Forest impacts on snow water resources: management and climate adaptation possibilities

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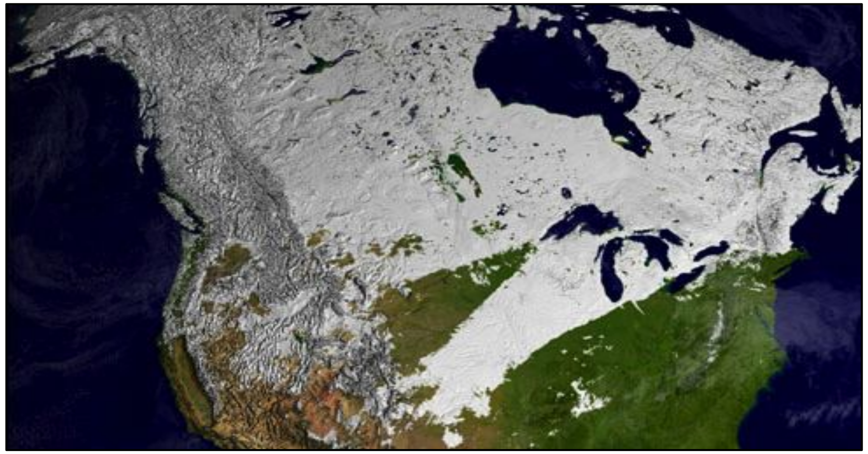
Photo: C. DeBeer

Cold region hydrology: Water and life from snow



- Snow affects half of the Northern Hemisphere, 1/6th of Earth's population, 1/4th of GDP

Barnett et al. (2005); Sturm et al. (2017)

- Impacts climatic, ecologic, hydrologic systems

- Mountain snow produces up to 80% of streamflow in western North America

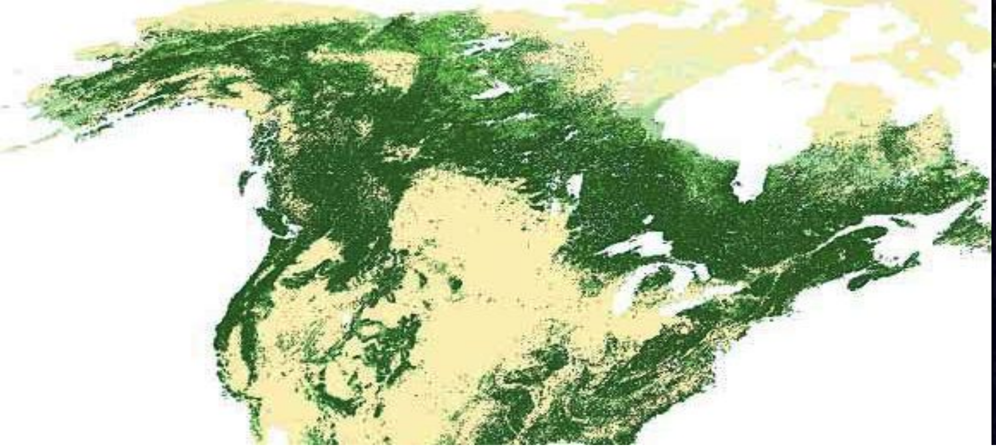
  ✓ agriculture ✓ hydropower

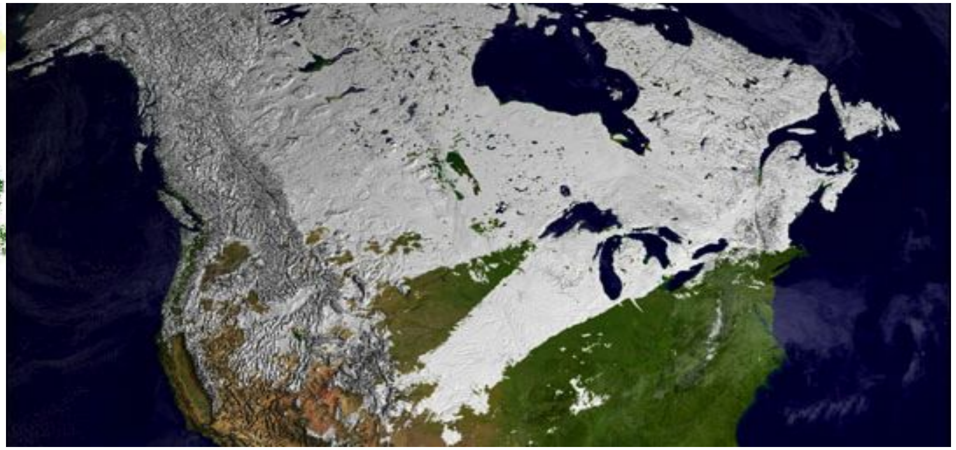
Li et al. (2017)

- Cools the climate: high albedo reflects solar energy back to space

Forest cover: extensive regional & local impacts on water resources

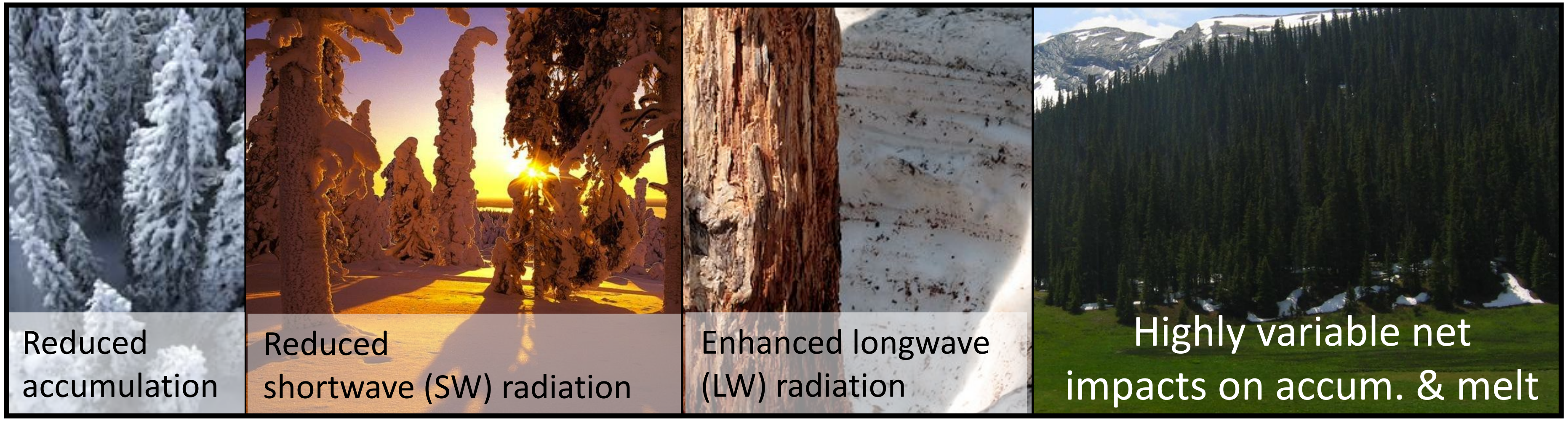
Regional





interception | attenuation | thermal heating | cumulative impact (time-integrated)

Local



Physical processes determine how much, when, and where meltwater is available

Ecosystem services: The products of the functioning natural environment that benefit people. Brown et al. (2007)

Classification of Ecosystem Services:

Millennium Ecosystem Assessment (2005)

- Provisioning
- Supporting
- Regulating
- Cultural

Provisioning:

- Fresh water
- Food
- Timber
- Fiber
- Medicine

Ecosystem services: The products of the functioning natural environment that benefit people. Brown et al. (2007)

Classification of Ecosystem Services:

Millennium Ecosystem Assessment (2005)

- Provisioning
- Supporting
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Supporting:

- Nutrient cycling
- Soil formation
- Primary production

<u>Ecosystem services</u>: The products of the functioning natural environment that benefit people. Brown et al. (2007)

Classification of Ecosystem Services:

Millennium Ecosystem Assessment (2005)

- Provisioning
- Supporting
- Regulating
- Cultural

- Flood control
- Water purification
- Climate stabilization
- Crop pollination

<u>Ecosystem services</u>: The products of the functioning natural environment that benefit people. Brown et al. (2007)

Classification of Ecosystem Services:

Millennium Ecosystem Assessment (2005)

- Provisioning
- Supporting
- Regulating
- Cultural
  - Recreational
  - Spiritual
  - Educational
  - Aesthetic

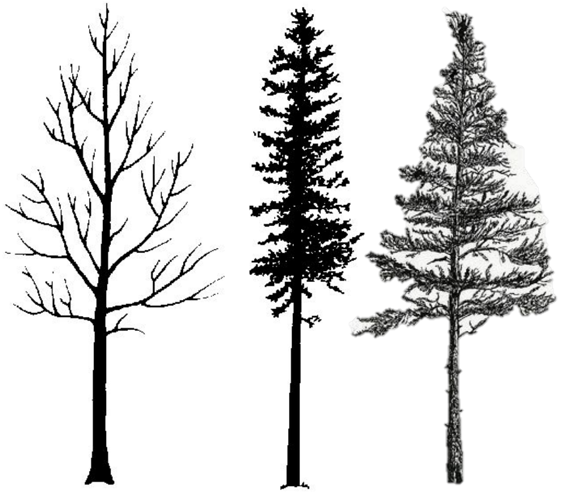
Assessing ecosystem services in montane forests requires consideration of snow-forest interactions.

Time-lapse of seasonal forest-snow conditions

The system is complex!

Snowpack observation station below Niwot Ridge, CO
Natural Resources Conservation Service
U.S. Department of Agriculture

Much of the snow intercepted by canopy sublimates to the atmosphere.



Aspen Pine Spruce

% of total seasonal snowfall lost to canopy sublimation:

mixed spruce–aspen:	13%
mature pine:	31%
mature spruce:	40%

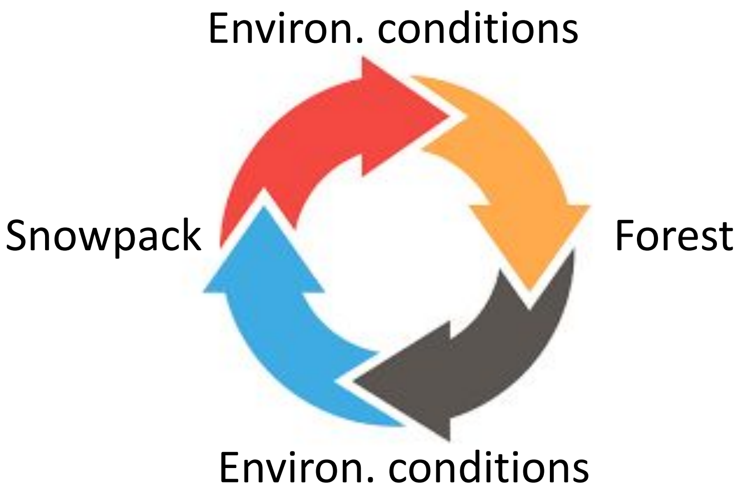
Southern boreal forest

Pomeroy et al. (1999)

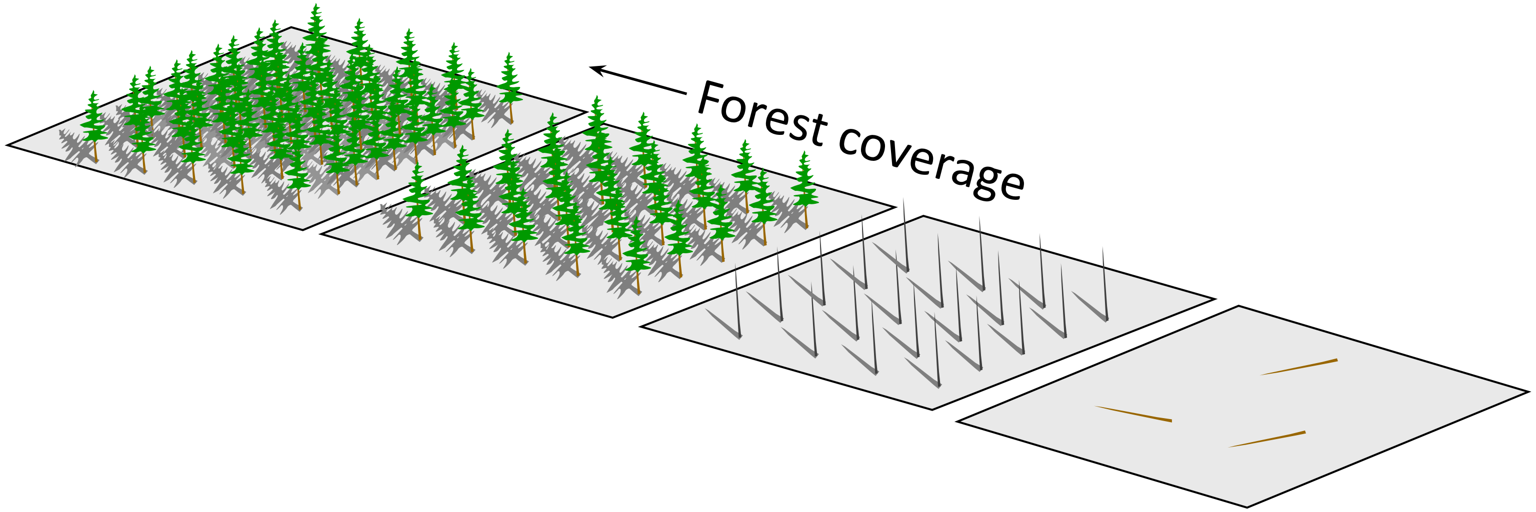
Denser forests have less snow beneath the canopy

Sun exposure & terrain aspect determine local environmental conditions.

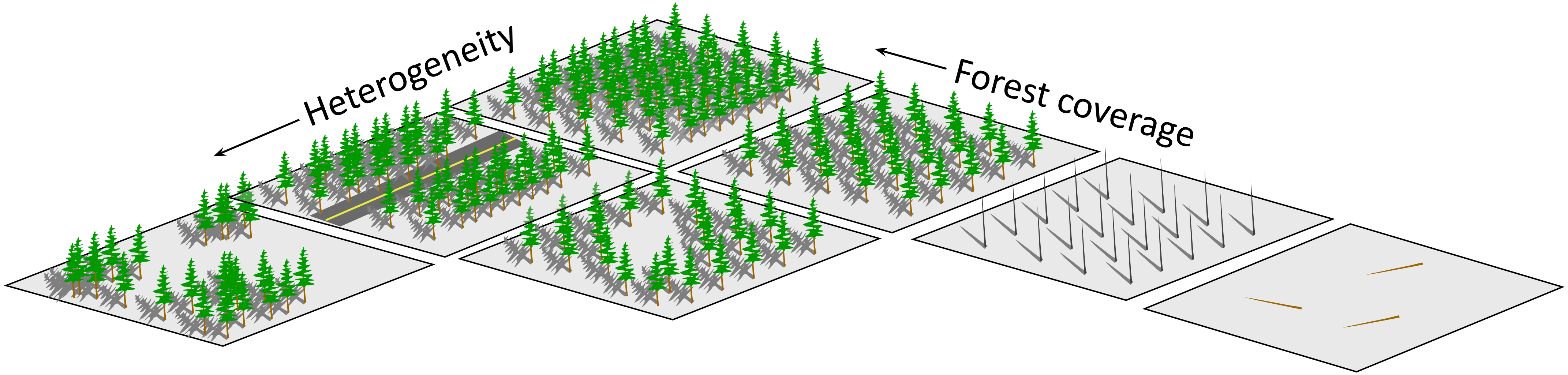
Complex feedbacks with vegetation to consider!



Ecohydrologic models perform optimally in homogeneous conditions



… but face challenges under increasingly heterogeneous conditions

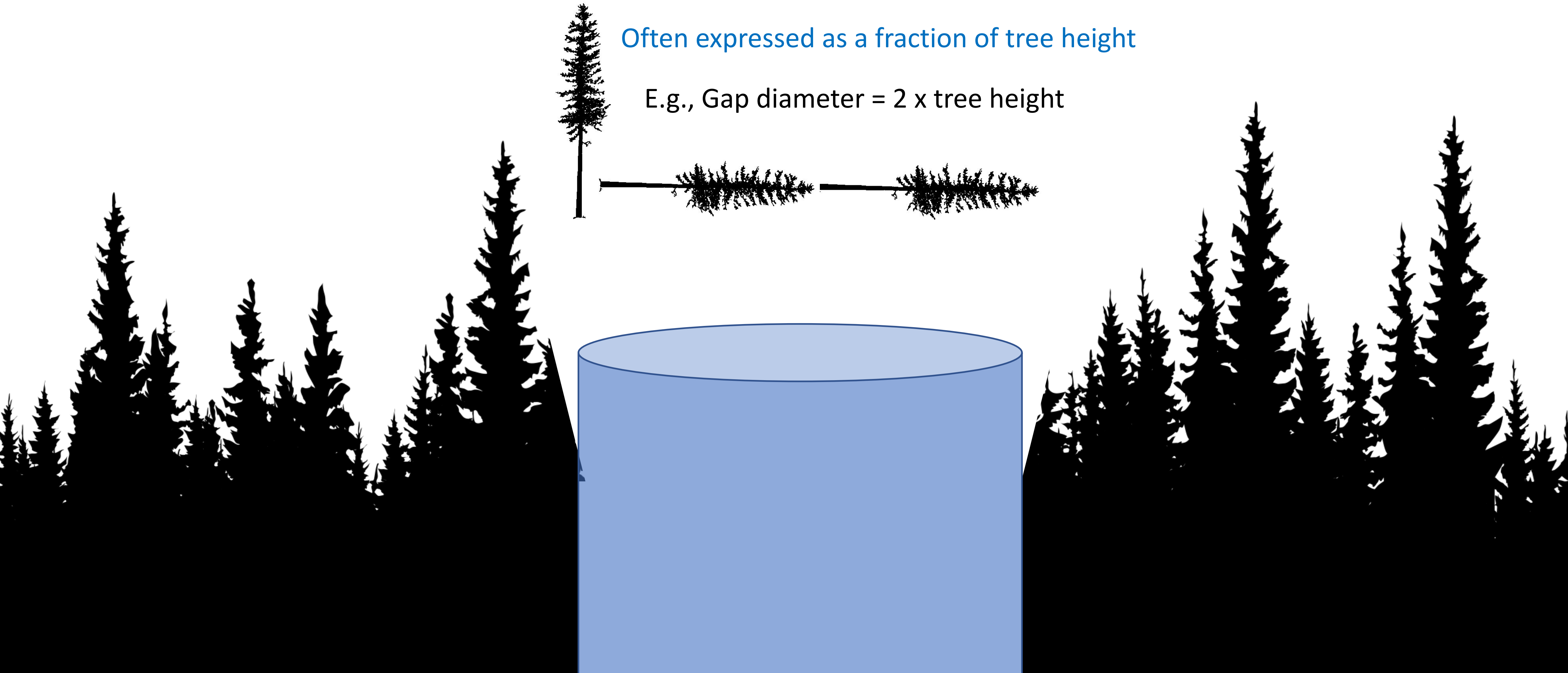


Forest structure coverage & heterogeneity impacts:

