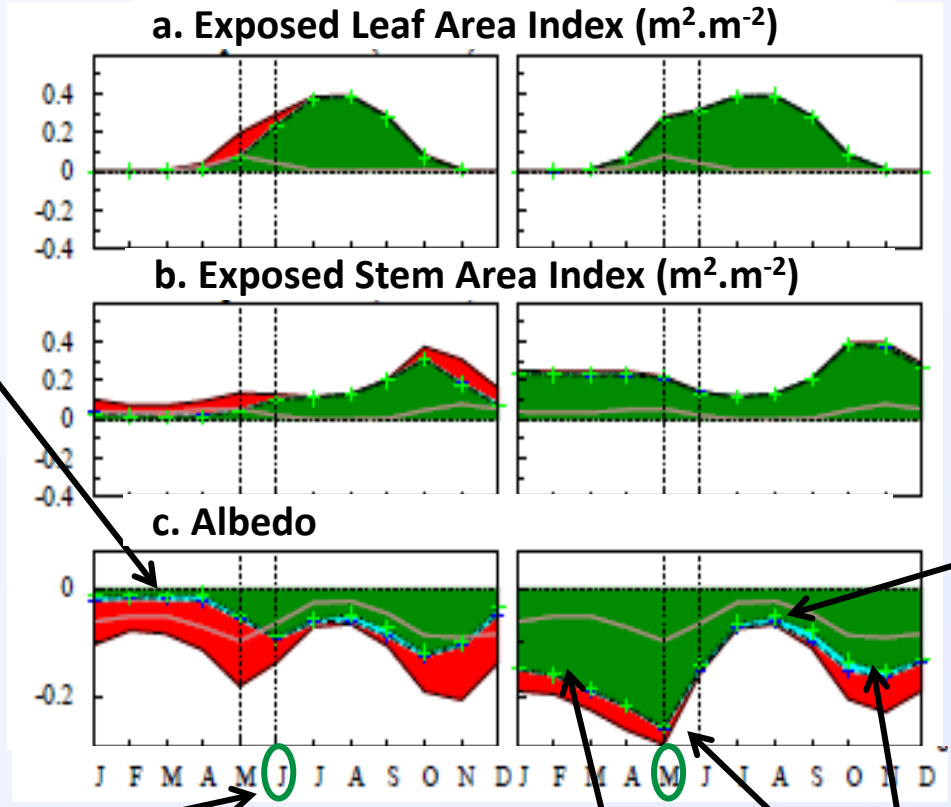
Added effect from 2xCO2

Small albedo difference between bare ground / shrubs in summer

Branches mask the snow in winter

Large decline in albedo, amplified as snow melts and plants leaf out

Exposed vegetation impacts the seasonal evolution of albedo



Effect of adding shrubs (FO)

