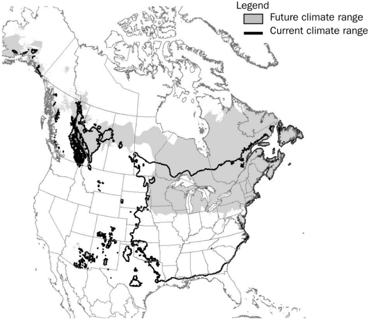
Critical transition at range limits slows down the response of forest trees to climate warming

Dominique Gravel

QUICCFOR
Quantifying and mapping the impact of climate change
on forest productivity in Eastern Canada

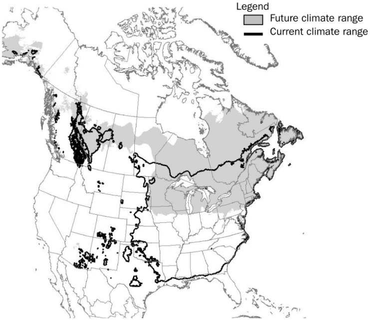
Distribution of sugar maple

EXPECTED FUTURE DISTRIBUTION



McKenney et al. 2007. Bioscience

EXPECTED FUTURE DISTRIBUTION

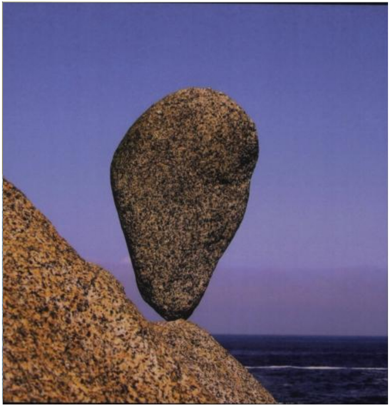


McKenney et al. 2007. Bioscience

- Phenomenological;
- No demography;
- No biotic interactions;
- No dispersal limitations;
- Equilibrium distribution;

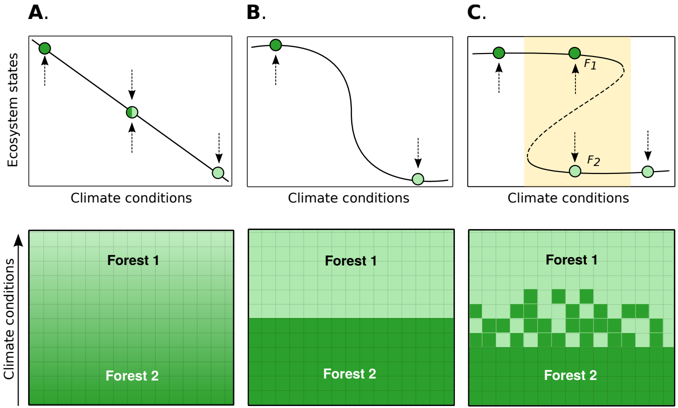
Do we have an appropriate theoretical framework?

WHAT ABOUT THE TRANSIENTS?

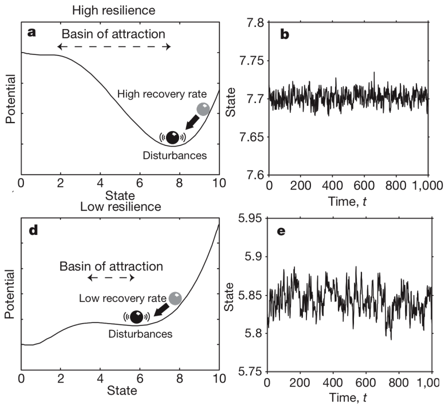


Scheffer (2009)

Non-linear transitions



CRITICAL SLOWING DOWN



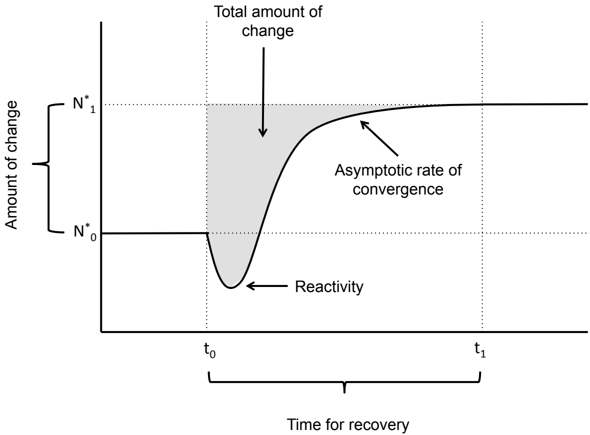
Scheffer et al. (2009) Nature.

OUTLINE

Objective: Propose a synthesis on the current theory for *range dynamics* and apply it to the understand migration of temperate forest ecosystems.