- Hydrology
  - Water yield
  - Soil moisture
- Ecology
  - Species diversity
  - Recruitment
  - Carbon dynamics
- Socioeconomics ($)
  - Thinning
  - Burn decisions
  - Wildfire response

Forest Gap Theory in Snow Hydrology

<u>Forest gaps</u>: breaks in the overhead canopy

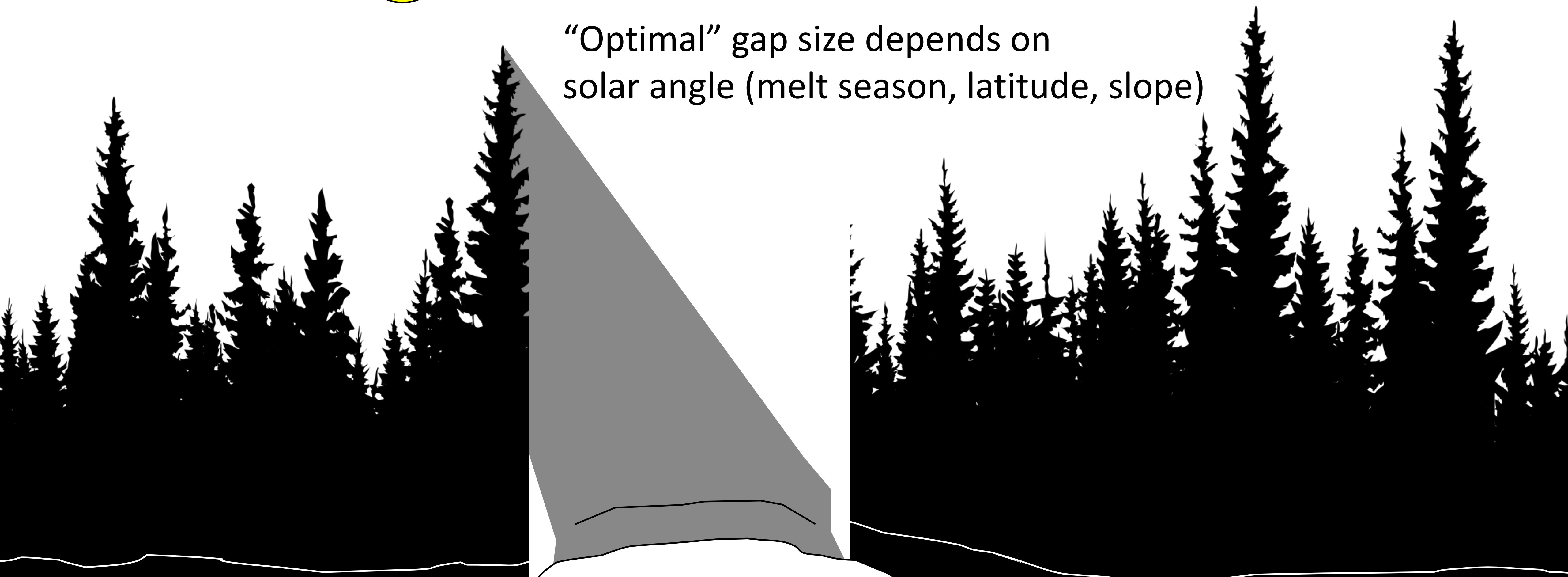


Forest Gap Theory in Snow Hydrology

<u>Forest gaps</u>: breaks in the overhead canopy

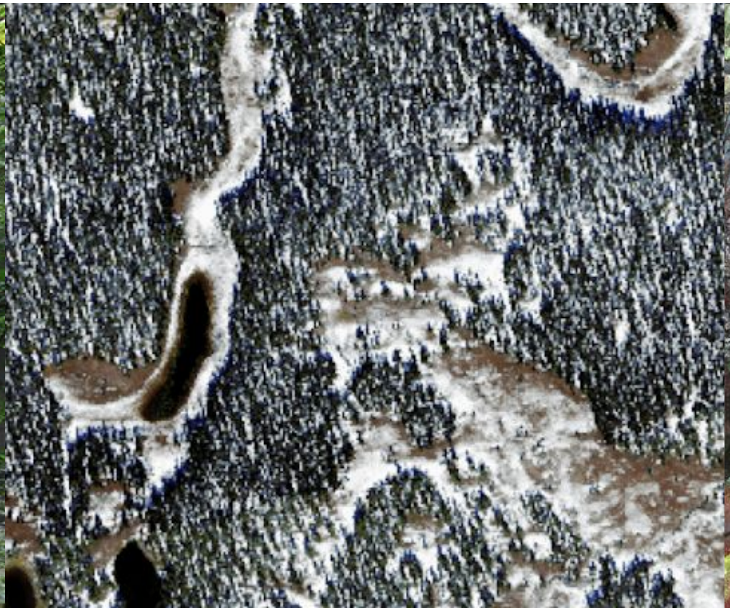
- Maximize snow accumulation
- Minimize sun exposure (solar radiation)
- Prolong seasonal snow-cover & melt

"Optimal" gap size depends on
solar angle (melt season, latitude, slope)



Forest gaps offer benefits beyond snow hydrology.

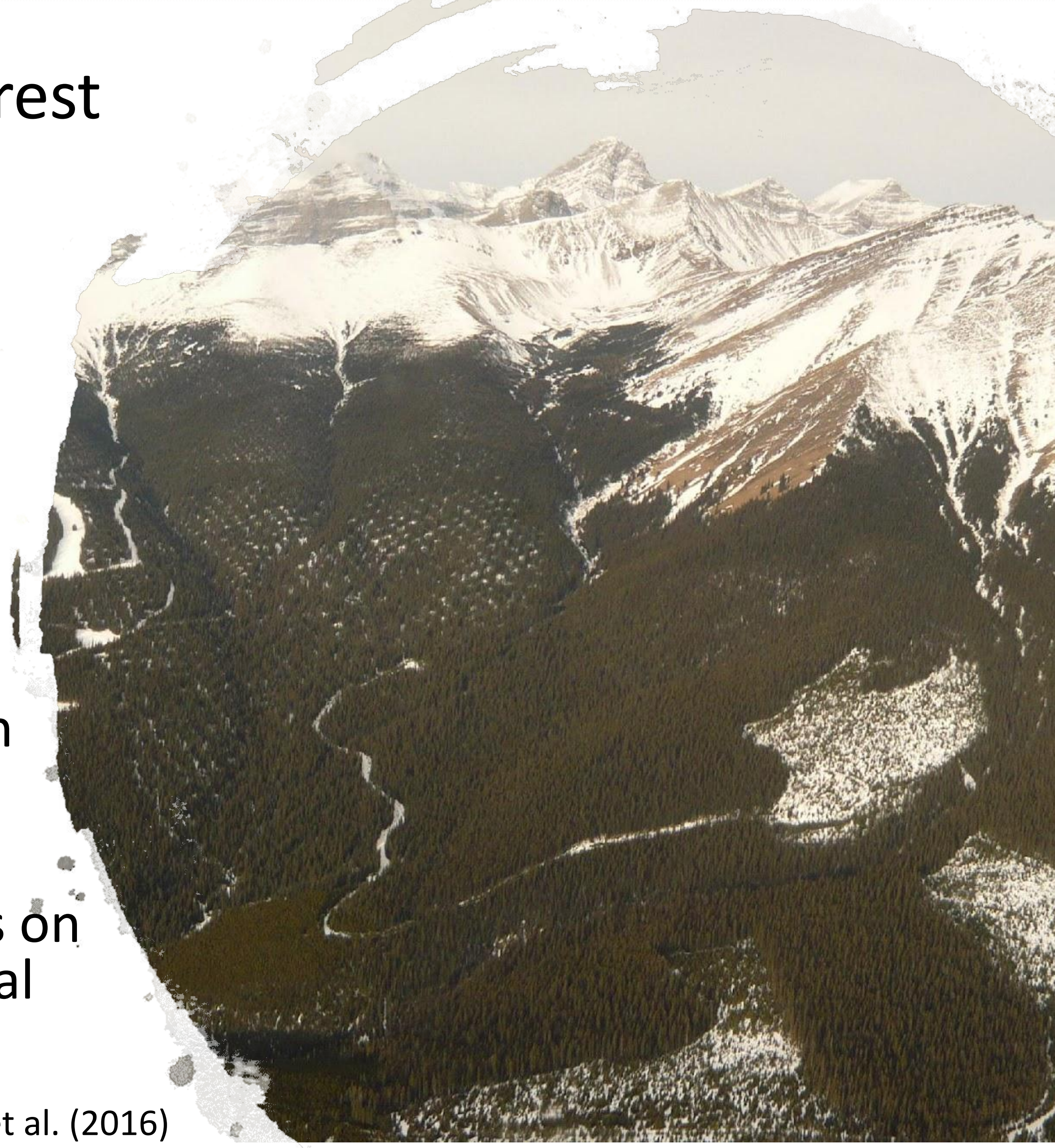
- A variety of microenvironments in forest gaps facilitate diverse communities of vegetation, animals, and insects.
- Forest gaps are increasingly being used as a measure of biodiversity.
- Provide Microrefugia – locations with favorable local climate conditions amidst unfavorable regional conditions.


Marmot Creek Experimental Forest, Alberta, Canada

Marmot Creek Experimental Forest (1970s – early 1980s)

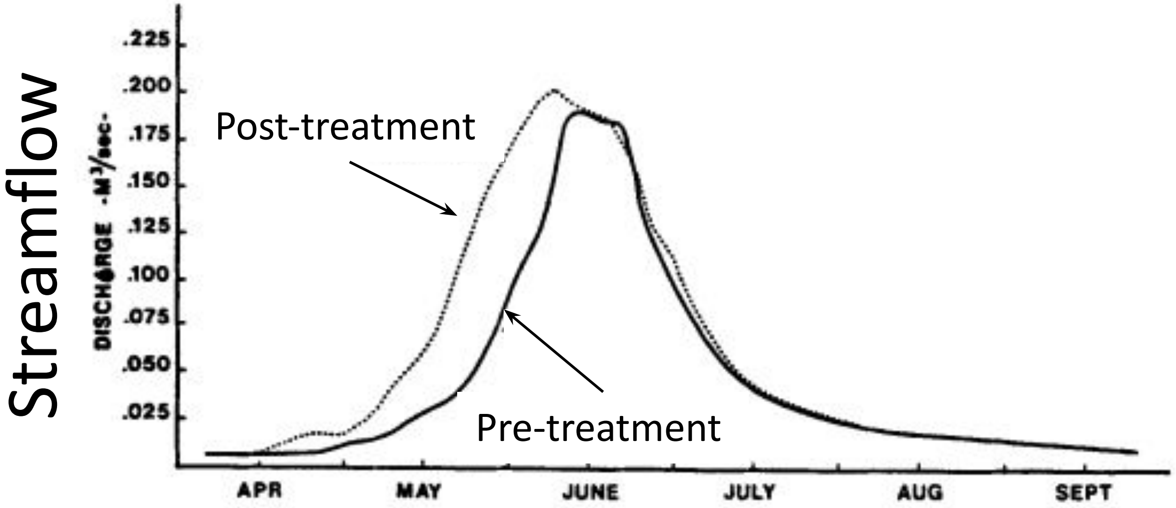
- Could forest manipulations modify streamflow?
- Small forest clearings increased snow accumulation
- Impacts on melt rates depended on clearing size, slope & aspect
- Manipulations had modest impacts on runoff timing & variability; only local impacts on streamflow volume



Rothwell et al. (2016)

Colorado forest manipulations

Creating clusters of trees (reducing forest density) has been shown to increase streamflow & snow persistence.



Source: Troendle, 1983

Fraser Experimental Forest, CO

To an extent, these natural systems 'self-manage' resources.

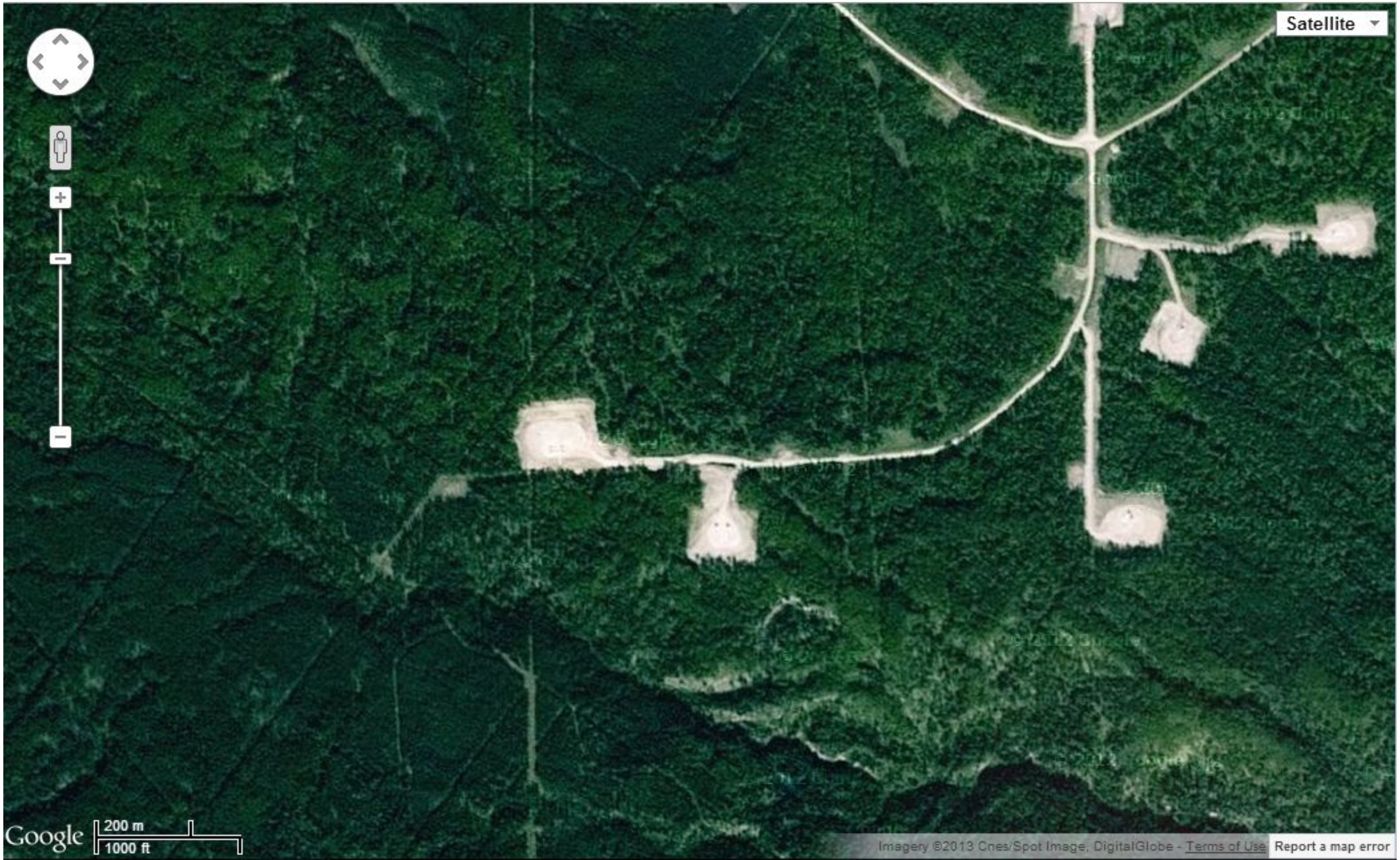
Thin spacing of a (managed) Sierra Nevada forest

Forest die-off during the recent California drought

Has fire suppression and greater forest density stifled water resources & forest resilience?

Forest heterogeneity and ecohydrologic challenges

Forest heterogeneity and ecohydrologic challenges



Forest heterogeneity and ecohydrologic challenges

Forest heterogeneity and ecohydrologic challenges

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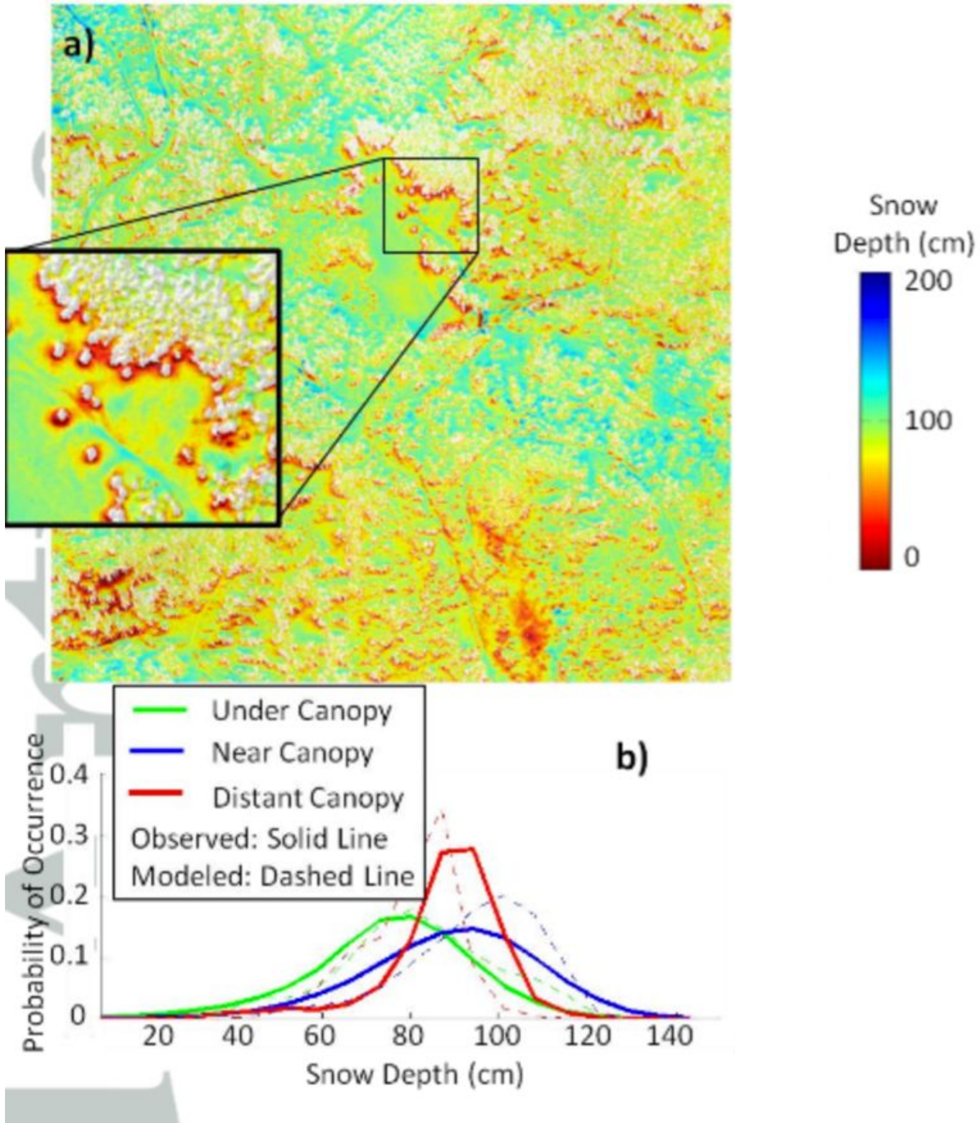
Forest heterogeneity and ecohydrologic challenges

Fine-scale application of snow / ecohydro. models are in their infancy. Recent advances are promising!

