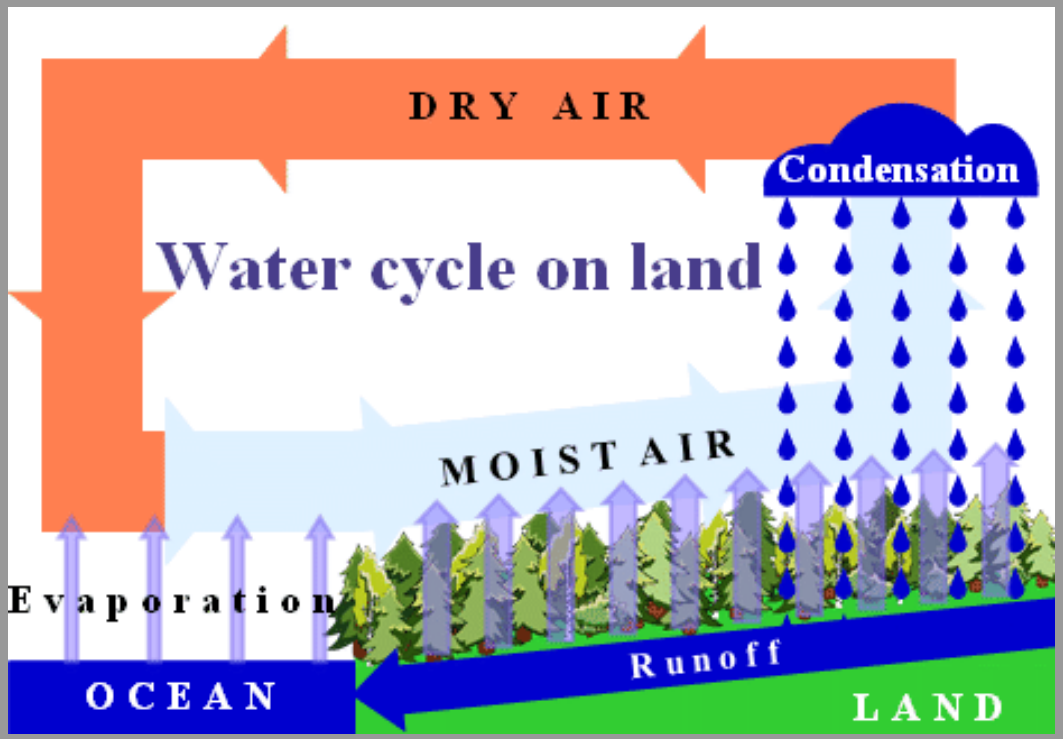
Biotic Pump of Atmospheric Moisture: Land re-moistening as a scientific challenge

Victor Gorshkov, Anastassia Makarieva
Theoretical Physics Division, Petersburg Nuclear Physics Institute, Russia
http://www.bioticregulation.ru

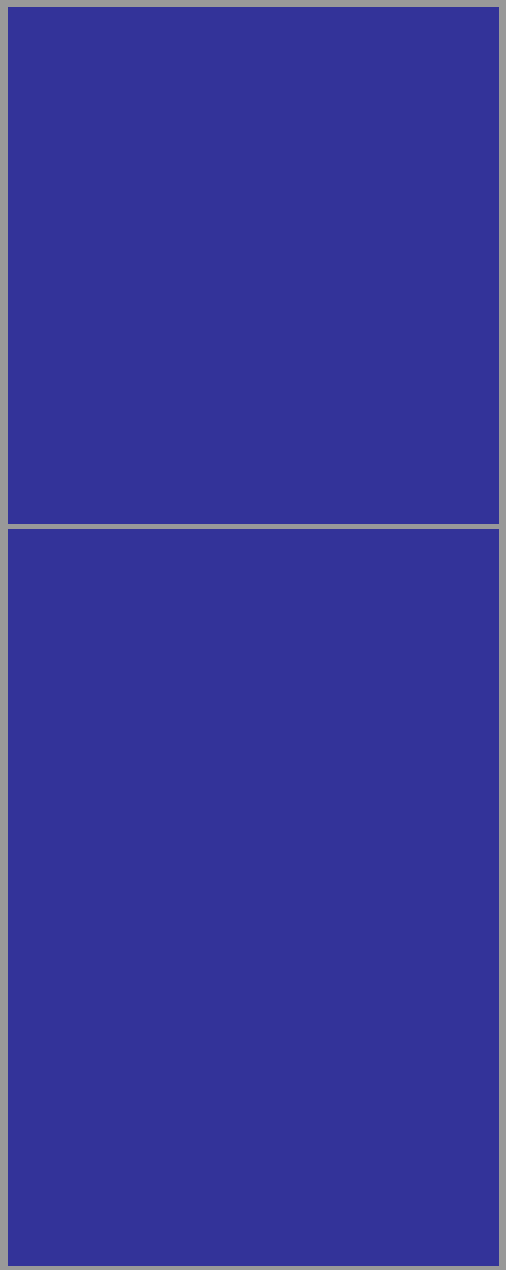
Biotic pump: Forest brings water from ocean to land