- Theory for transient range dynamics;
- Modelling range limits with a 2-states metapopulation framework;
- Investigation of the stability with a 4-states metacommunity framework;

QUANTIFYING THE TRANSIENTS



Model for range limits

Metapopulation dynamics:

$$\frac{dp(E)}{dt} = \underbrace{c(E)p(E)(h(E) - p(E))}_{\text{Colonisation}} - \underbrace{e(E)p(E)}_{\text{Extinction}}$$

Which yields the equilibrium distribution:

$$\overline{p}(E) = h(E) - \frac{e(E)}{c(E)}$$

The sensitivity of the system to a changing environment is thus given by:

$$\frac{\partial \overline{p}(E)}{\partial E}$$

Asymptotic rate of convergence

Consider a small deviation to the equilibrium under the new environmental conditions, E_1, called δ:

$$\frac{d(\bar{p}(E_1)+\delta)}{dt} = \frac{d\bar{p}(E_1)}{dt} + \frac{d\delta}{dt}$$

With:

$$\delta = \frac{\partial\bar{p}(E_1)}{\partial E}$$

Linearization of the system around this equilibrum gives the dynamics of the small deviation (the leading eigenvalue in thecase of a system of equations).

Within the range limit:

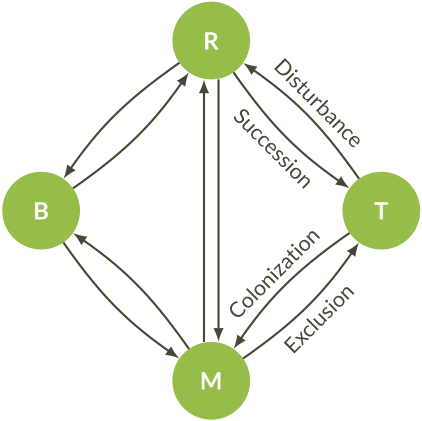
$$\lambda = e(E) - c(E)$$

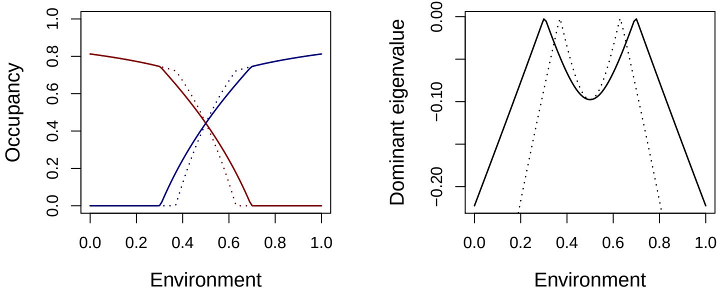
Outside the range limit:

$$\lambda = c(E) - e(E)$$

A the range limit:

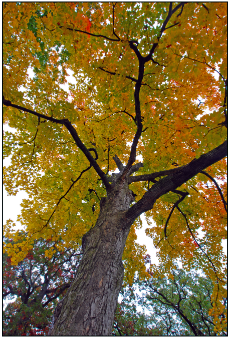
$$\lambda = c(E) - e(E) = 0$$


R
B
T
M
Disturbance
Succession
Colonization
Exclusion


Occupancy
0.0
0.2
0.4
0.6
0.8
1.0
Environment
Dominant eigenvalue
−0.20
−0.10
0.00
Environment

Temperate-boreal transition

SUGAR MAPLE

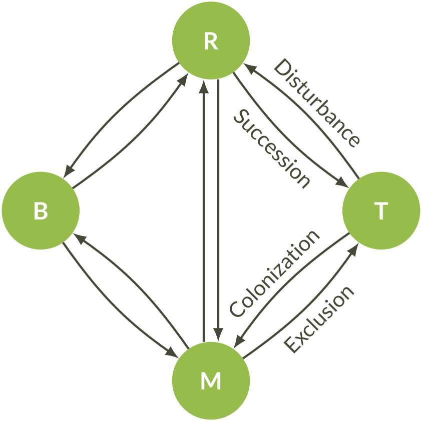


- Highly shade tolerant;
- High fecundity;
- Seedling bank;
- Small-distance dispersal;
- Requires well drained and rich soils;
- Fast litter decomposition rate;
- Arbuscular mycorhizae;

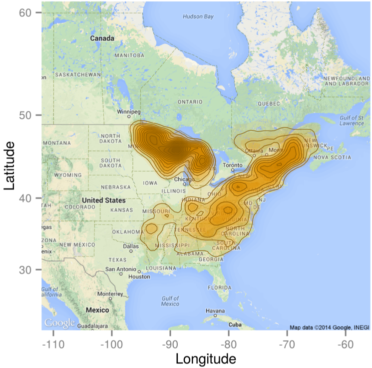
BALSAM FIR

- Highly shade tolerant;
- High fecundity;
- Seedling bank;
- Small-distance dispersal;
- Found on all types of soils;
- Slow litter decomposition rate, build-up of a resistant humus layer;