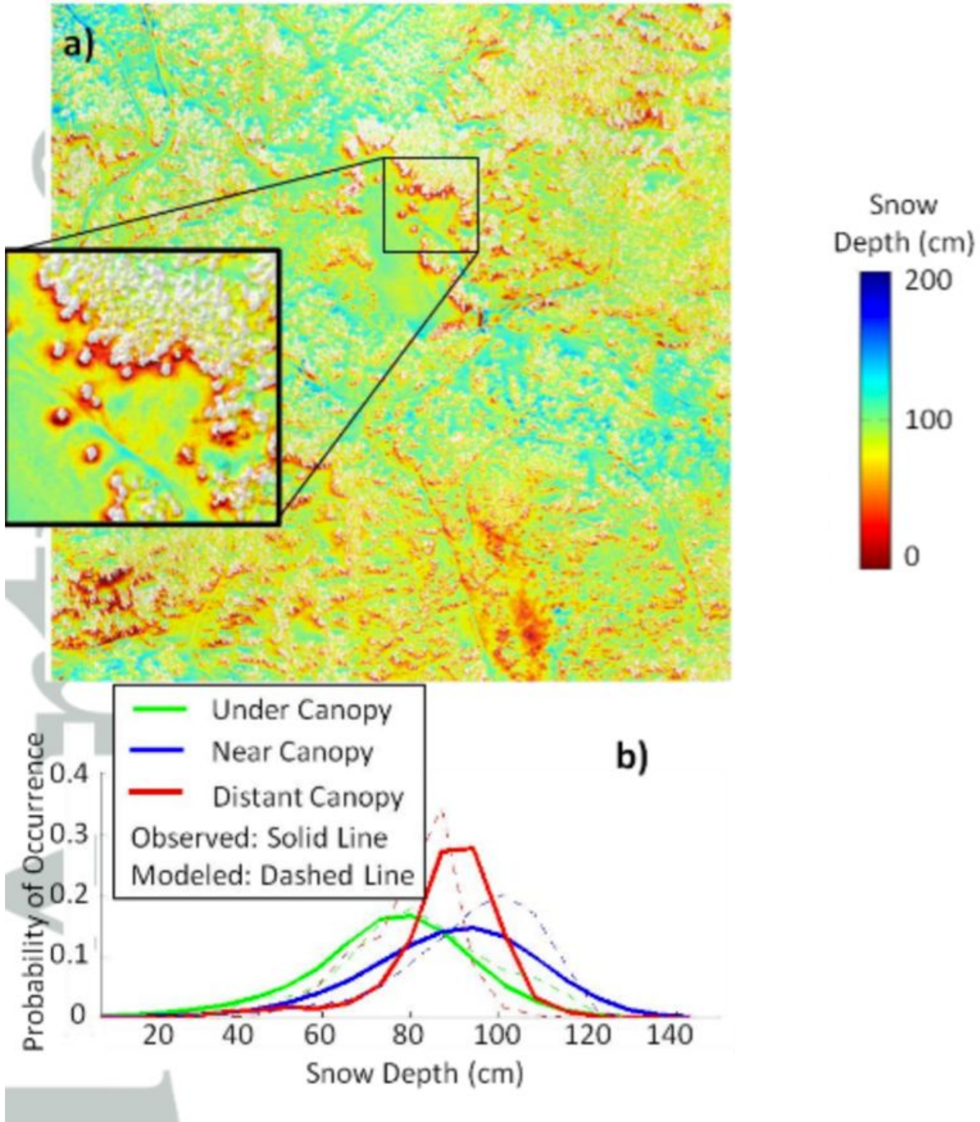


Seminal paper on lidar-informed, fine-scale snow modeling: Broxton et al. (2015)

- SnowPALM model (Univ. Arizona)

Broxton, P. D., Harpold, A. A., Biederman, J. A., Troch, P. A., Molotch, N. P., & Brooks, P. D. (2015). Quantifying the effects of vegetation structure on snow accumulation and ablation in mixed-conifer forests. *Ecohydrology*

Fine-scale application of snow / ecohydro. models are in their infancy. Recent advances are promising!



- Community need to verify process representation (model skill) at these new scales.
- Need to develop similar techniques to improve hydrologic, vegetation demography models.
- In some cases, new analytical methods will be required.

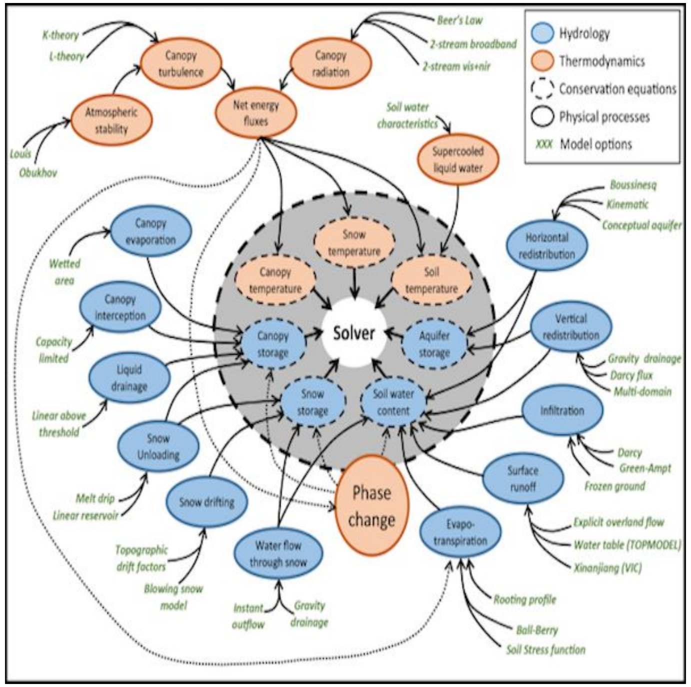
VISION

Toward a new model framework:
a virtual experimental forest

- Co-developed with decision-makers to support management decisions
  - Multiple objectives related to water yield, climate, drought and fire resilience, ecological diversity, etc.

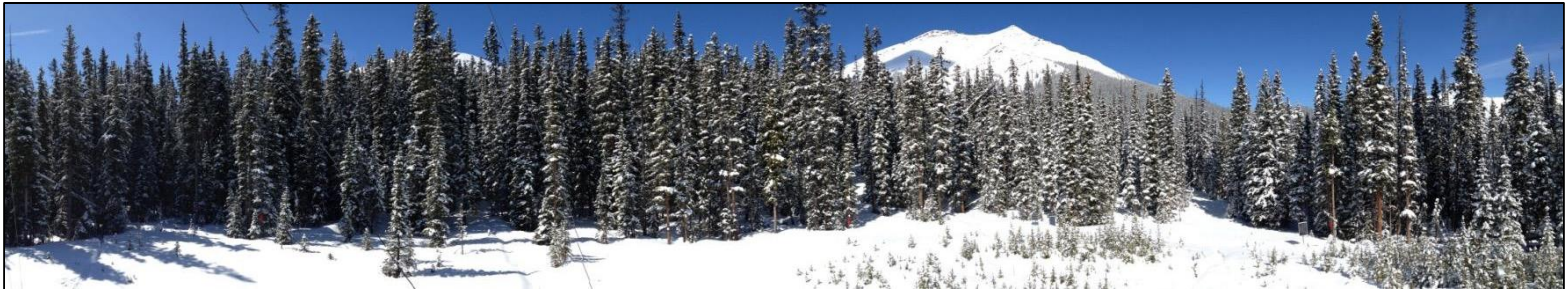
- Test hypotheses and decisions too costly to implement experimentally

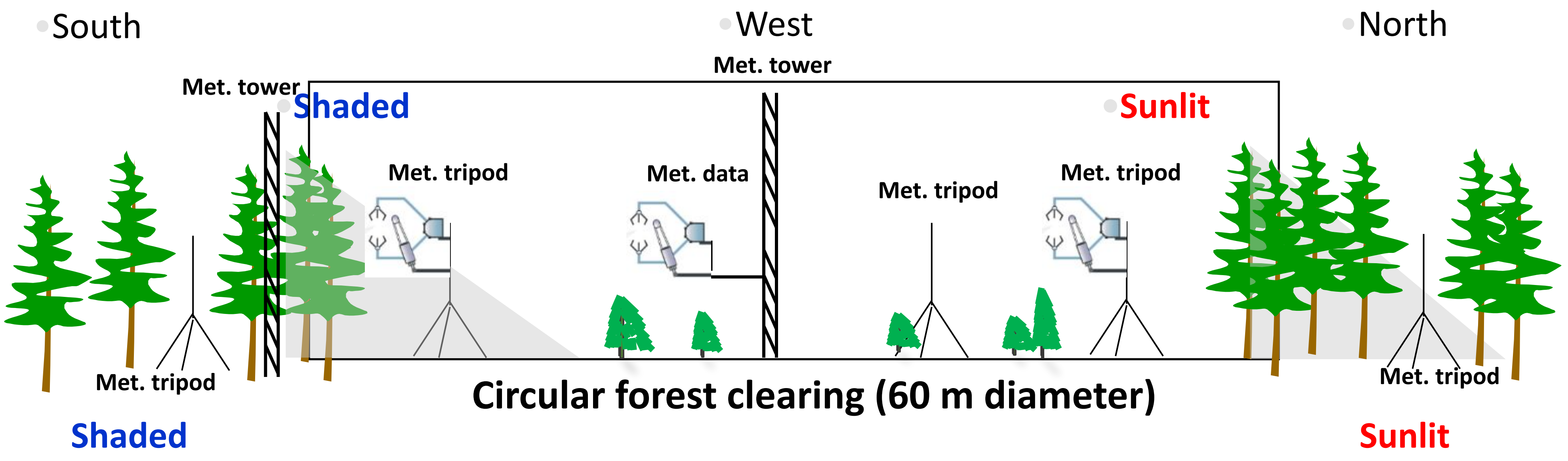
- Better understand interactions among forest, fire, water, and biogeochemistry



Virtual experimental forest.

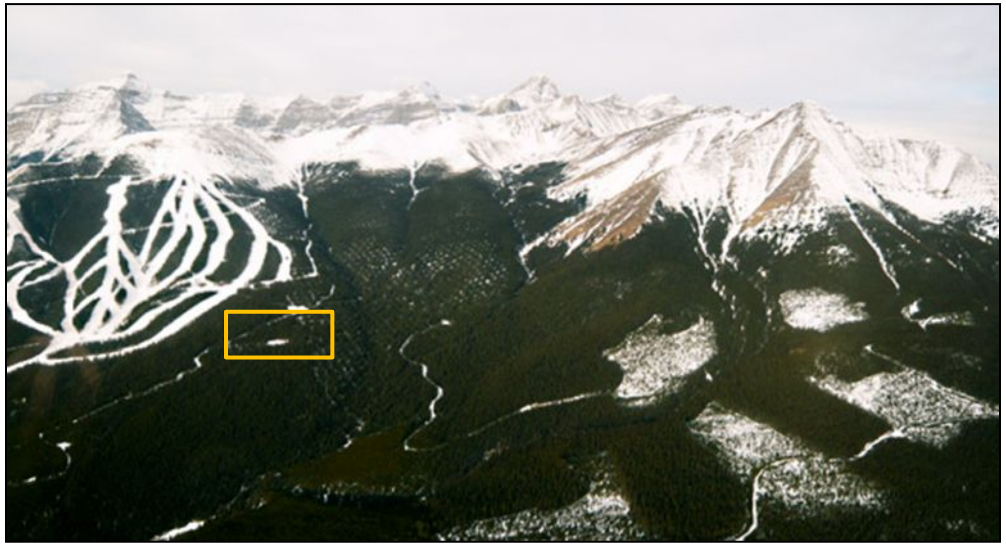
Marmot Creek Forest Gap Experiment
Alberta, Canada
2013-2014