There is very little fresh water on land. Global river runoff (around 17 thousand cubic kilometers per year) could deplete fresh water on land in less than 10 (ten) years. A continuous process replenishing moisture is needed...

- Water vapor condensation drives winds
- Winds bring moisture from ocean to land
- This moisture sustains condensation and compensates for the river runoff
- Forest transpiration is key: it moistens the air and thus kicks off the moisture transport processes

How it works



- Atmospheric air pressure is balanced by the weight of air column above the considered point. Scale height

$$h = \frac{RT}{Mg} \sim 10 \text{ km}$$

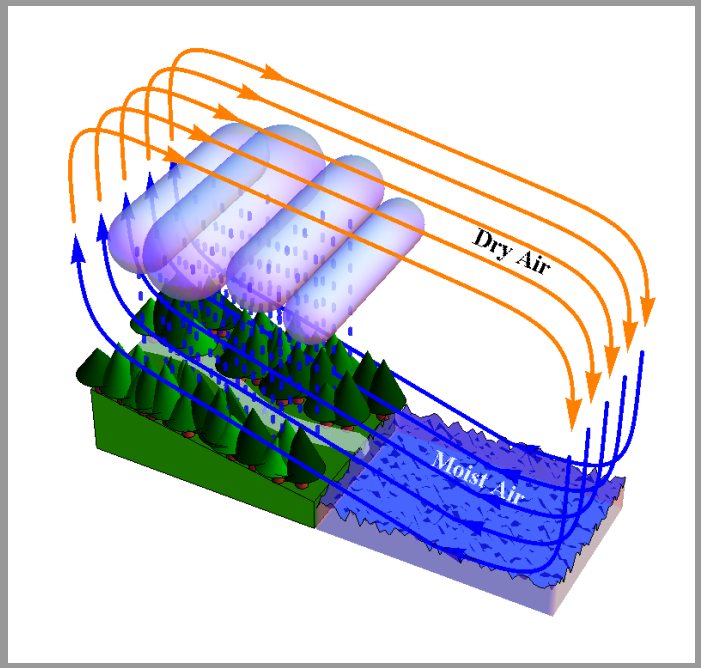
- Water vapor turns to liquid when moist air rises along the vertical temperature gradient. Scale height

$$h_v = \frac{RT^2}{L\Gamma} \sim 2 \text{ km} \ll h$$

- This lowers the column weight and surface pressure by the maximum amount of $\Delta p \sim p_v$, where p_v is partial pressure of water vapor at the surface. At 30 deg C and 100% relative humidity $\Delta p \sim 40$ hPa.