THE MODEL



DATA



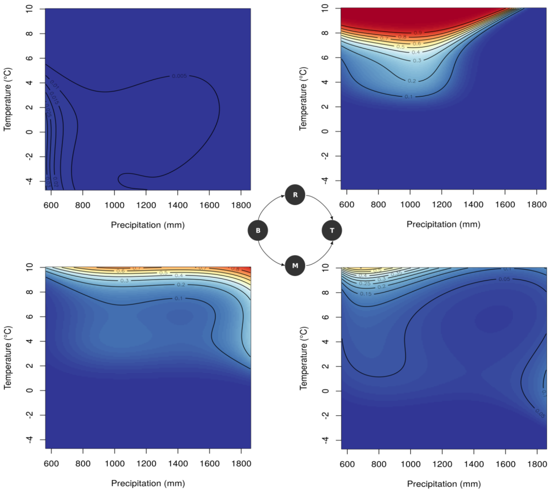
- Permanent Forest Inventory plots from U.S. and Canada;
- Single tree measurements;
- 2-4 measurements;
- 5-15 years return interval;
- Classification into 4 states based on presence-absence;

Fitting procedure

- 2-states and 4-states models;
- Each transition is a multinomial model;
- Approximation of the propagule pressure;
- Each transition is a function of annual average temperature and total precipitations;
- Bayesian parameter estimation with MCMC;

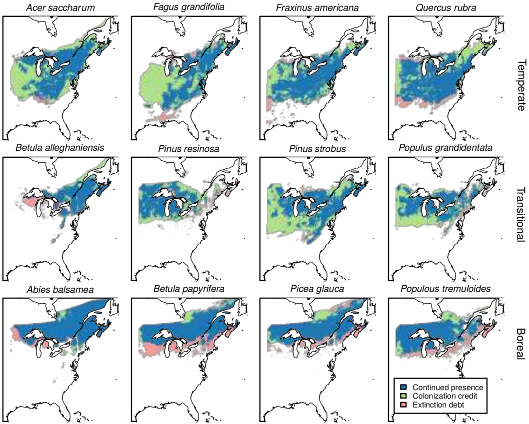
Q1. Are transitions between states function of climatic conditions ?

Climate effects on transitions

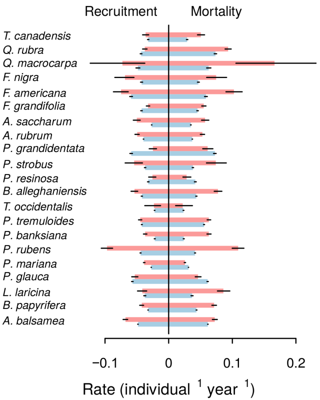


Q2. Are the colonization-extinction dynamics responsible for range limits?

Solving for range limits 2-states

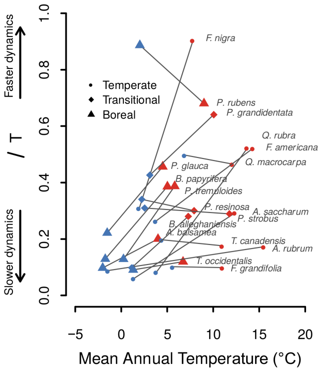


$$\underbrace{r(E, R)}_{\text{Intrinsic growth}} > 0$$

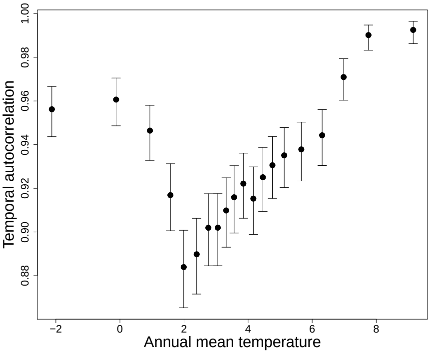

Recruitment
Mortality
T. canadensis
Q. rubra
Q. macrocarpa
F. nigra
F. americana
F. grandifolia
A. saccharum
A. rubrum
P. grandidentata
P. strobus
P. resinosa
B. alleghaniensis
T. occidentalis
P. tremuloides
P. banksiana
P. rubens
P. mariana
P. glauca
L. laricina
B. papyrifera
A. balsamea
−0.1
0
0.1
0.2
Rate (individual 1 year 1)

Q3. Do we find critical slowing down at range boundaries?