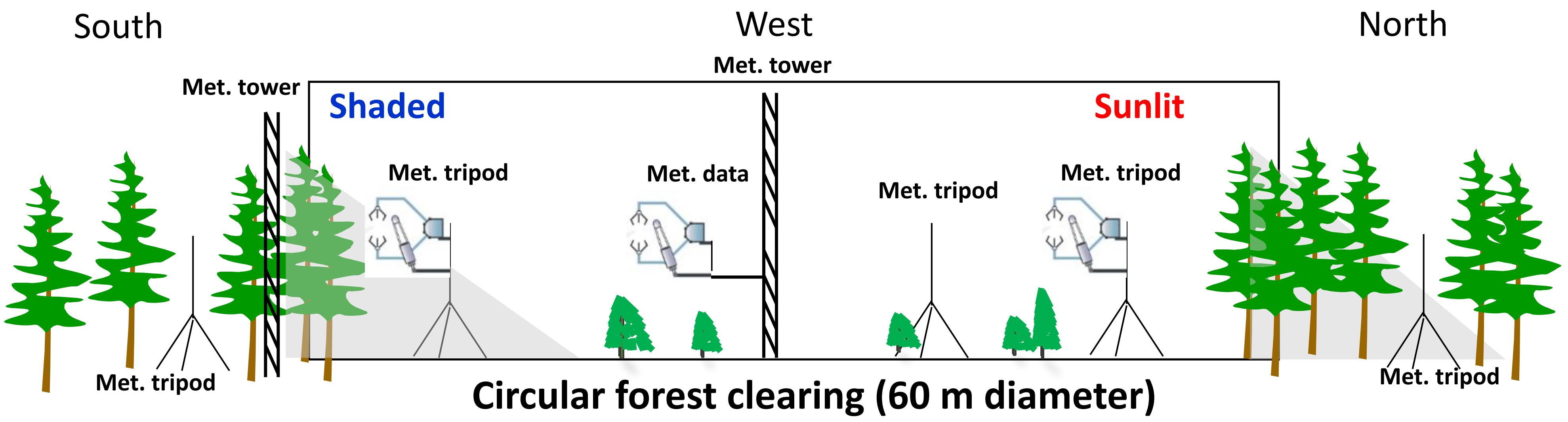


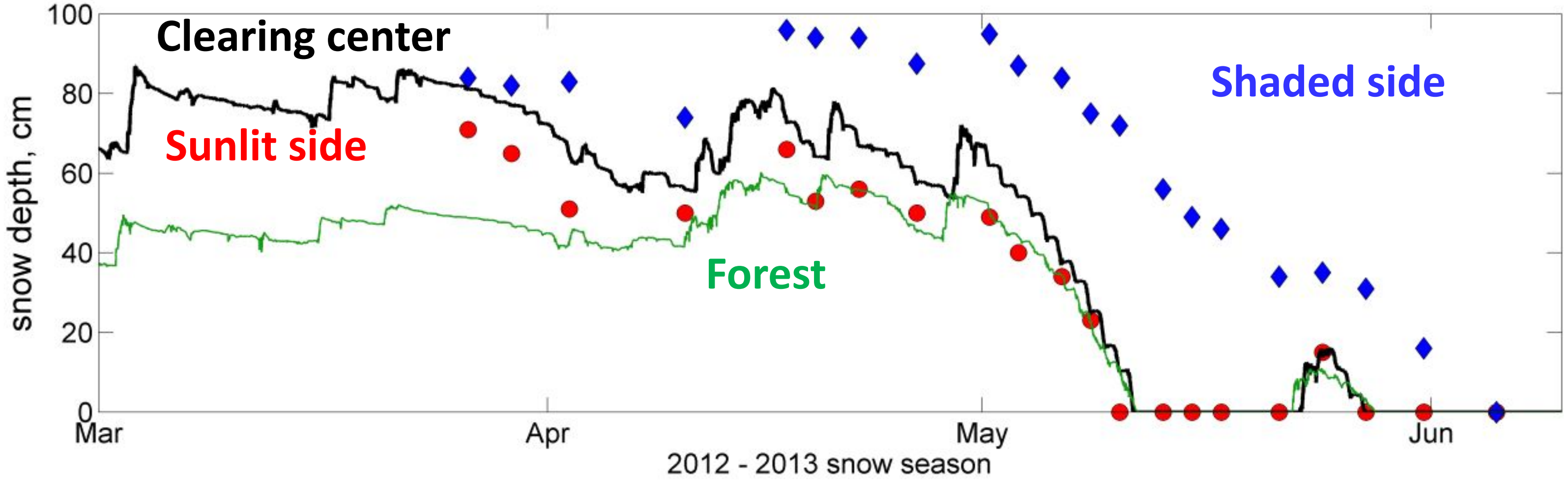


Marmot Creek Research Basin

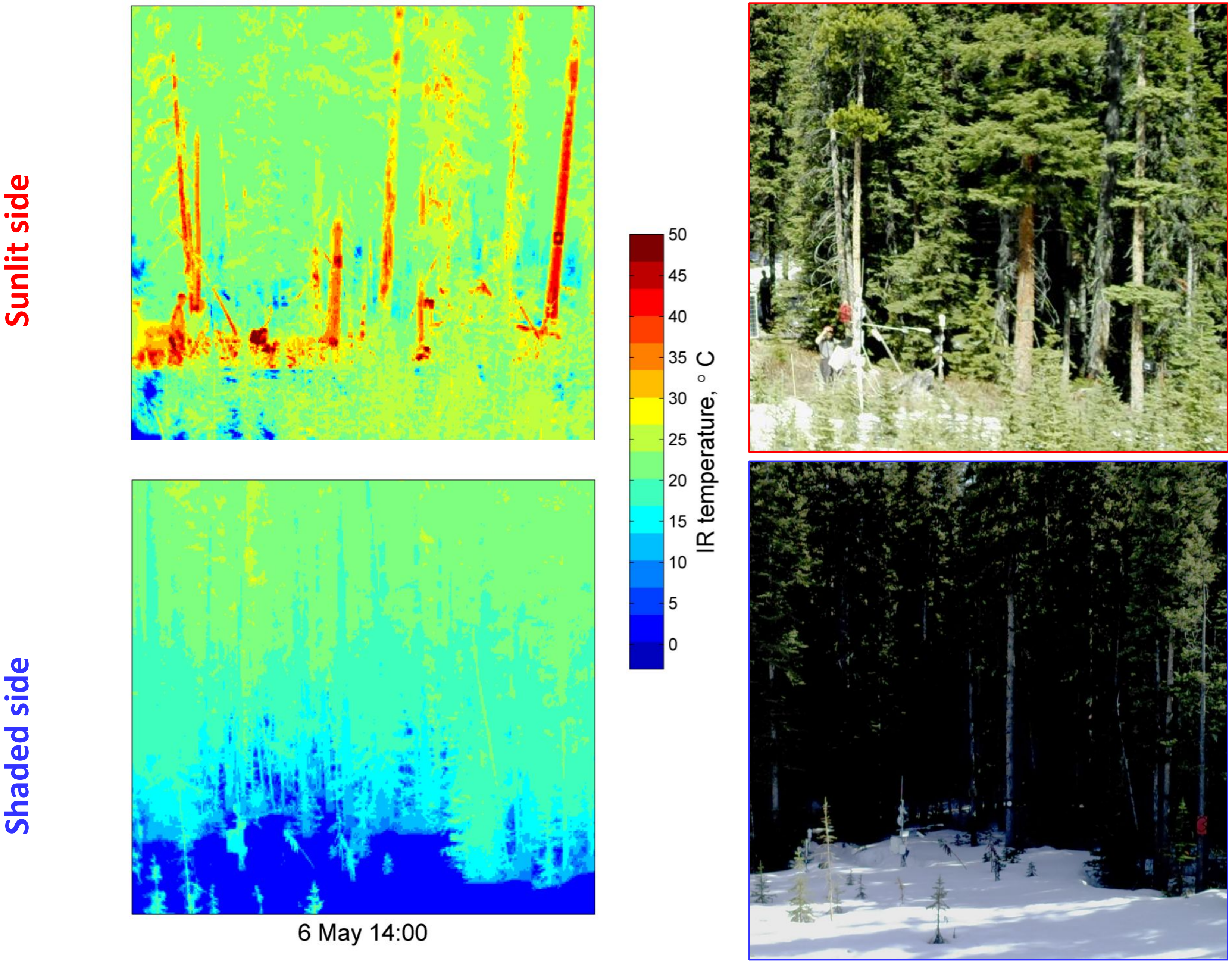
- incoming SW & LW radiation
- wind speed, air temp., RH
- trunk & needle temperatures
- snow depth and water equivalent
- soil moisture, temperature, heat flux







“Cold hole” phenomenon

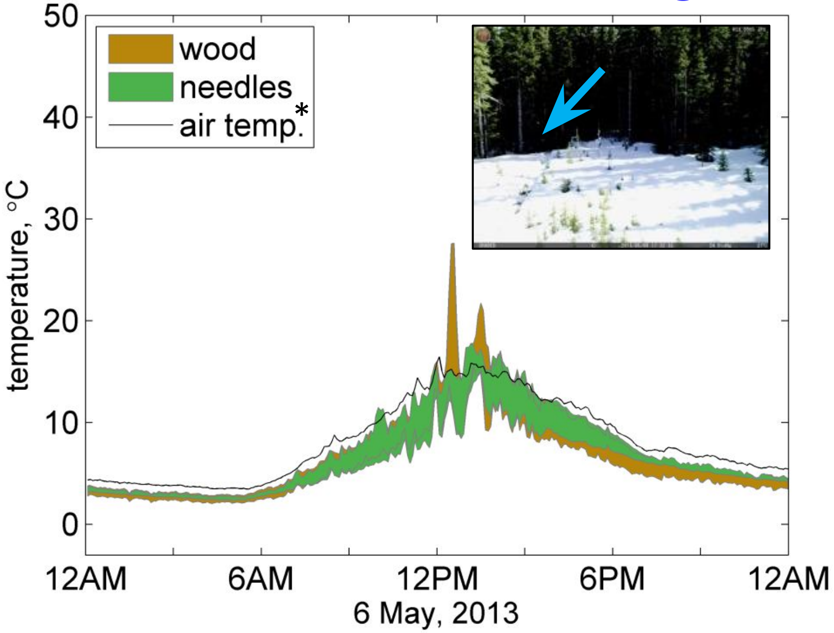

Sunlit side
Shaded side
50
45
40
35
30
25
20
15
10
5
0
IR temperature, ° C
6 May 14:00

Impact of canopy edge solar exposure on the thermal environment:

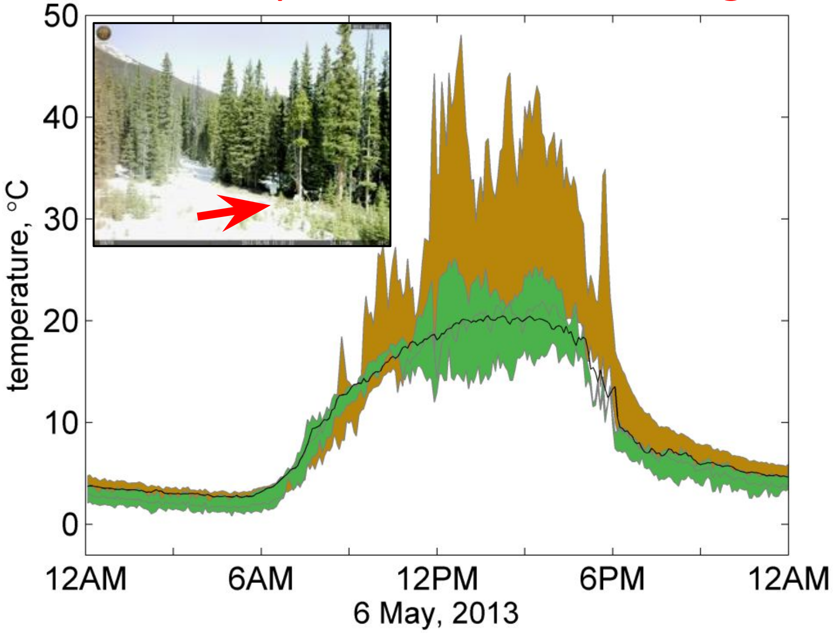
Trunk / wood temperatures

Needle temperature

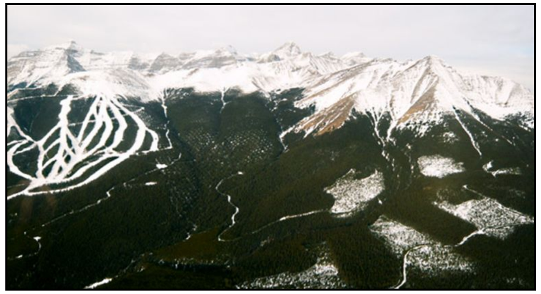
Shaded side of clearing



Sun-exposed side of clearing



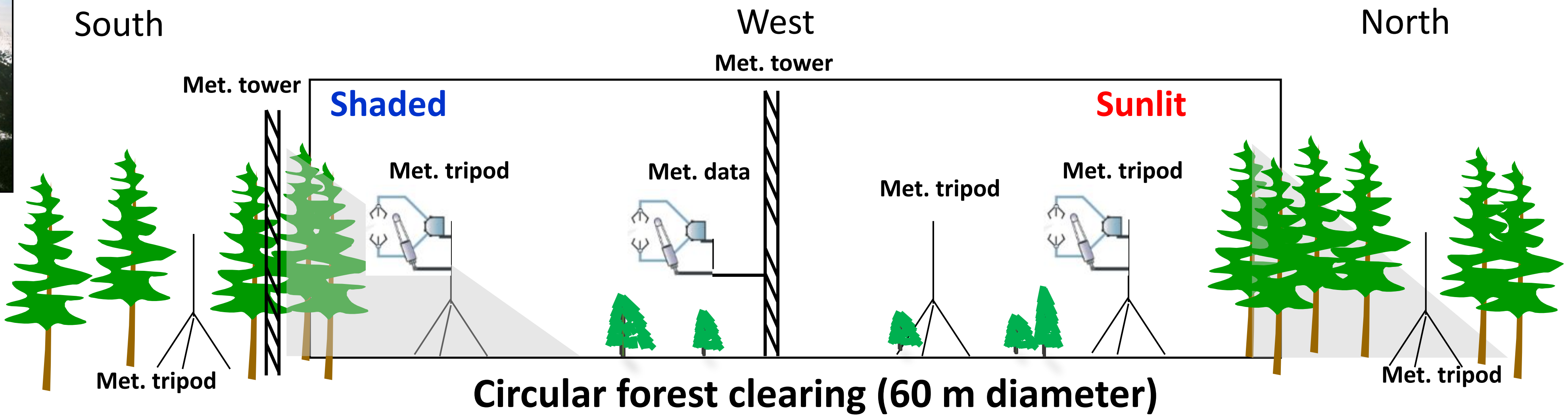
Musselman and Pomeroy (2017)

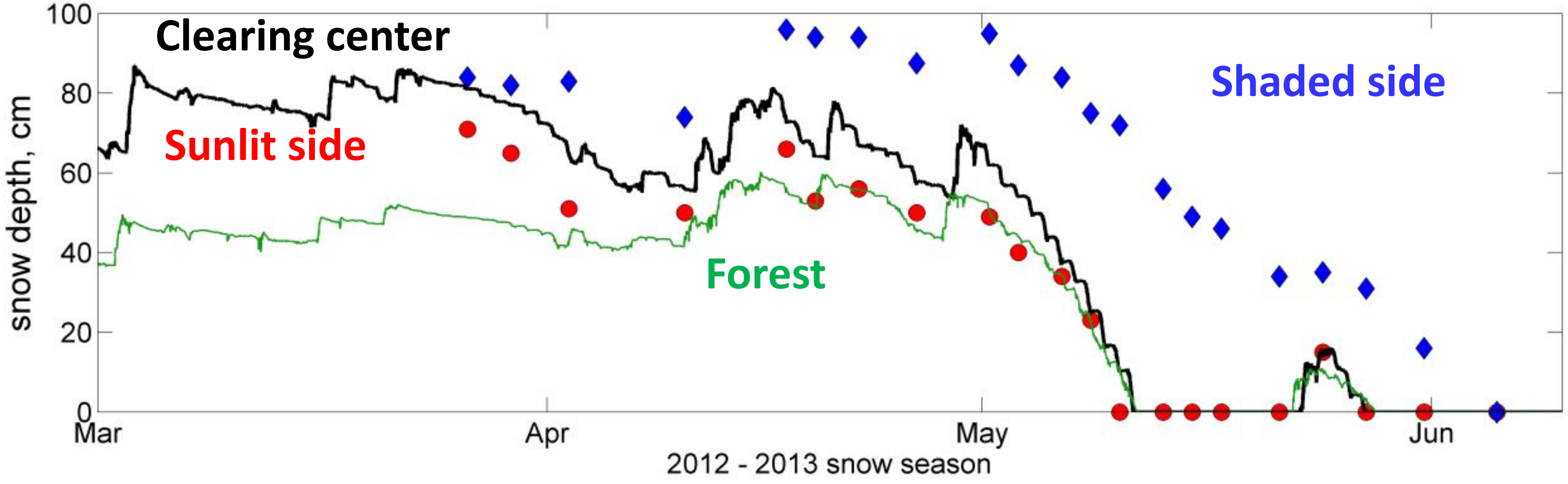


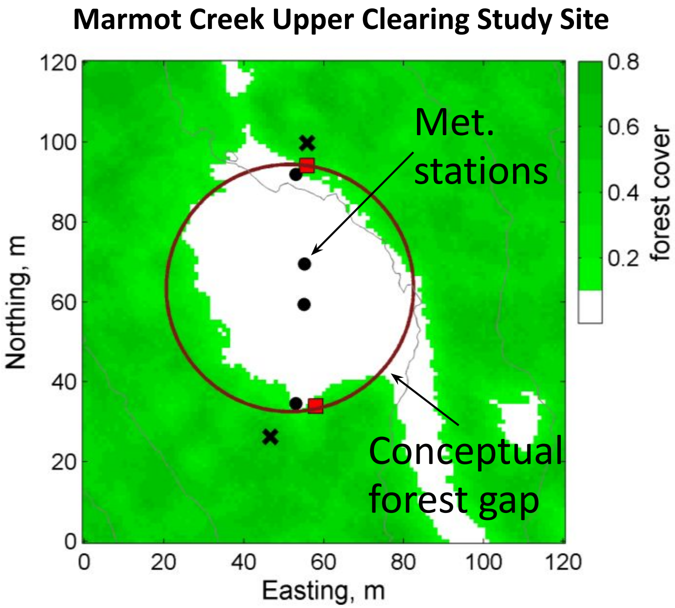
Marmot Creek Research Basin

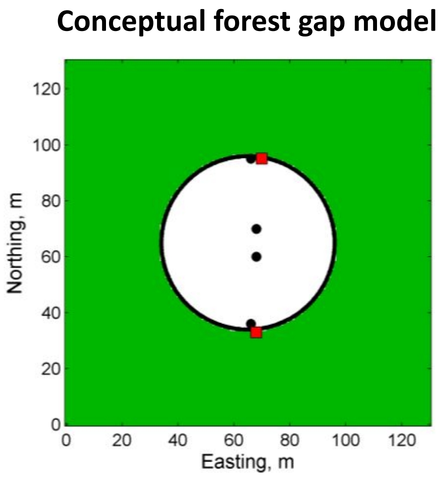
forest gap experiment

(2013-2014)





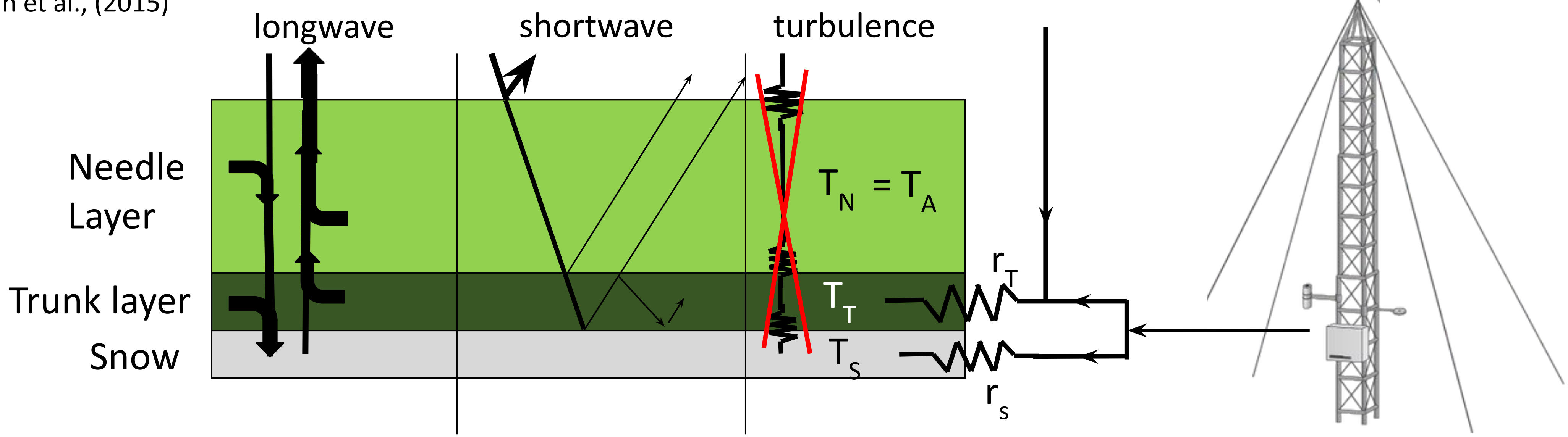




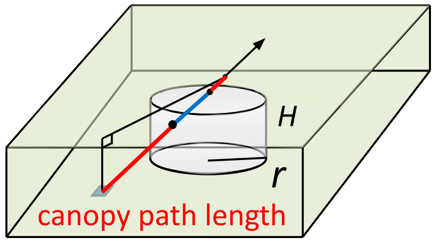
- Conceptualize the forest gap as an upright cylinder surrounded by homogeneous forest
- Model domain at 1 m spatial resolution

Modified from Verseghy et al. (1993)
Gouttevin et al., (2015)

Two-source canopy model:



ray-tracing



Canopy transmittance of SW and LW radiation: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journal homepage: www.elsevier.com/locate/agrformet

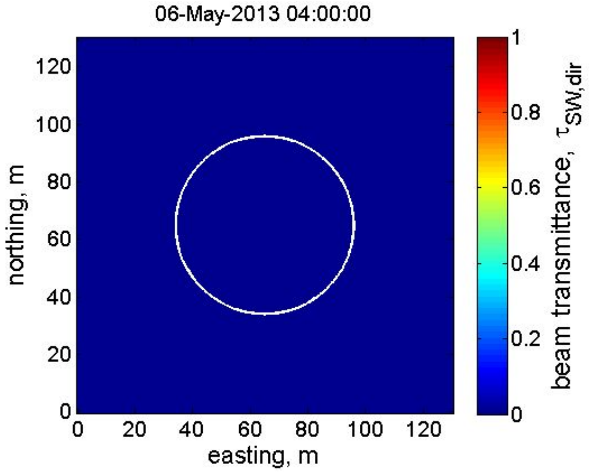
ELSEVIER

Variability in shortwave irradiance caused by forest gaps: Measurements, modelling, and implications for snow energetics

Keith N. Musselman*, John W. Pomeroy, Timothy E. Link

University of Saskatchewan, Centre for Hydrology, 117 Science Place, Saskatoon, Saskatchewan S7N 5C8, Canada