Added effect from IO

Added effect from 2xCO2

Ineffective snow masking in winter

Becomes more effective under $2xCO_2$

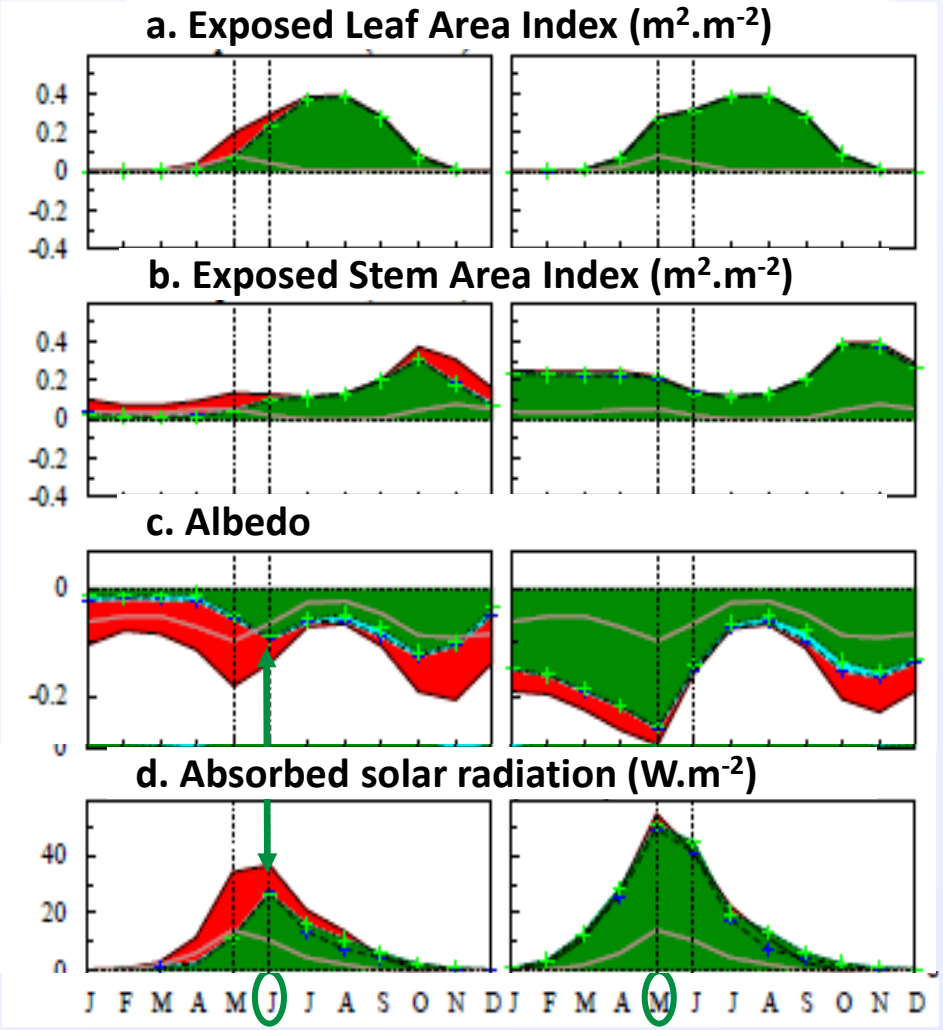
Small albedo difference between bare ground / shrubs in summer

Decline in albedo is weaker and peaks later

Branches mask the snow in winter

Large decline in albedo, amplified as snow melts and plants leaf out

This affects the energy balance when the sun returns



Effect of adding shrubs (FO)

Added effect from IO

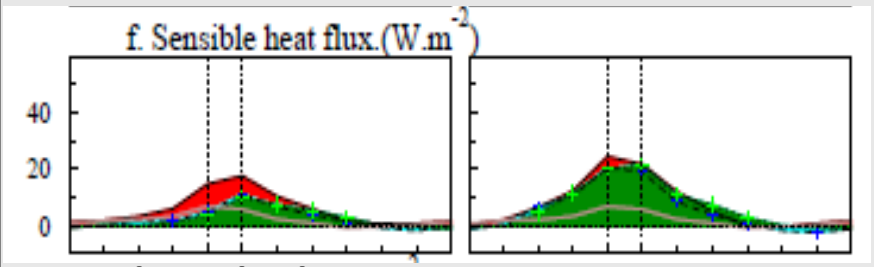
Added effect from 2xCO2

increase is smaller and occurs later, peaking in June

more absorbed solar radiation available for SH

With short shrubs, both albedo and ET feedbacks are weaker and delayed

Albedo feedback



Short shrub case

Tall shrub case

Limited /delayed increase in sensible heat

More surface sensible heat

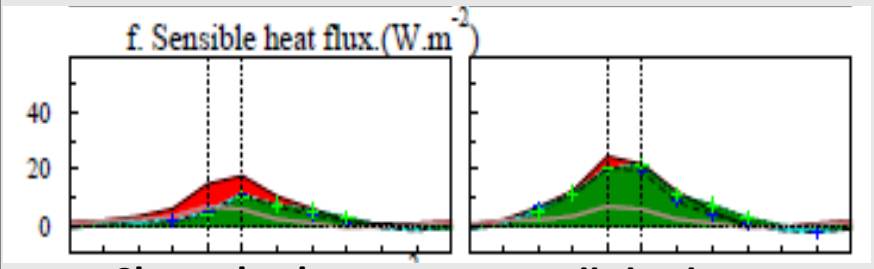
Effect of adding shrubs (FO)