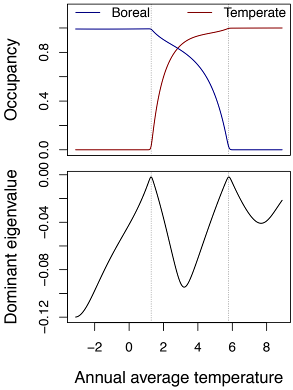
RATE OF RESPONSE 2 STATES

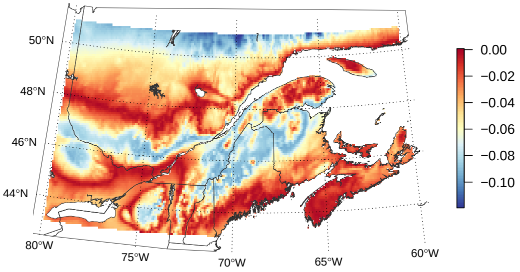


Rate of response 4 states



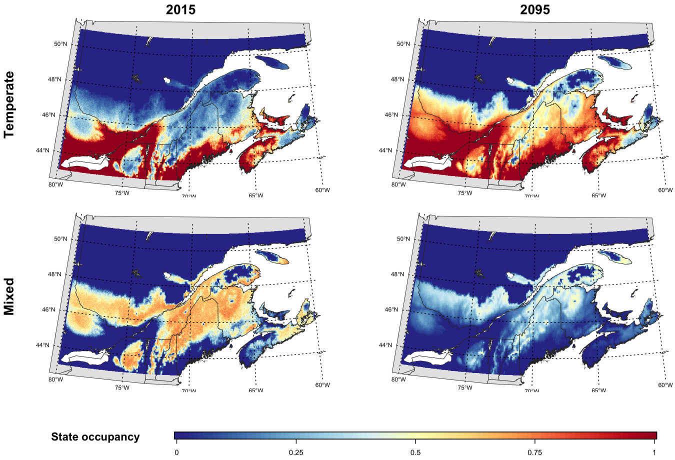
Rate of response 4 states

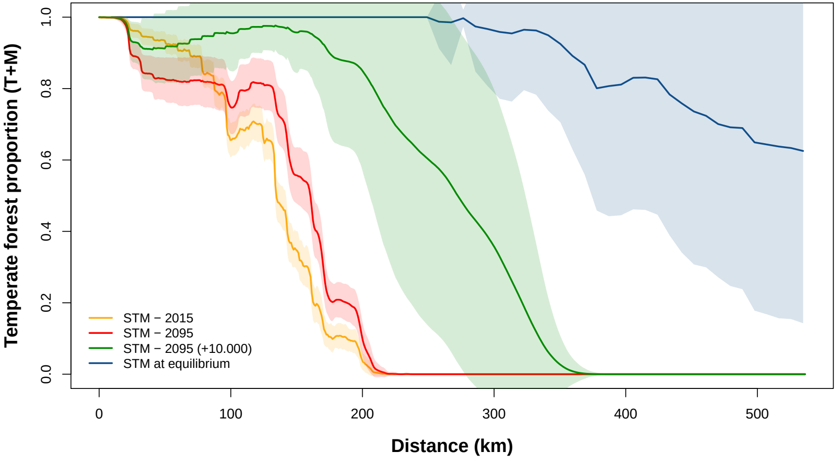




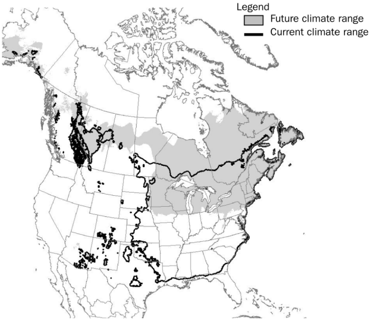
Q4. What about the total amount of change under a realistic climate change scenario?

Climate change scenarios




Temperate forest proportion (T+M)
Distance (km)
0.0
0.2
0.4
0.6
0.8
1.0
0
100
200
300
400
500
STM − 2015
STM − 2095
STM − 2095 (+10.000)
STM at equilibrium

Discussion Relevance of the theory



- A regional perspective on range limits appears to be more appropriate for forest ecosystems;
- The framework better accounts for transients;
- Many components of the response to climate change;
- The statistical approach solves several limitations of SDMs;

Discussion Critical slowing down at range margins

- Transition betweeb biomes is non-linear;
- Stability drops at the range limit;
- Stability is minimal where most changes will occur;
- Compression of the transition and almost extinction of mixed stands;
- Tension between potential vegetation and the observed one;

- Demography of forest ecosystems;
- Dispersal limitations;
- Biotic interactions;

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