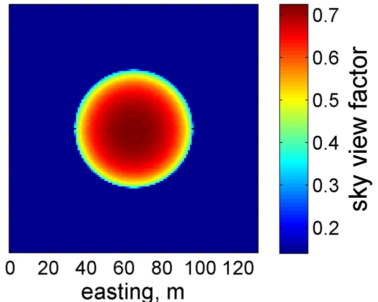
beam transmittance, $\tau_{SW dir}$



Net shortwave at the snow surface:

$$SW_{net} = SW_{net,dir} + SW_{net,dif}$$

sky view factor, svf

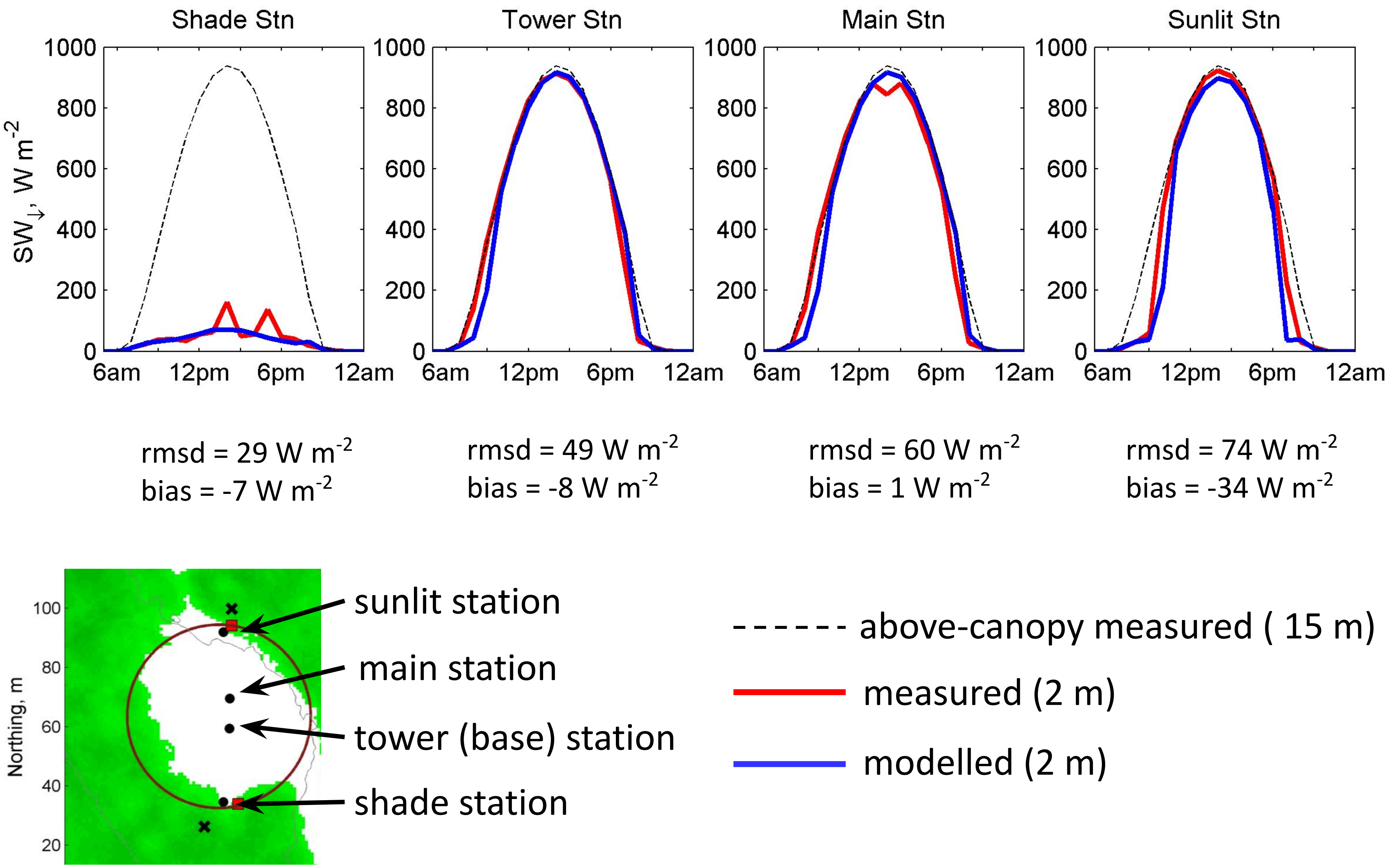


Direct beam:

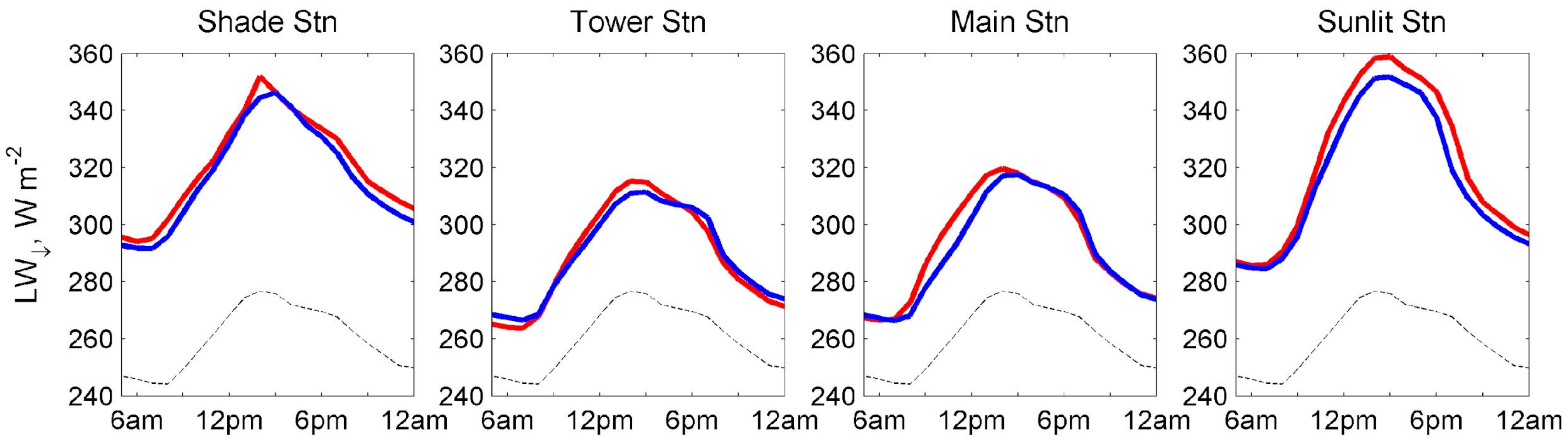
$$SW_{net,dir} = \frac{SW_{\downarrow dir}(1-\alpha_s)\tau_{SW dir}}{1-\left((1-\tau_{SW,dir})\alpha_s\alpha_c\right)}$$

Diffuse:

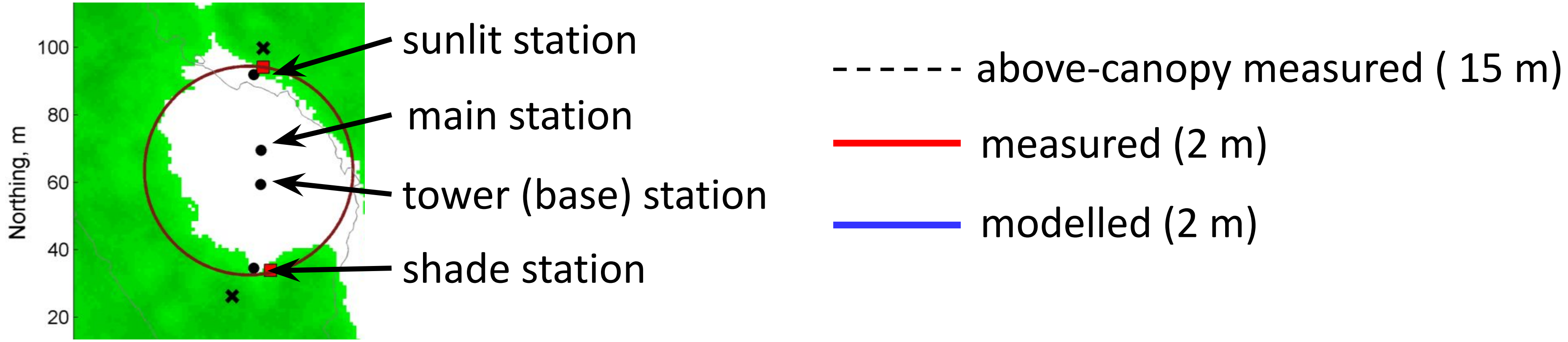
$$SW_{net,dif} = \frac{SW_{\downarrow dif}(1-\alpha_s)svf}{1-\left((1-svf)\alpha_s\alpha_c\right)}$$



Musselman and Pomeroy, in prep.)



Shade Stn	Tower Stn	Main Stn	Sunlit Stn
rmsd = 4 W m^{-2}	rmsd = 3 W m^{-2}	rmsd = 4 W m^{-2}	rmsd = 6 W m^{-2}
bias = -4 W m^{-2}	bias = 0 W m^{-2}	bias = -2 W m^{-2}	bias = -5 W m^{-2}

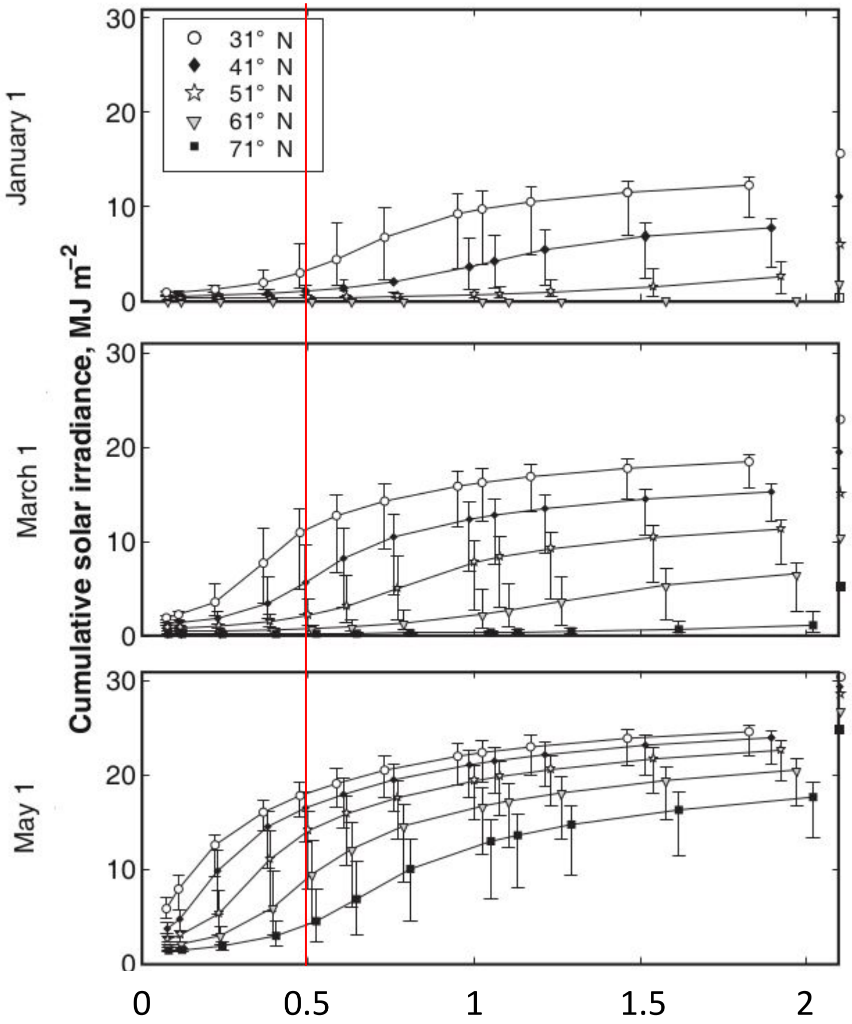


Musselman and Pomeroy, in prep.

Modeled Solar Radiation in Gaps

Winter

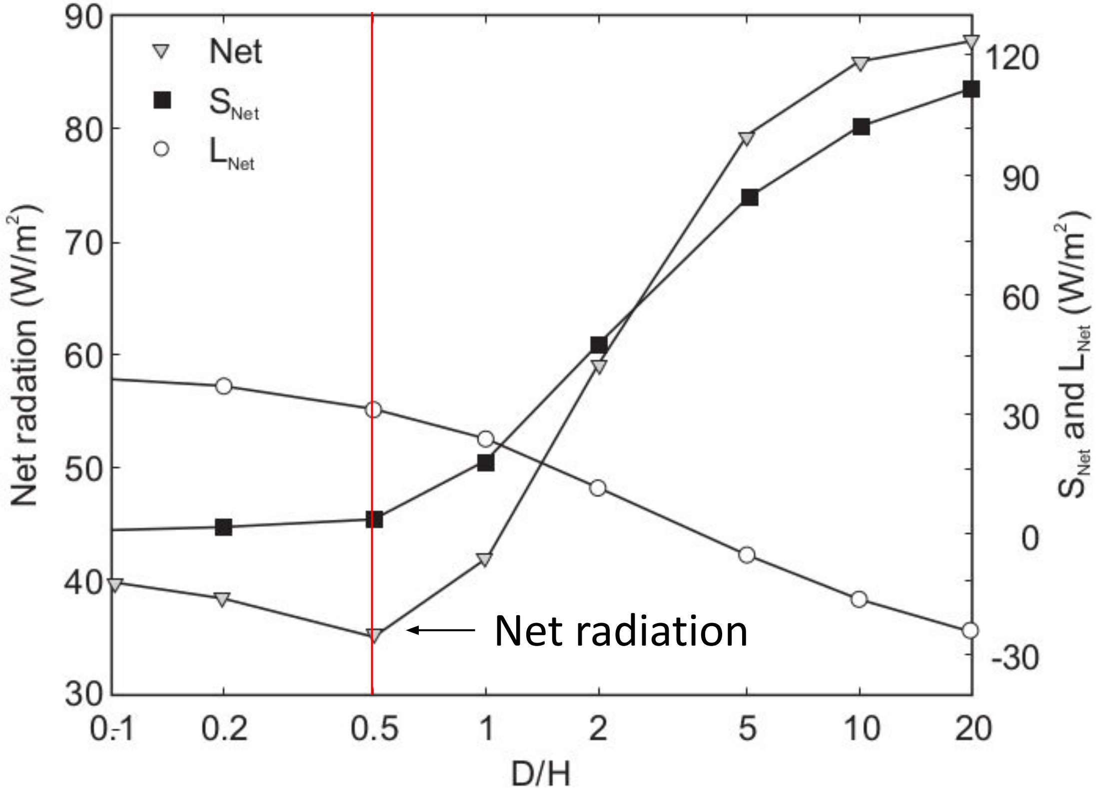
Spring



Gap Diameter / Tree Height

Modeled Net Radiation in Gaps

Net radiation = Net Shortwave + Net Longwave



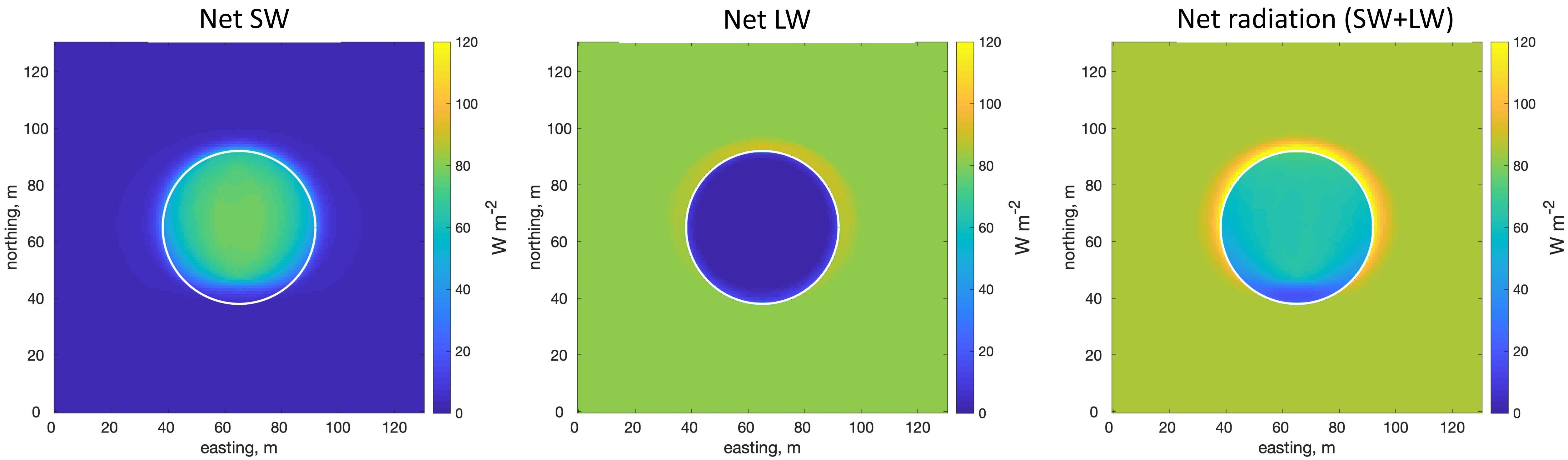
Gap Diameter / Tree Height

Small gaps (diameter = half tree height) minimize net radiation & SW input

Musselman, Link and Pomeroy (2015)

Seyednasrollah and Kumar (2014)

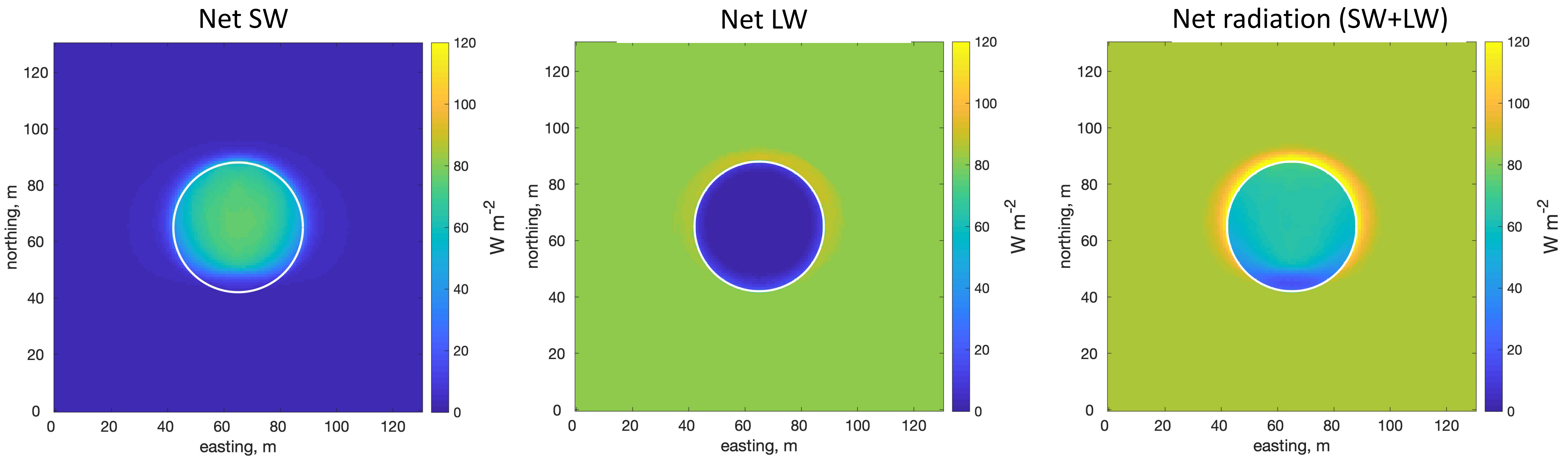
Circular forest gap radiation patterns
Melt season (mid-May) 5-day average



Gap diameter: 4.5 x tree height

Musselman and Pomeroy, in prep.