Added effect from IO

Added effect from 2xCO2

With short shrubs, both albedo and ET feedbacks are weaker and delayed

Albedo feedback



Short shrub case **Tall shrub case**

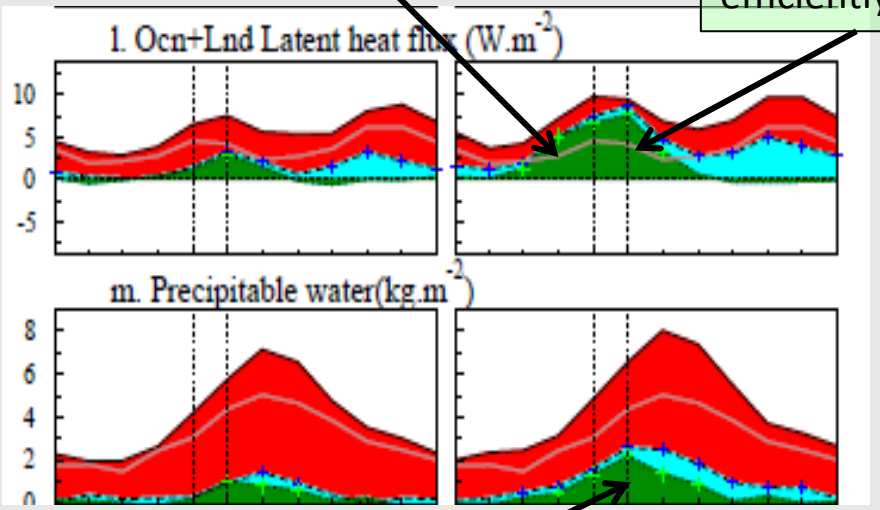
Limited /delayed increase in sensible heat

More surface sensible heat

Evapotranspiration feedback

Before leaf-out: More soil evaporation (more energy available, rougher tall trees)

After leaf-out: taller shrubs transpire more efficiently



Short shrub case **Tall shrub case**

The atmospheric moisture content, and the GHG warming are amplified

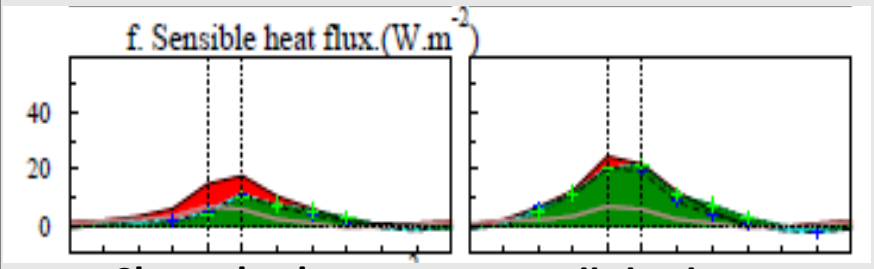
Effect of adding shrubs (FO)