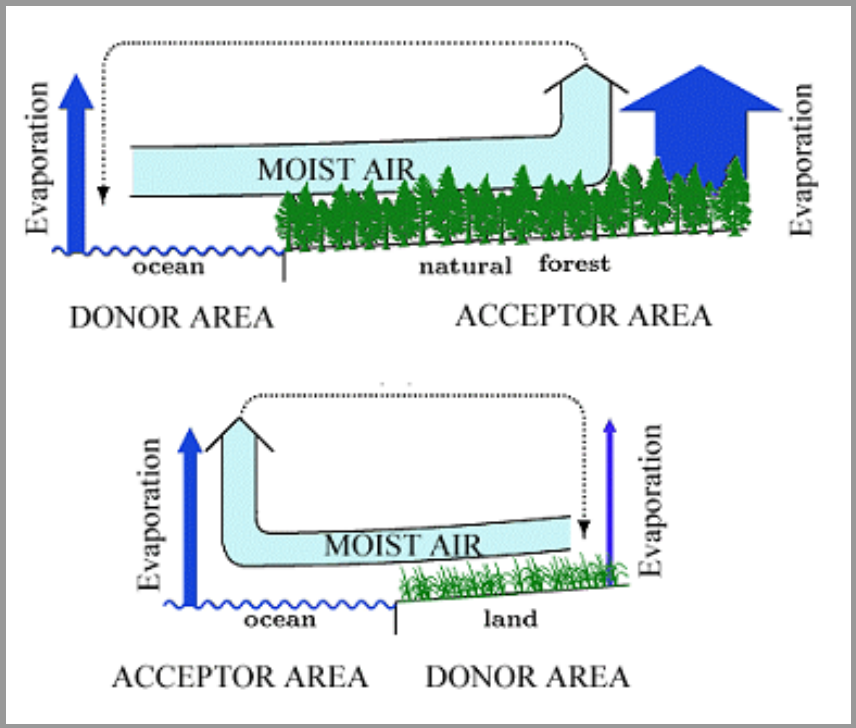
Biotic pump of atmospheric moisture

- Forest moistens the air
- Moist air rises and cools
- Water vapor condenses
- Pressure drop pulls the air upward
- Pressure shortage at the surface draws moist air from over the ocean to land
- Dry air returns to the ocean in the upper atmosphere
- Water imported from the ocean compensates for the river runoff



Key process: air moistening by the forest
The forest must be able to store water, to transpire efficiently and to switch condensation on/off as needed

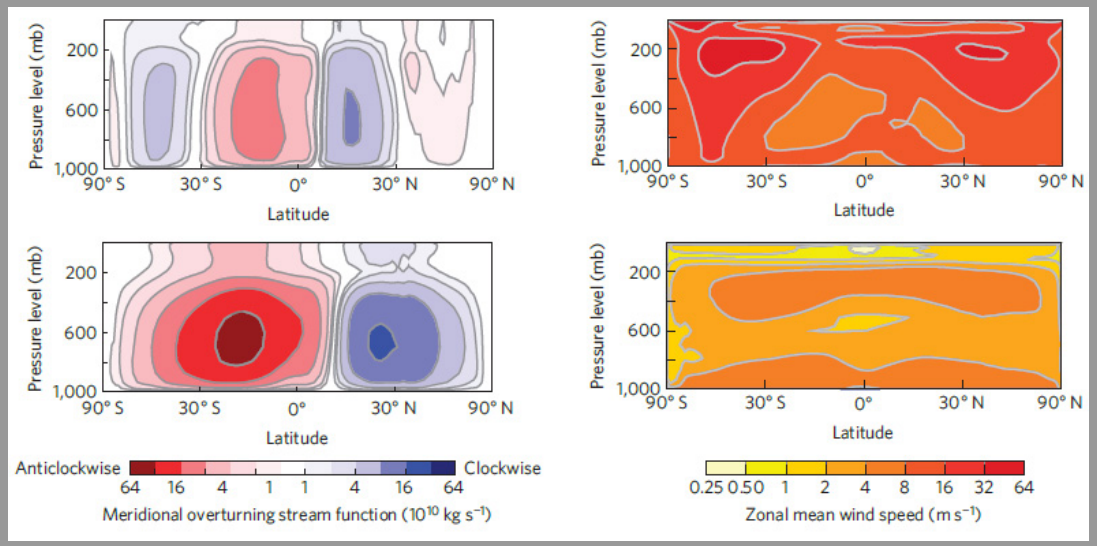
Forest wins the tug-of-war with the ocean



High evaporation from the forest cover allows the forest to win the moisture "tug-of-war" with the ocean.