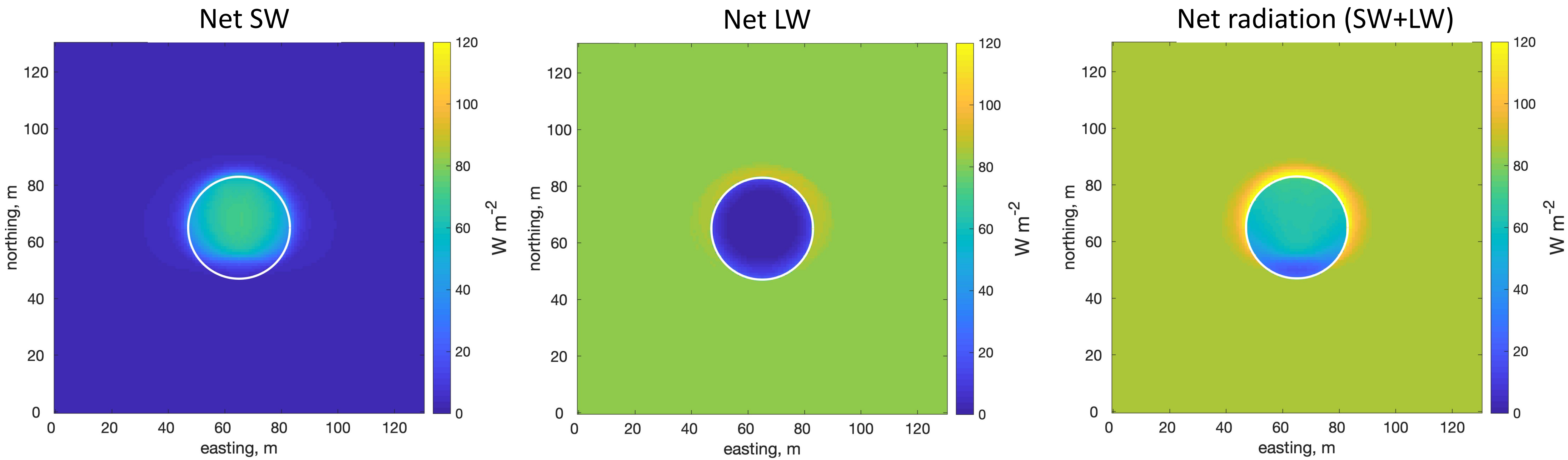
Circular forest gap radiation patterns
Melt season (mid-May) 5-day average



Gap diameter: 4 x tree height

Musselman and Pomeroy, in prep.

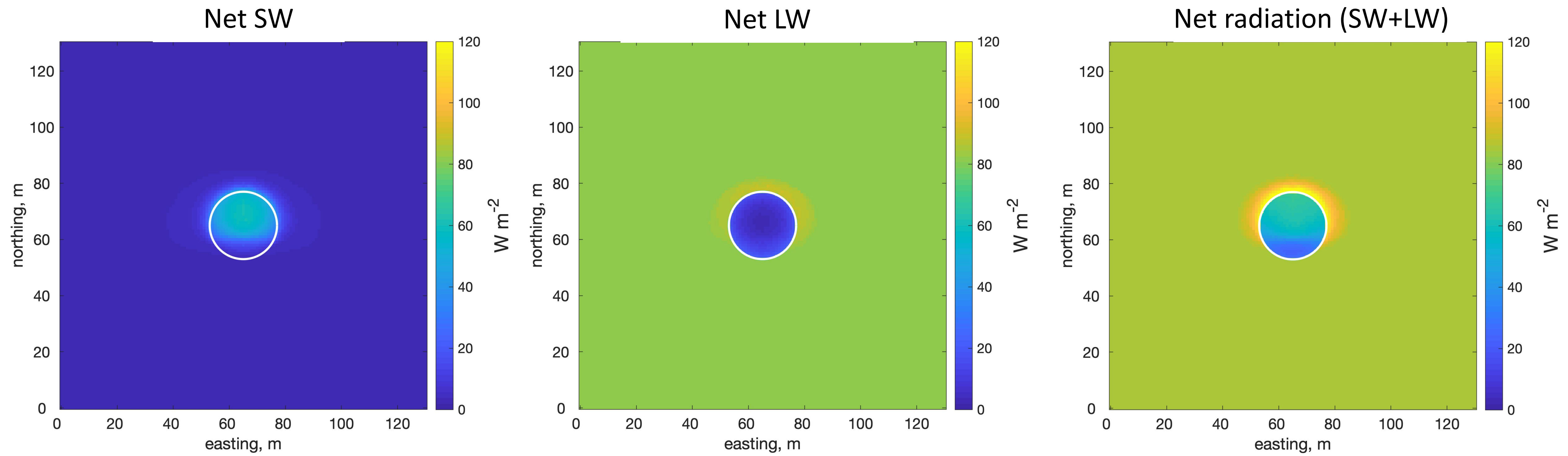
Circular forest gap radiation patterns
Melt season (mid-May) 5-day average



Gap diameter: 3 x tree height

Musselman and Pomeroy, in prep.

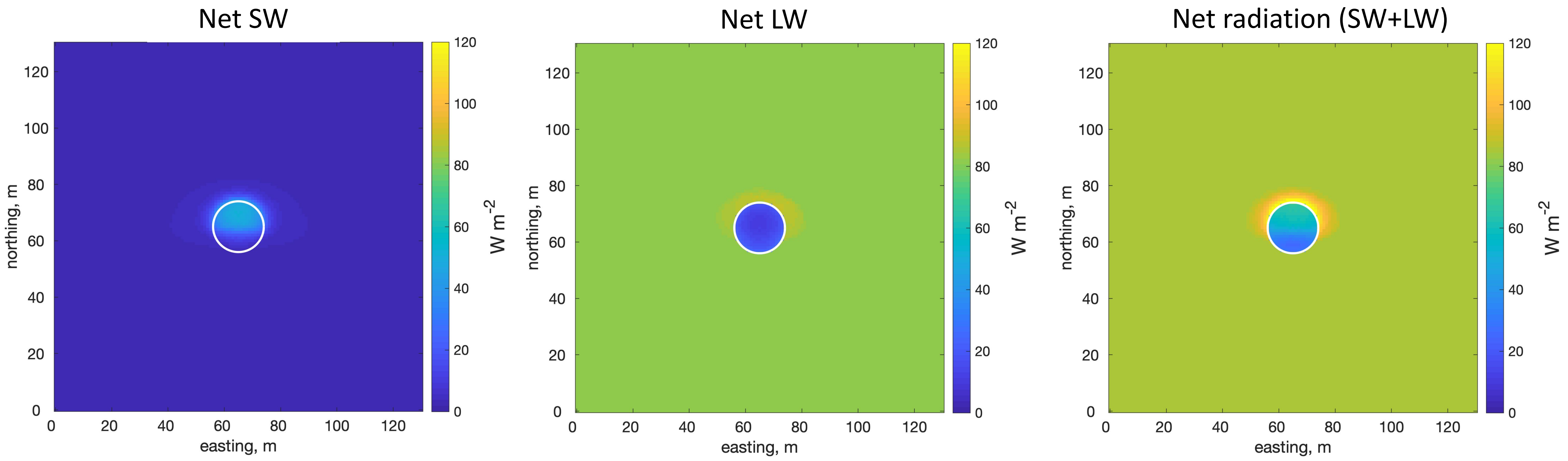
Circular forest gap radiation patterns
Melt season (mid-May) 5-day average



Gap diameter: 2 x tree height

Musselman and Pomeroy, in prep.

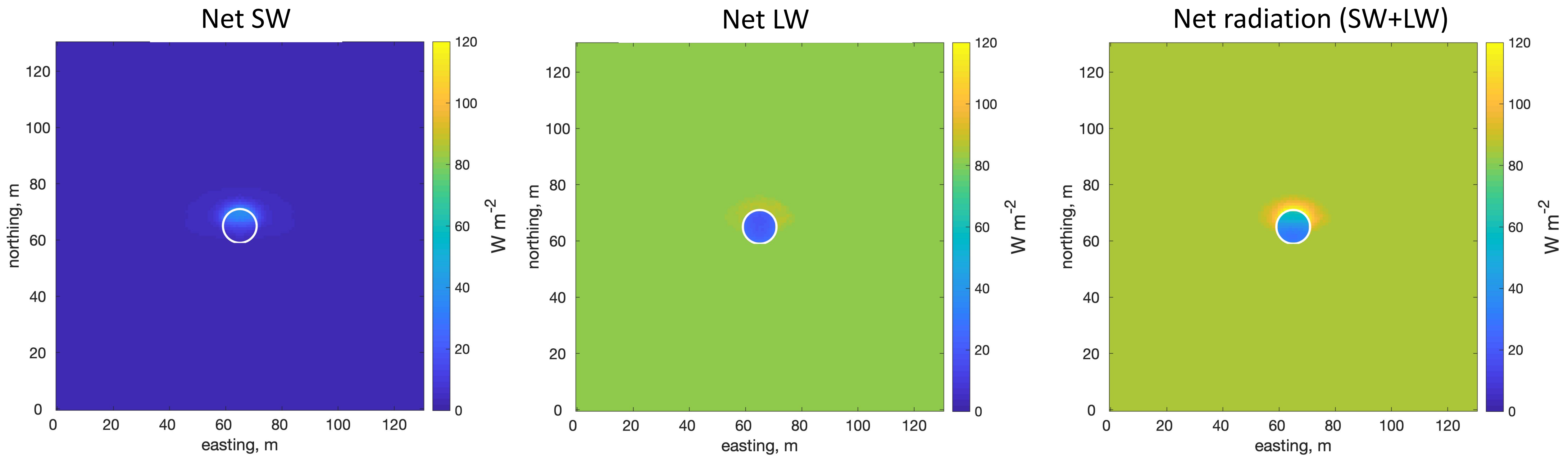
Circular forest gap radiation patterns
Melt season (mid-May) 5-day average



Gap diameter: 1.5 x tree height

Musselman and Pomeroy, in prep.

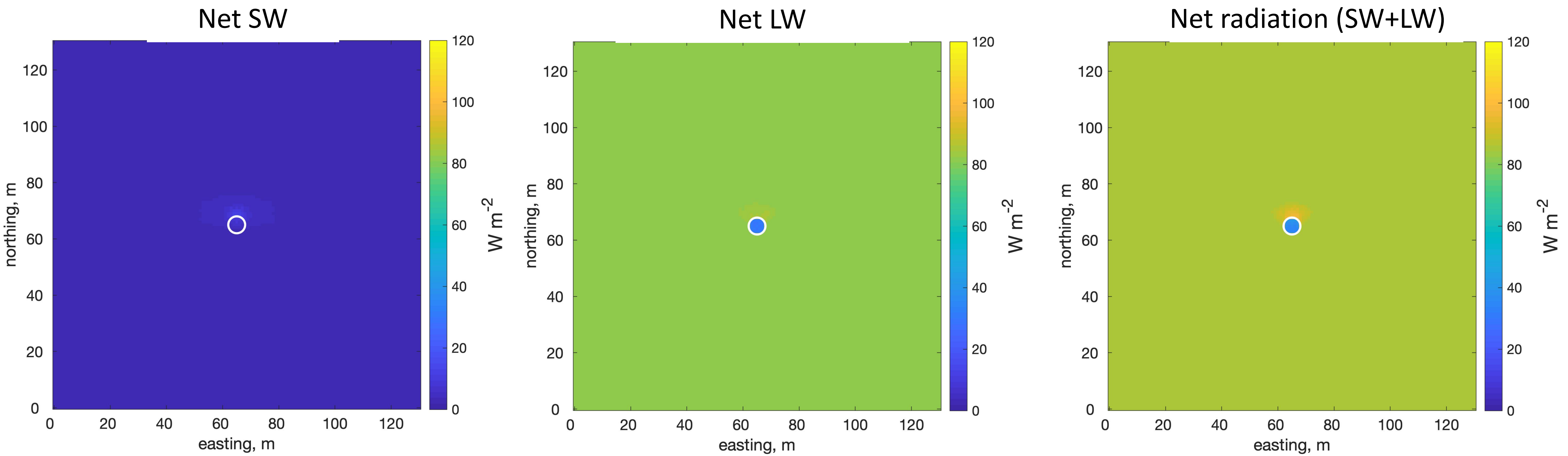
Circular forest gap radiation patterns
Melt season (mid-May) 5-day average



Gap diameter: 1 x tree height

Musselman and Pomeroy, in prep.

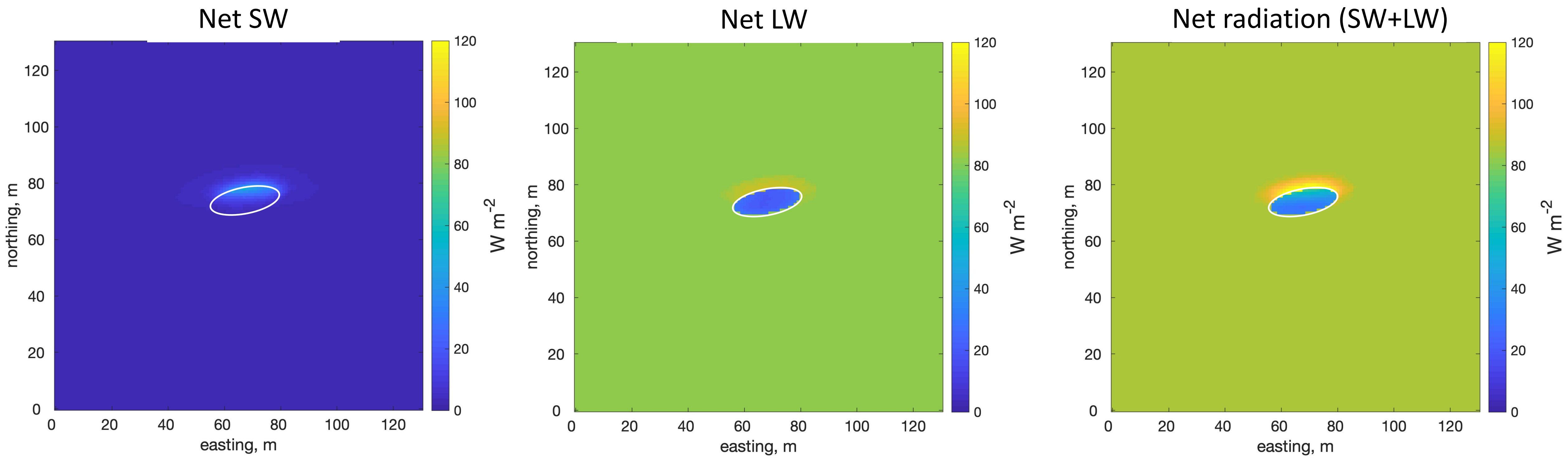
Circular forest gap radiation patterns
Melt season (mid-May) 5-day average



Gap diameter: 0.5 x tree height

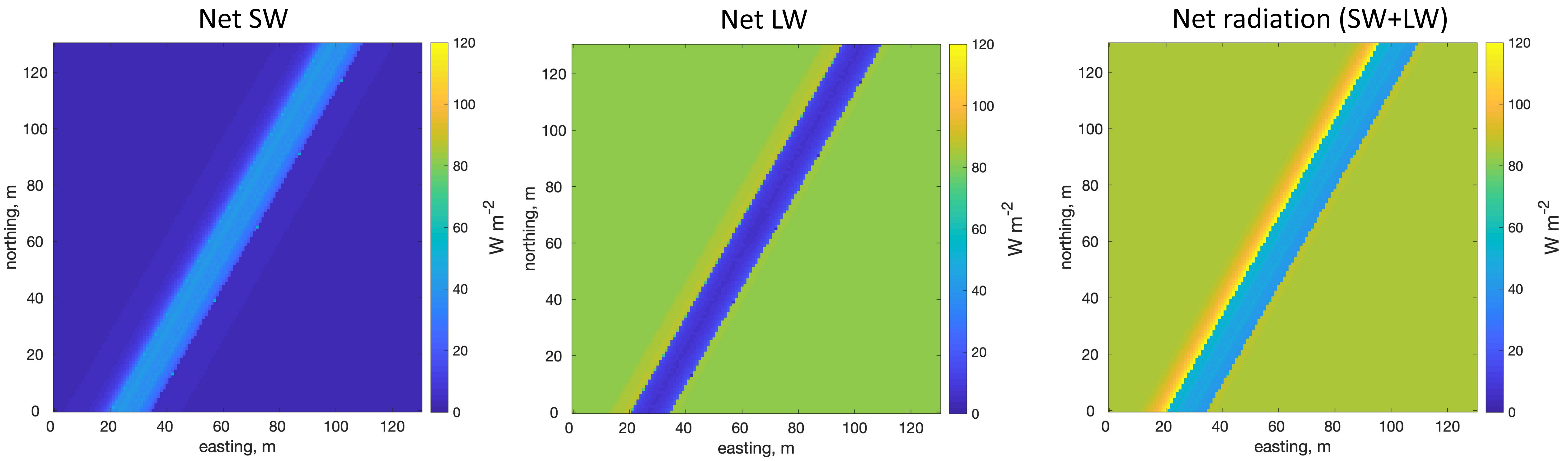
Musselman and Pomeroy, in prep.

Ellipsoidal forest gap radiation patterns
Melt season (mid-May) 5-day average



Musselman and Pomeroy, in prep.