Added effect from IO

Added effect from 2xCO2

With short shrubs, both albedo and ET feedbacks are weaker and delayed

Albedo feedback

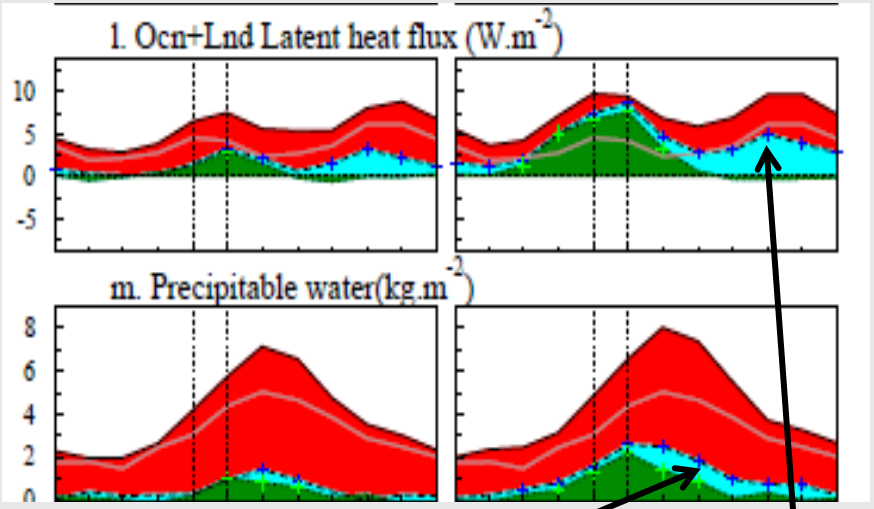


Short shrub case **Tall shrub case**

Limited /delayed increase in sensible heat

More surface sensible heat

Evapotranspiration feedback



Short shrub case **Tall shrub case**

The atmospheric moisture content, and the GHG warming are further amplified

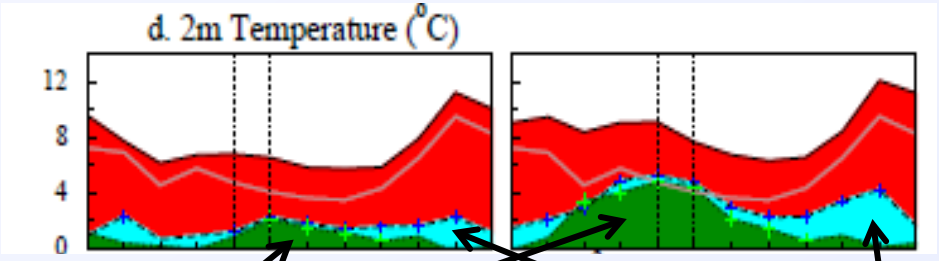
With IO, decrease in sea-ice albedo and increase ocean evaporation contribute to a stronger ET feedback

Effect of adding shrubs (FO)

Added effect from IO

Added effect from 2xCO2

In consequence, the surface warming is more important in the tall shrub case



In spring/summer: the amplitude and timing of the albedo and ET feedbacks are sensitive to shrub height

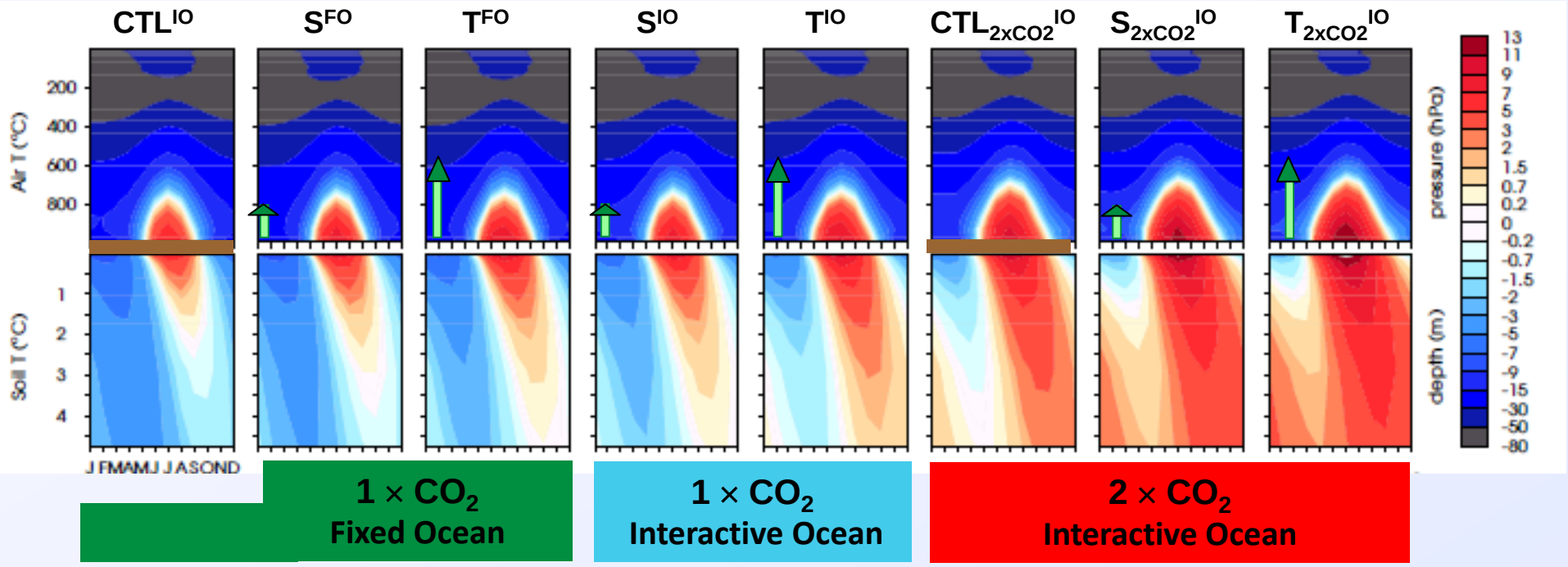
All year long: These mechanisms increase, in turn, the strength of the sea-ice/ ocean feedbacks