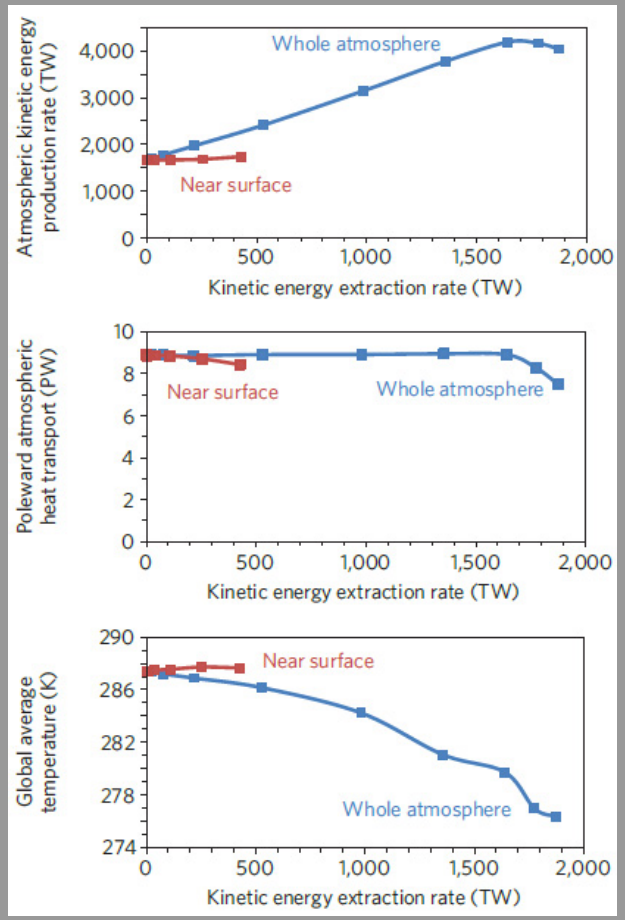
- The air flows towards the low pressure area where condensation occurs
- For there to be a stable ocean-to-land inflow of moist air, condensation should predominantly occur over the forest
- In this case the forest is the acceptor area (receiving moist air) and the ocean is the donor area (supplying moist air)
- If condensation predominantly occurs over the ocean, then the ocean steals moisture from the continent

Why circulation is important for climate (change)