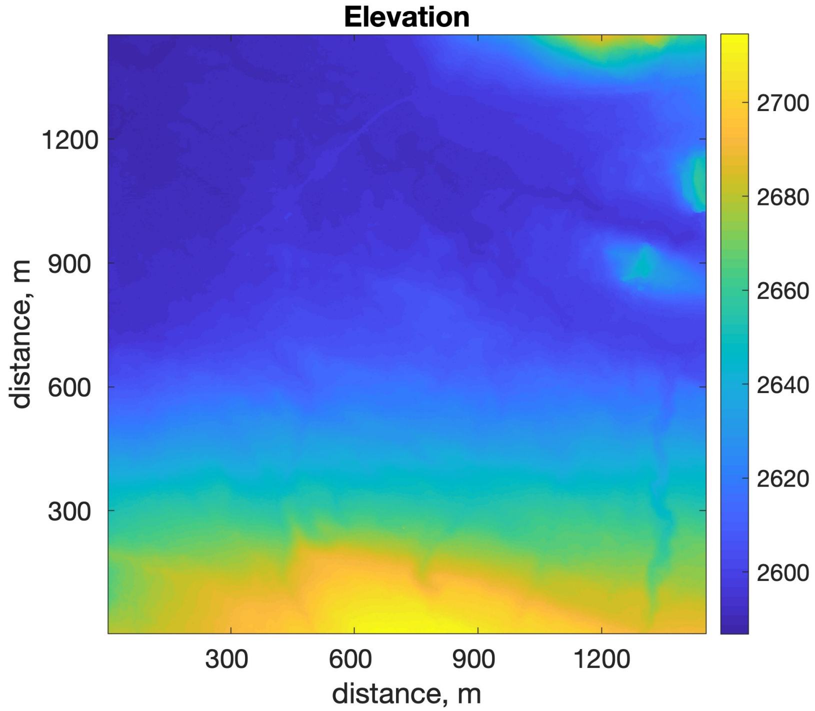
Linear disturbance radiation patterns
Melt season (mid-May) 5-day average

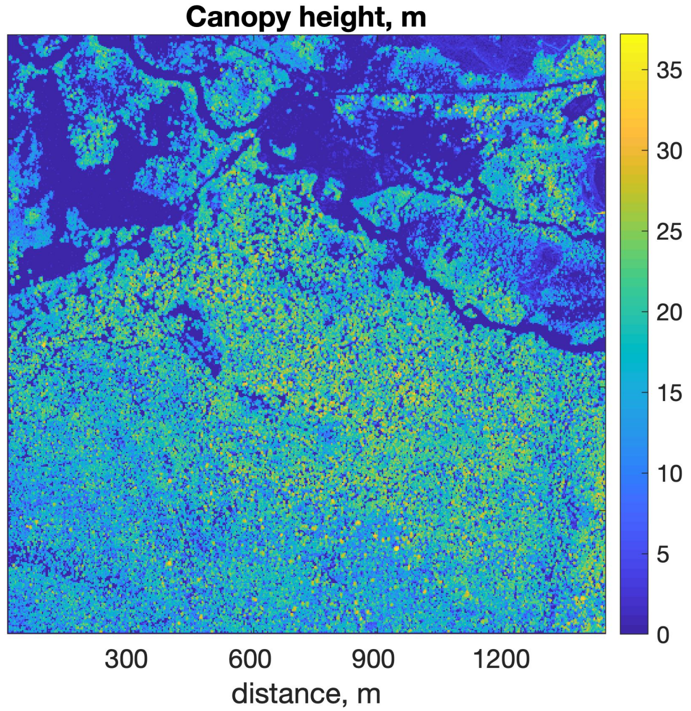


Road width: 2.5 x tree height

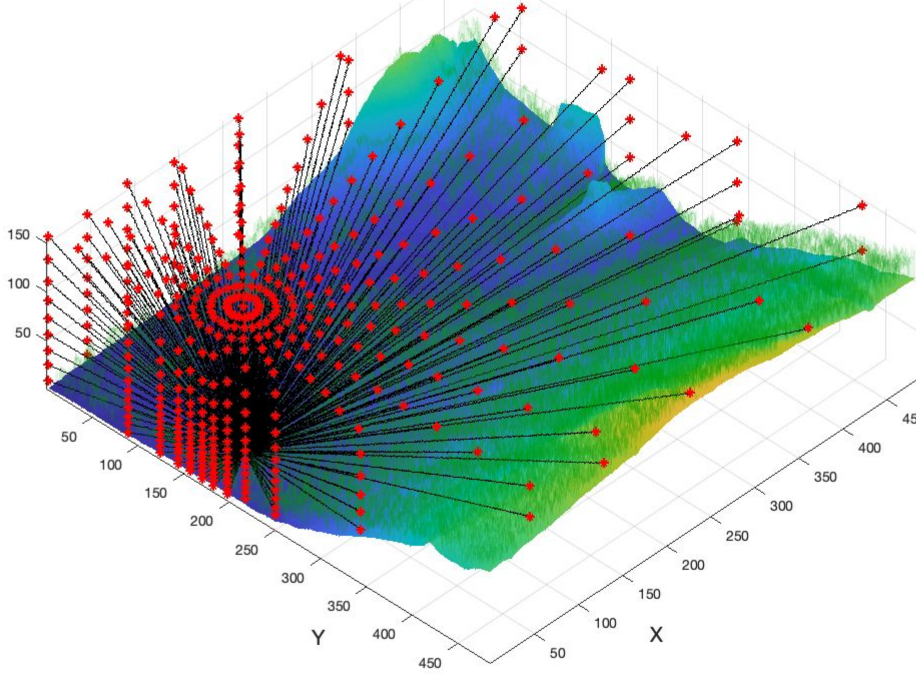
Musselman and Pomeroy, in prep.

Raytracing of lidar-produced complex terrain and forest structure





Raytracing



Lidar from ASO Inc., Tuolumne basin, CA

Lidar: light detection and ranging

Sub-canopy solar radiation, W m^{-2}

Winter

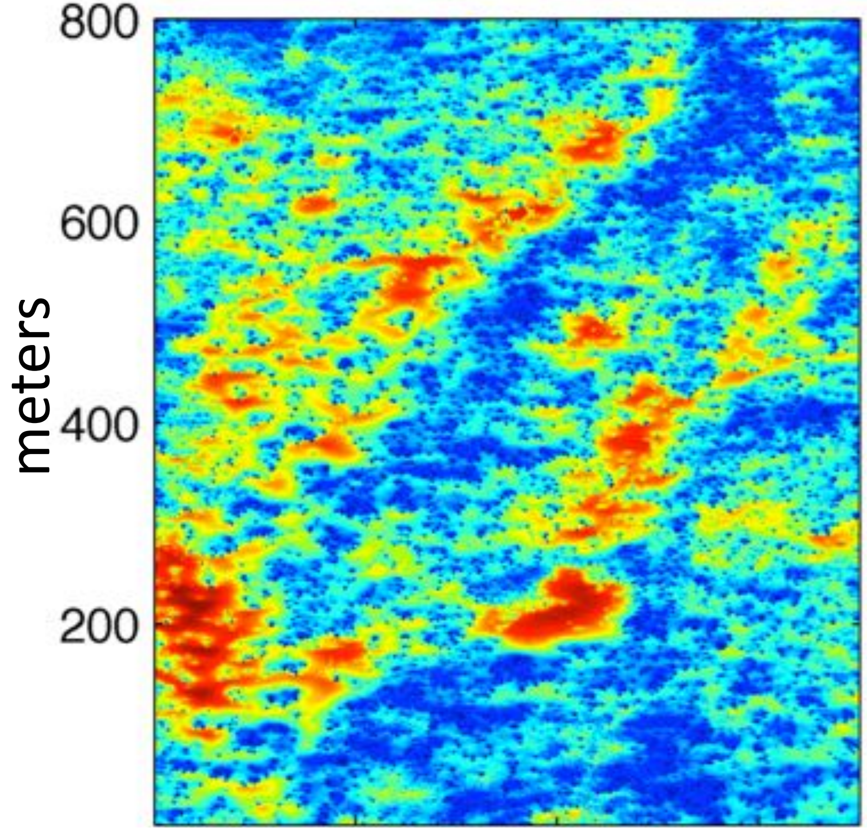
Late spring

0 0.5 1 1.5
km

0 0.5 1 1.5
km

Hot spots and hot moments – when is this detail critical?

Solar radiation from airborne LiDAR
(local- to basin-scale)

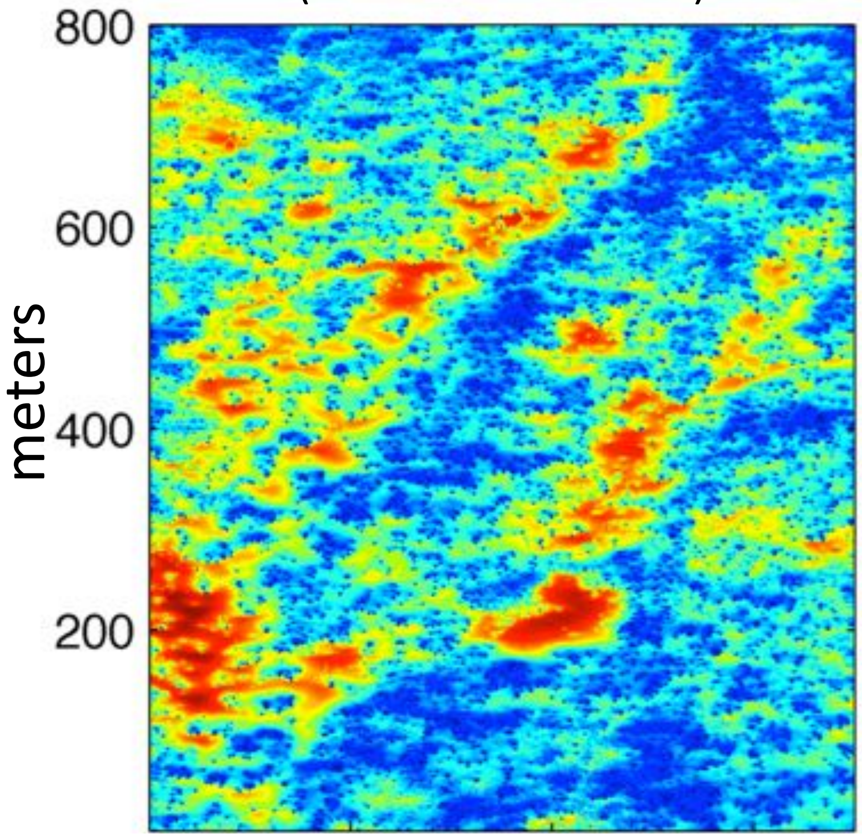


How do we retain critical information at regional / macrosystems scales?

Musselman et al., (2013) Remote Sensing of Environment

How can fine-resolution dynamics be scaled to support *parsimonious* simulations at regional to global scales?

Solar radiation modeled with LiDAR
(local- to basin-scale)



Musselman et al., (2013)
Remote Sensing of Environment

Aerial imagery
(regional to continental)

Available on your phone

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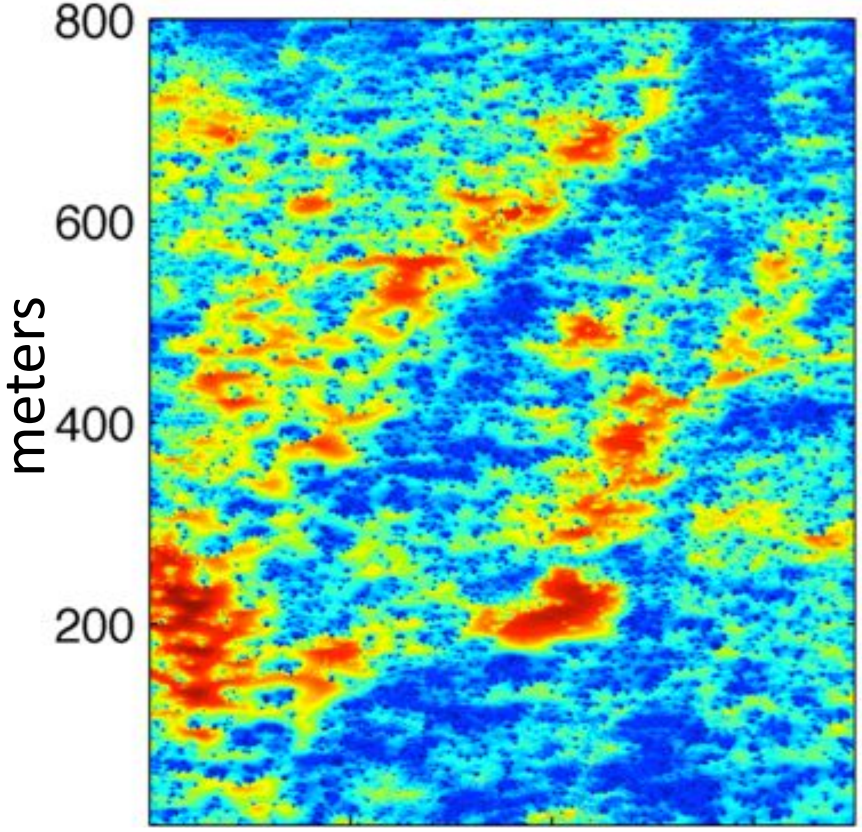
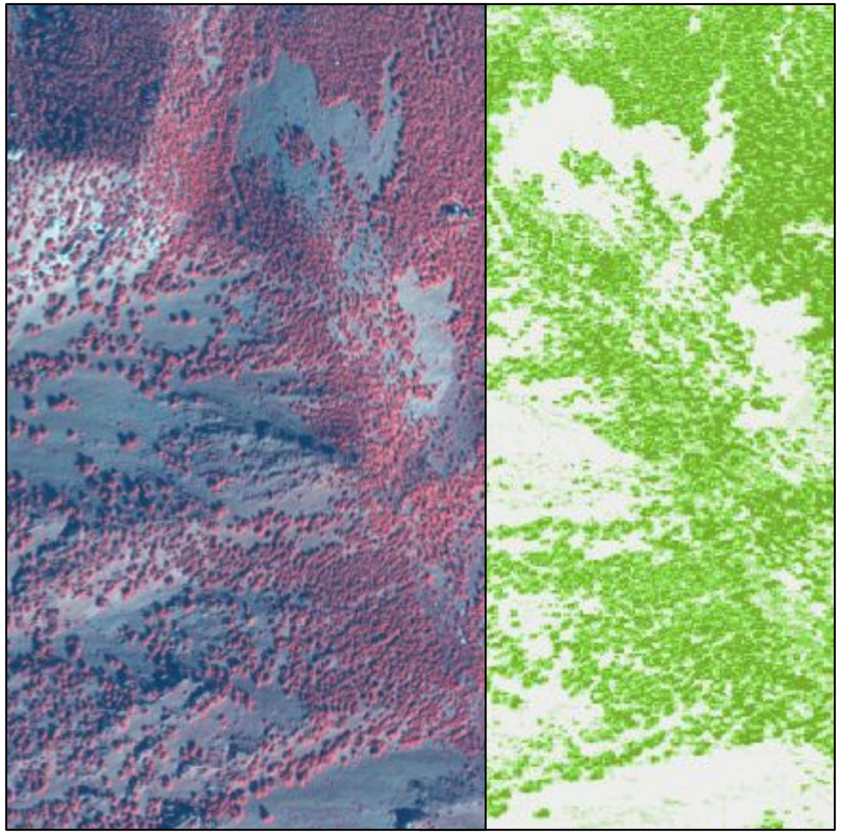


Musselman et al., (2013)
Remote Sensing of Environment

Aerial imagery
(regional to continental)

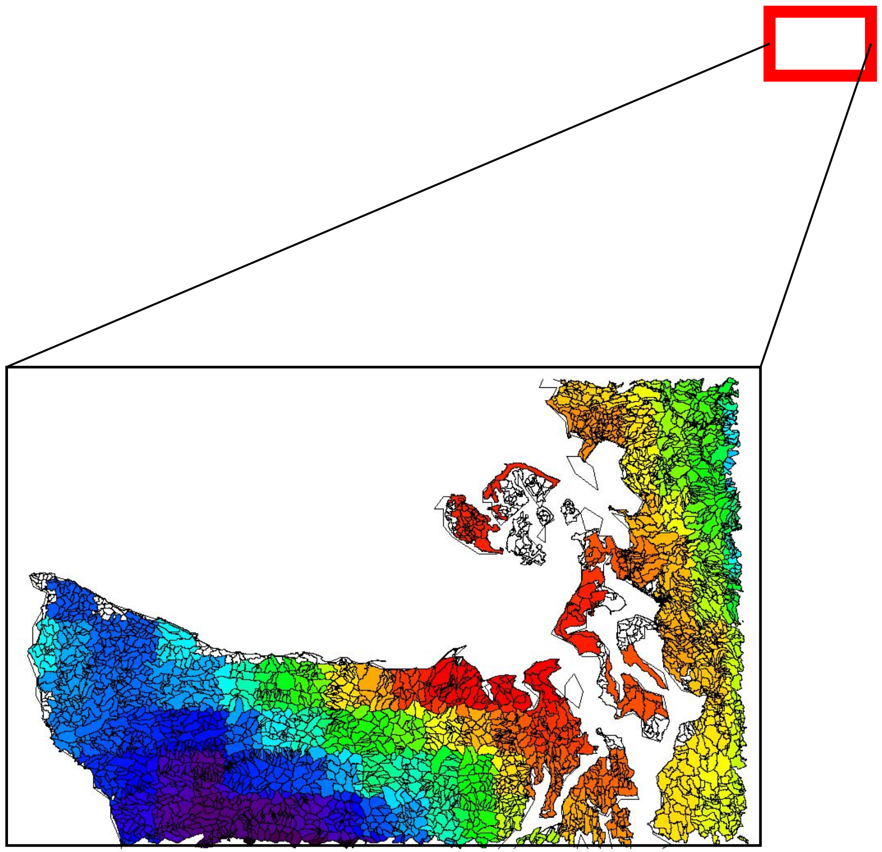
Available on your phone

Commercial satellite
(global)



Rittger and Musselman, in prep.

Community-led vision: Large-scale hydrologic and Earth System models to improve forecasts & future projections of water resources.