Effect of adding shrubs (FO)

Added effect from IO

Added effect from 2xCO2

Permafrost vulnerability (annual cycle of T)



- The active layer thickness (ALT) deepens with the invasion of shrubs and further when the ocean is active. The below-freezing season shortens.
- Shrub expansion + 2xCO2: the refreezing of the soil only occurs in the top meter of soil. Below: soil no longer refreezes, formation of taliks, accumulation of soil heat content

Conclusions

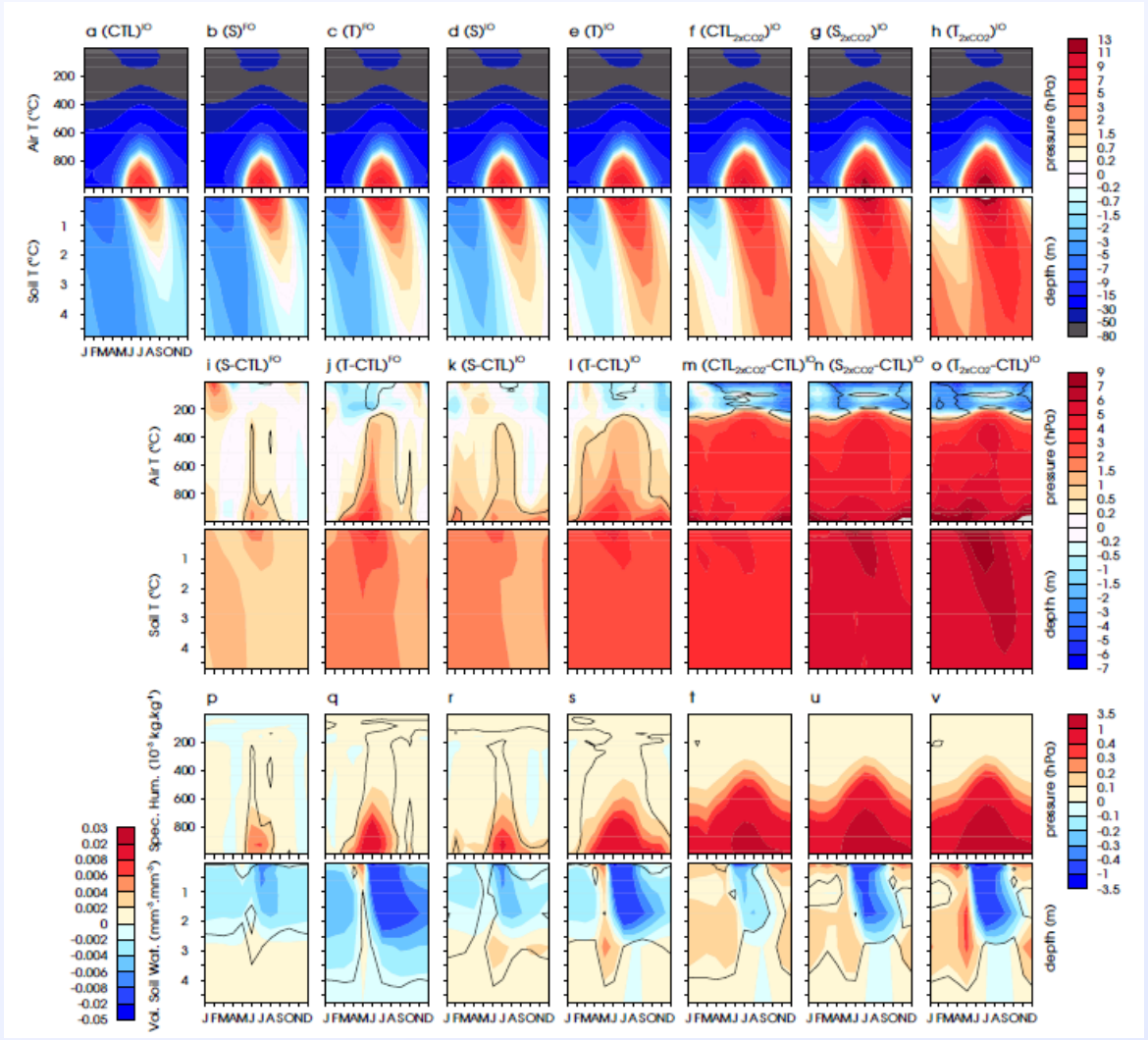
➡ Shrub expansion leads to substantial atmospheric heating through two feedbacks (albedo and ET)

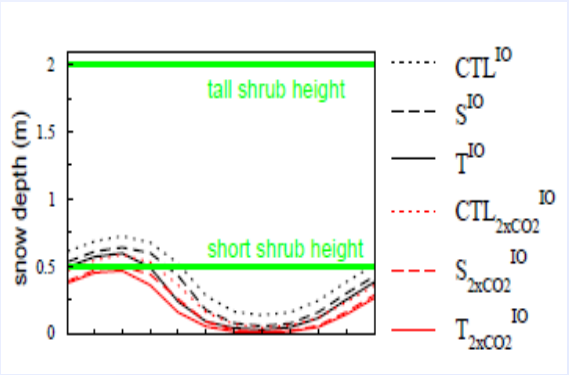
➡ The strength and timing of these feedbacks are sensitive to shrub height

➡ They impact, in turn, the strength of the indirect sea-ice/ocean feedbacks contributing to additional regional warming

➡ Finally, tall shrubs invasion systematically warm the soil, deepen the active layer, and destabilize the permafrost more substantially than short shrubs

- Thanks!


a (CTL)IO
b (S)IO
c (T)IO
d (S)IO
e (T)IO
f (CTL2xCO2)IO
g (S2xCO2)IO
h (T2xCO2)IO
Air T (°C)
Soil T (°C)
pressure (hPa)
depth (m)
J FMAMJ JASOND
i (S-CTL)IO
j (T-CTL)IO
k (S-CTL)IO
l (T-CTL)IO
m (CTL2xCO2-CTL)IO
n (S2xCO2-CTL)IO
o (T2xCO2-CTL)IO
p
q
r
s
t
u
v
Spec. Hum. (10-3 kg.kg-1)
Vol. Soil Wat. (mm3.mm-3)


snow depth (m)
tall shrub height
short shrub height
CTL IO
S IO
T IO
CTL 2xCO2 IO
S 2xCO2 IO
T 2xCO2 IO