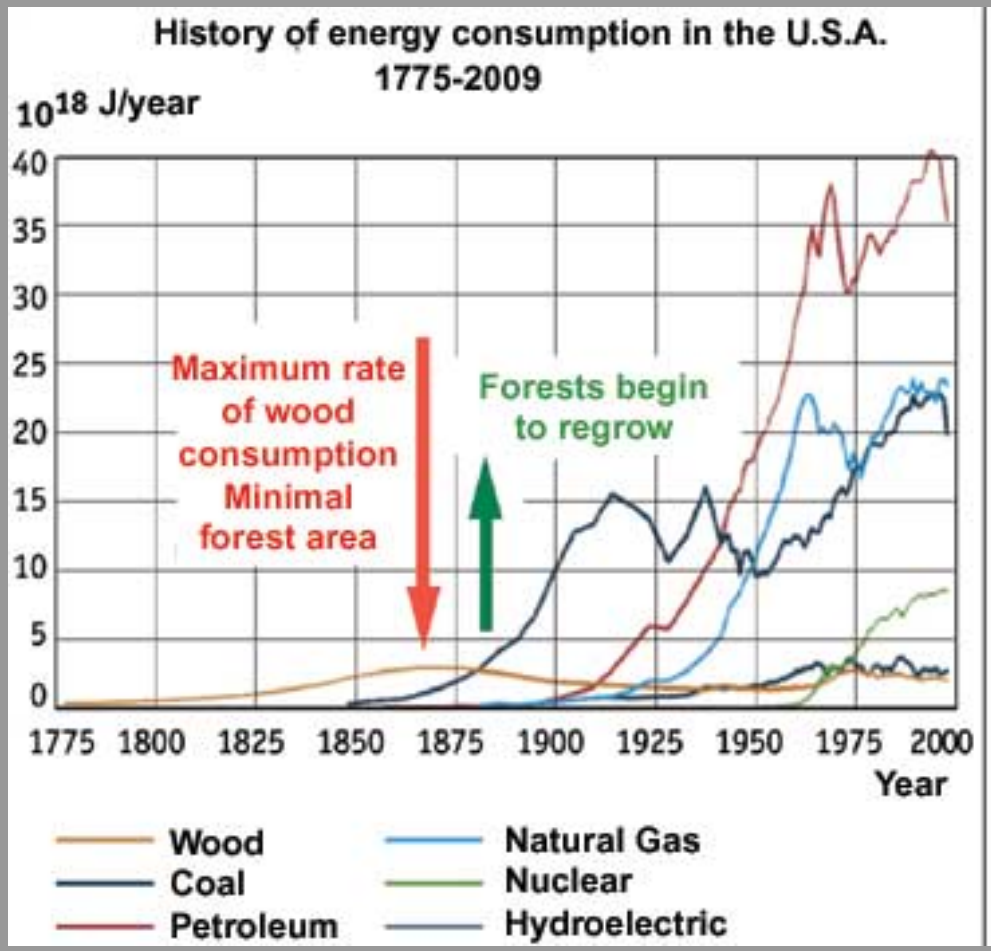


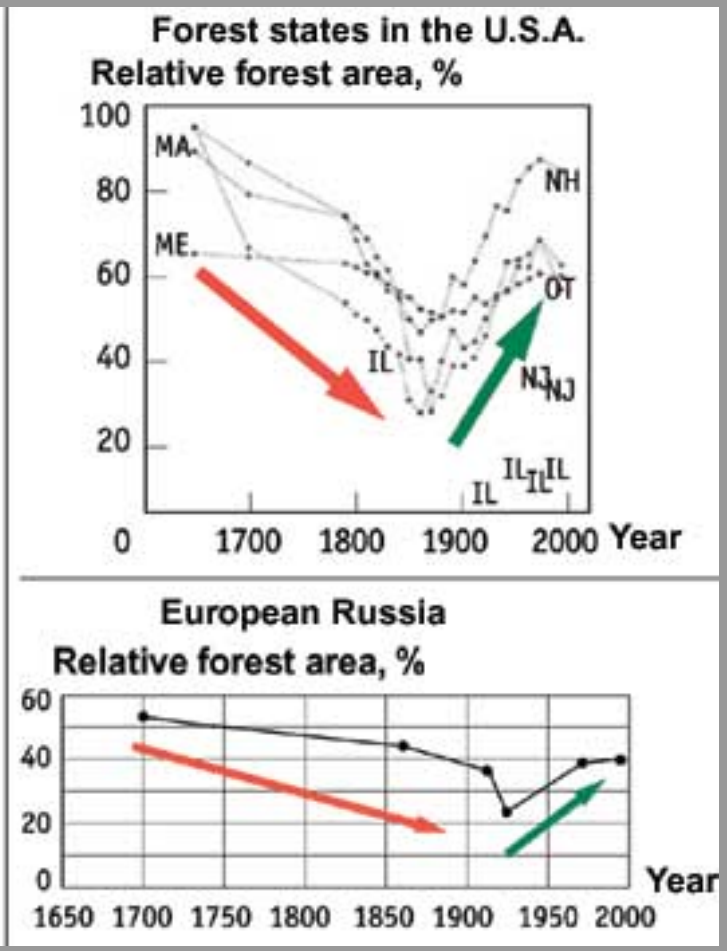
Marvel et al. 2013 Nature Climate Change
doi:10.1038/NCLIMATE1683

Increasing circulation power in a Global Climate Model leads to stretching of the Hadley Cell towards the pole and a decline of global temperature by 12 K.



Non-linear forest decline and climate change

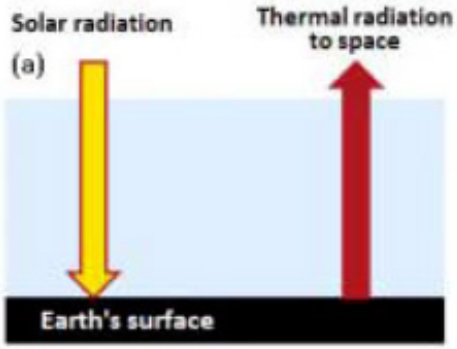


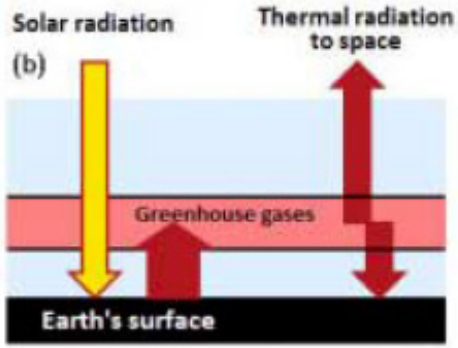


As dictated by population growth and technological progress, our civilization had long been increasing its consumption of forest wood. Forest areas progressively declined. However, at some point the use of coal and later oil reached a level comparable to the ever increasing wood consumption (about 3×10^{18} J/year in power units in the United States). Immediately wood consumption began to decline, and the forests began to regrow. In the second half of 20th century, tropical deforestation accelerated.