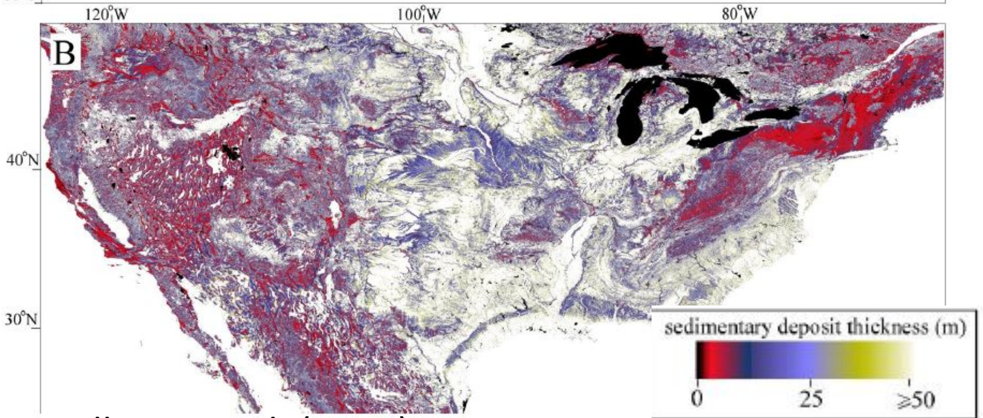
Grouped Response Units

Example: soil moisture and drought

Courtesy: Martyn Clark

Model and remote sensing accuracy is advancing but needs to remain grounded by empiricism & guided by stakeholders to gain trust and encourage use.

Parameterization & scaling w/ large-scale data



Pelletier et al. (2016)

Regional, continental, global prediction

Point-scale observations

Co-defining climate change refugia to inform effective management of mountain headwater systems

A new $3.6M, 5-yr NSF-funded project lead by CU Boulder

Climate-change refugia – mappable landscape units sufficiently buffered from climate change to enable the persistence of physical, ecological, and sociocultural resources (Morelli et al. 2016).

Research Question:

Can sociocultural values, stakeholder needs, and scientific advances be linked to co-define, map, and project climate change refugia for headwater ecosystem services at the urban-wildland interface?

Vision:

Refugia are delineable landscape units co-mediated by energy and water

They can be modeled

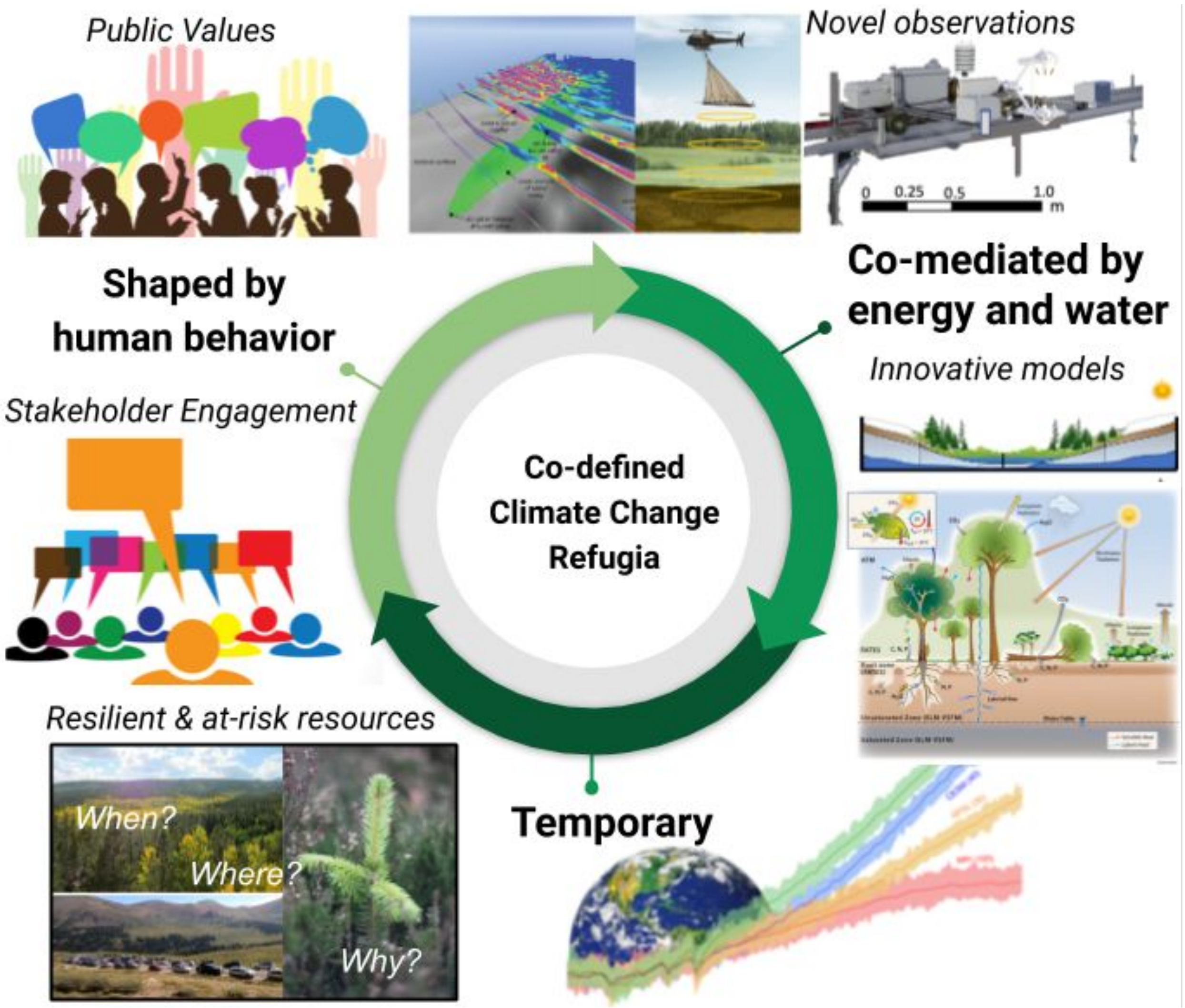
Refugia are shaped by human behavior and linked to human values

Surveys to understand preferences of diverse sociocultural groups in Front Range corridor

Partner with decision-makers (maybe you?!) to form an advisory committee to co-define relevant refugia metrics

Refugia are temporary

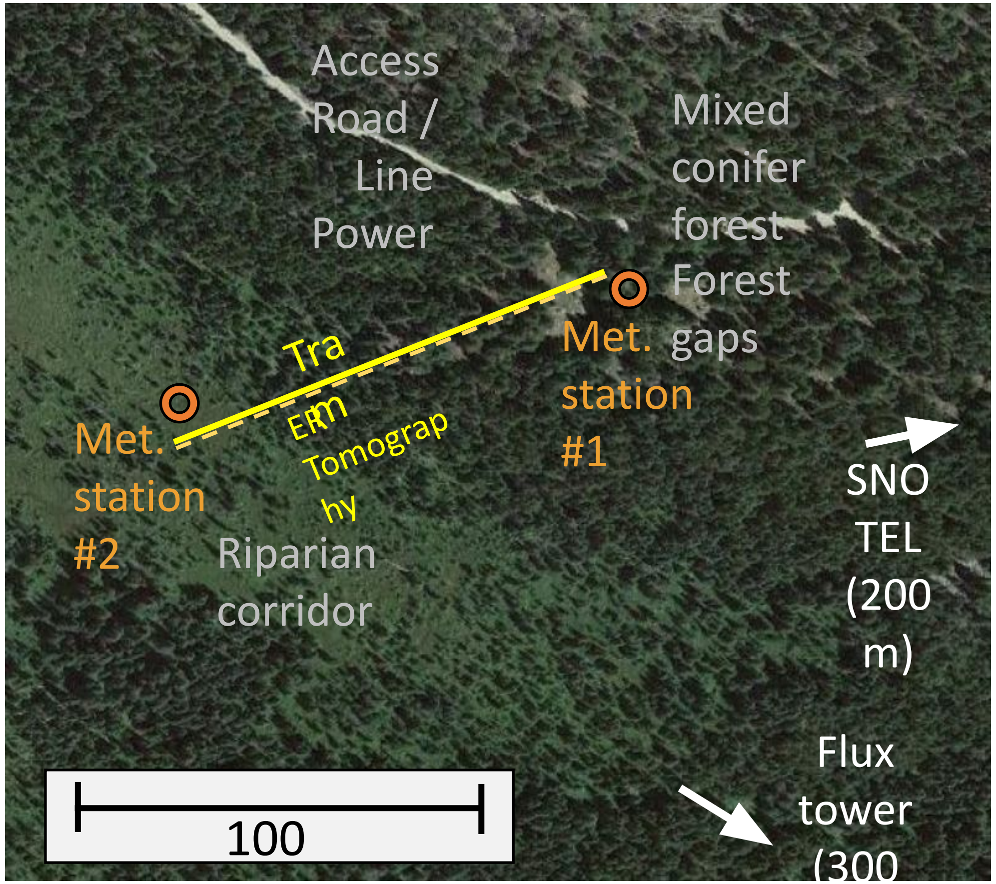
Projections of when and at what regional warming level co-defined refugia persist or face risk will be used to separate non-refugial areas from climate change refugia

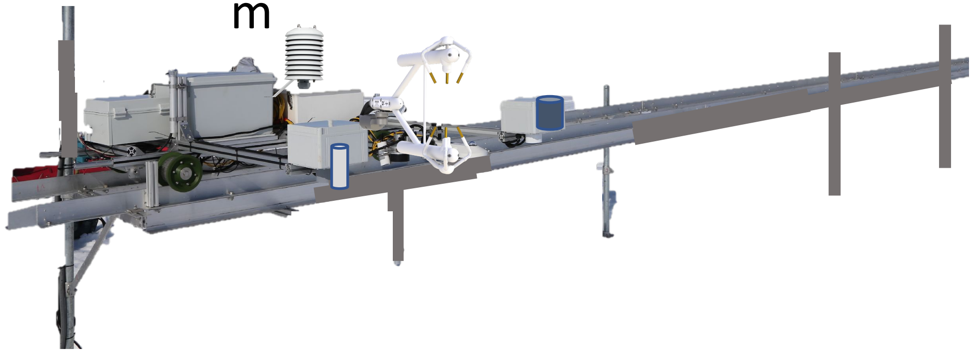


Tram measurement system traversing water, energy and phenological gradients.

Coming spring 2022 to Como Creek, below Niwot Ridge, CO

- Co-located observations of
  - hydrometeorology,
  - geophysical and biogeochemical soil states,
  - plant and tree phenology
- Using mobile instrumentation, study plots, and surface and sub-surface remote sensing techniques.



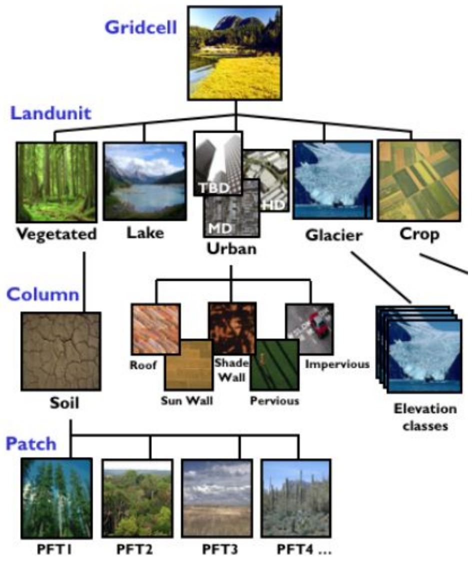


Models tested against observations

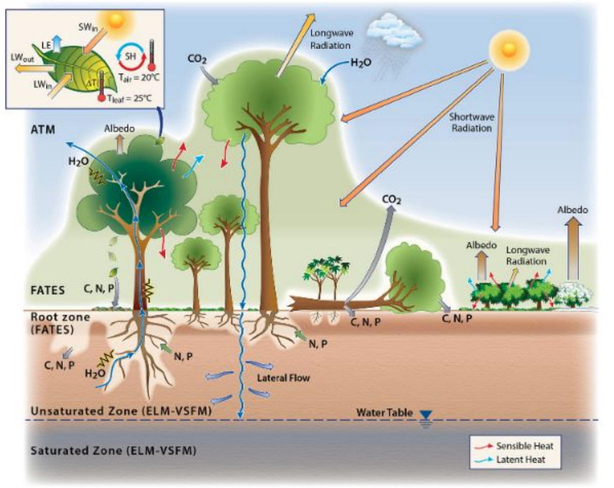
- Community Land Model (CLM)
- Hillslope hydrology
- Functionally Assembled Terrestrial Ecosystem Simulator (FATES)
- Downscaled Community Earth System Model (CESM2) Large Ensemble

Used to assess climate change refugia for the Front Range headwaters.

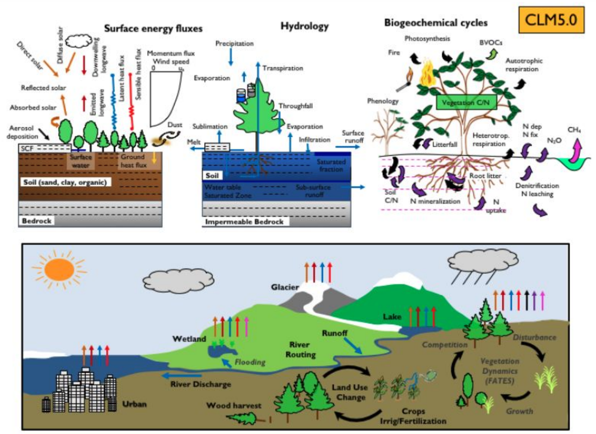
Hillslope Connectivity & Heterogeneity



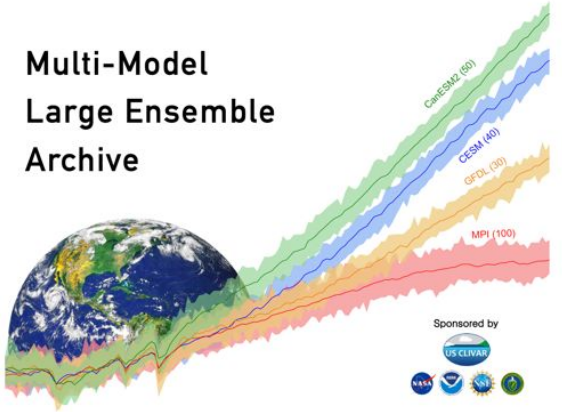
Dynamic ecosystem simulator



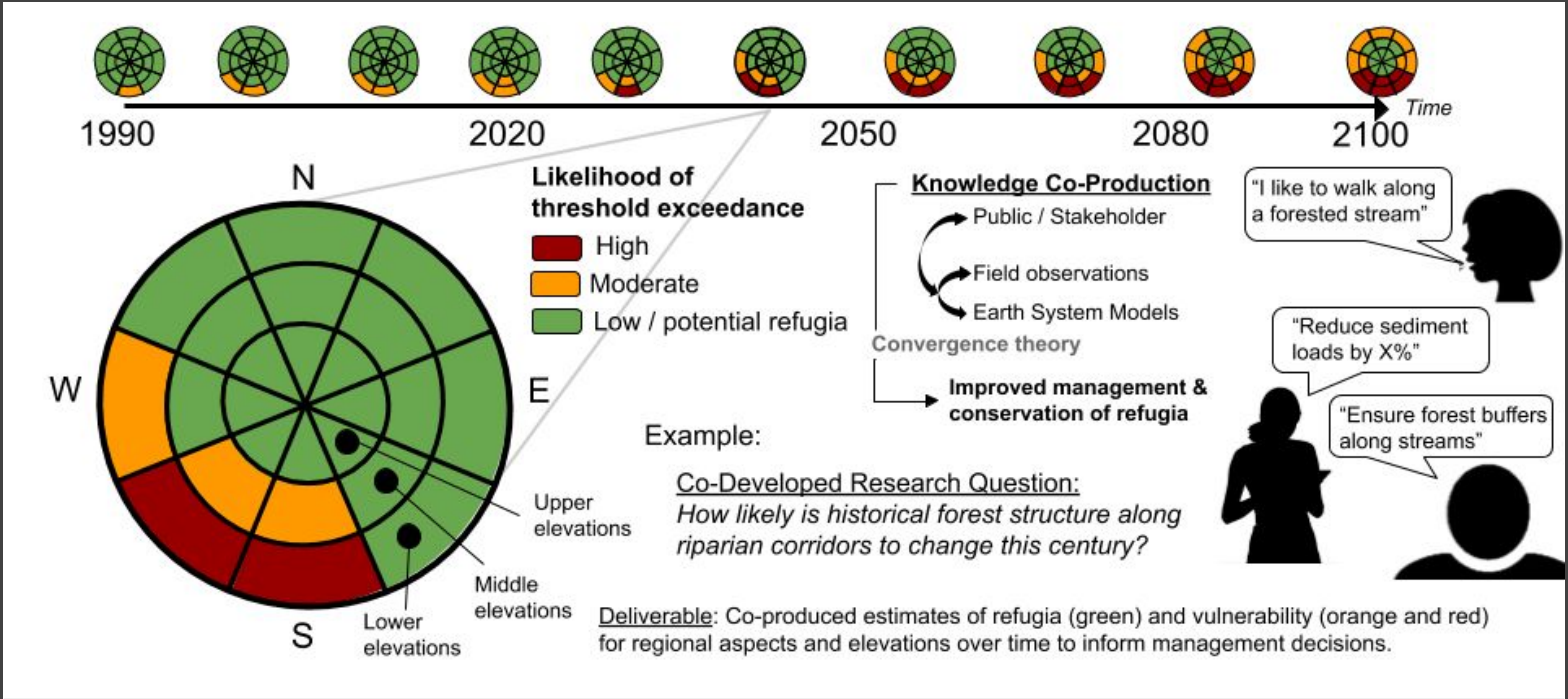
Land surface model



Climate model large ensemble



NCAR



1990
2020
2050
2080
2100
Time
N
W
E
S
Likelihood of threshold exceedance
High
Moderate
Low / potential refugia
Upper elevations
Middle elevations
Lower elevations
Knowledge Co-Production
Public / Stakeholder
Field observations
Earth System Models
Convergence theory
Improved management & conservation of refugia
"I like to walk along a forested stream"
"Reduce sediment loads by X%"
"Ensure forest buffers along streams"
Example:
Co-Developed Research Question:
How likely is historical forest structure along riparian corridors to change this century?
Deliverable: Co-produced estimates of refugia (green) and vulnerability (orange and red) for regional aspects and elevations over time to inform management decisions.

Summary

- Forests influence snow by reducing accumulation via canopy interception losses and delaying snowmelt via shading.

- Overly dense forests reduce snow accumulation and streamflow.
- Forest manipulations / management provide multiple benefits. Decisions must be made judiciously and informed by process-based models co-developed across disciplines & w/ stakeholders.

- There is great need for a community-developed forest model capable of resolving variability in water, energy and plant physio. relevant to scientists, stakeholders and societal values.

A community science challenge


Thank you!
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