Forest transpiration and greenhouse effect: Possible link

(a) Zero greenhouse effect; the atmosphere is transparent to thermal radiation



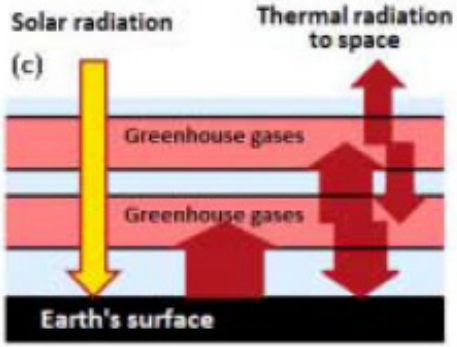


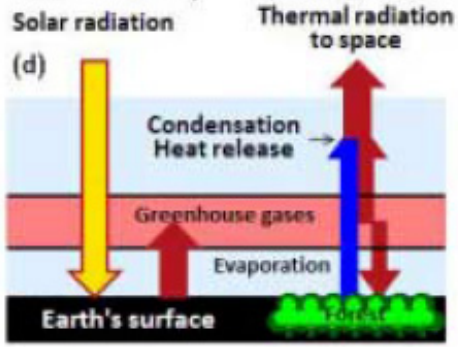
(b) Greenhouse gases capture thermal radiation and re-direct it back to the surface; Earth is warmer than in (a)

Afforestation
Cooling

Deforestation
Warming

(c) Double amount of greenhouse substances; Earth is even warmer than in (b)

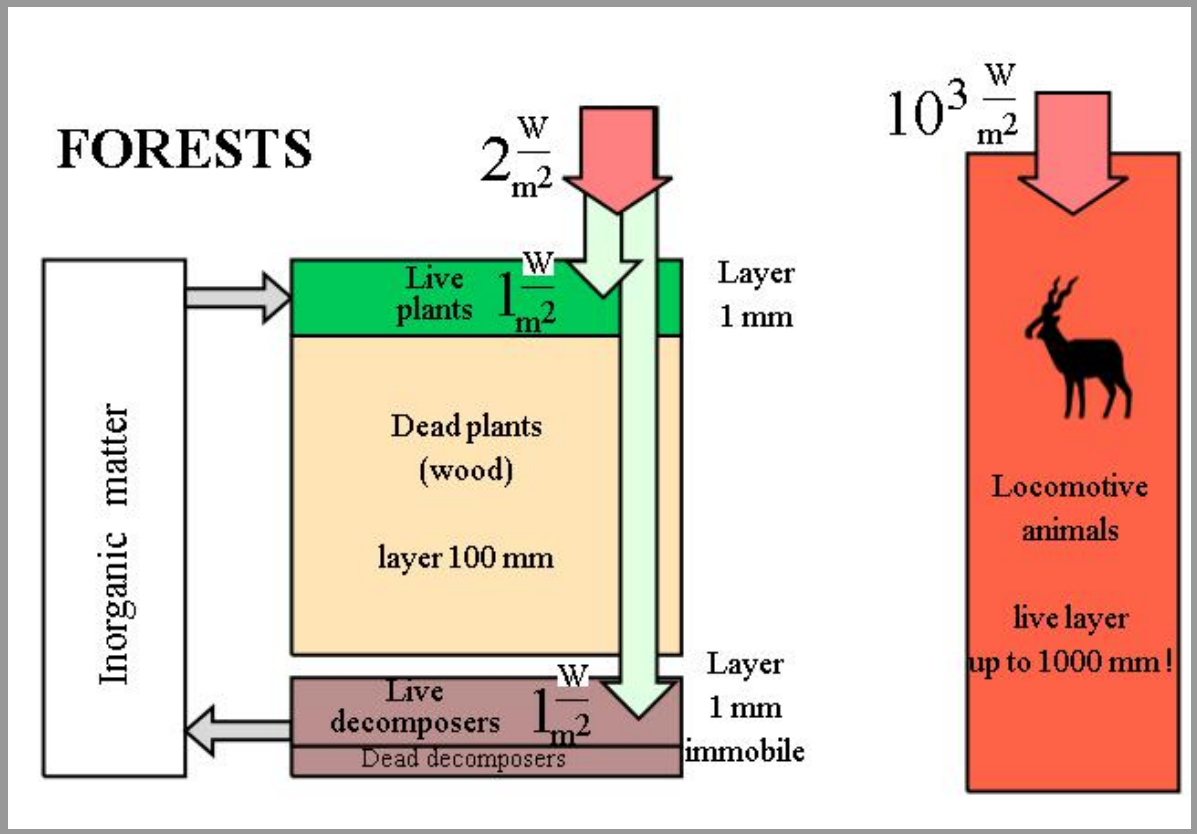




(d) Plants capture half of solar radiation in transpiration; heat release occurs ABOVE the layer where most greenhouse gases are located; from here, thermal radiation leaves unimpeded to space; greenhouse effect is reduced compared to (b)

Physical idea of cooling via evaporation: J.R. Bates (1999) A dynamical stabilizer in the climate system: a mechanism suggested by a simple model. Tellus 51A: 349-372.

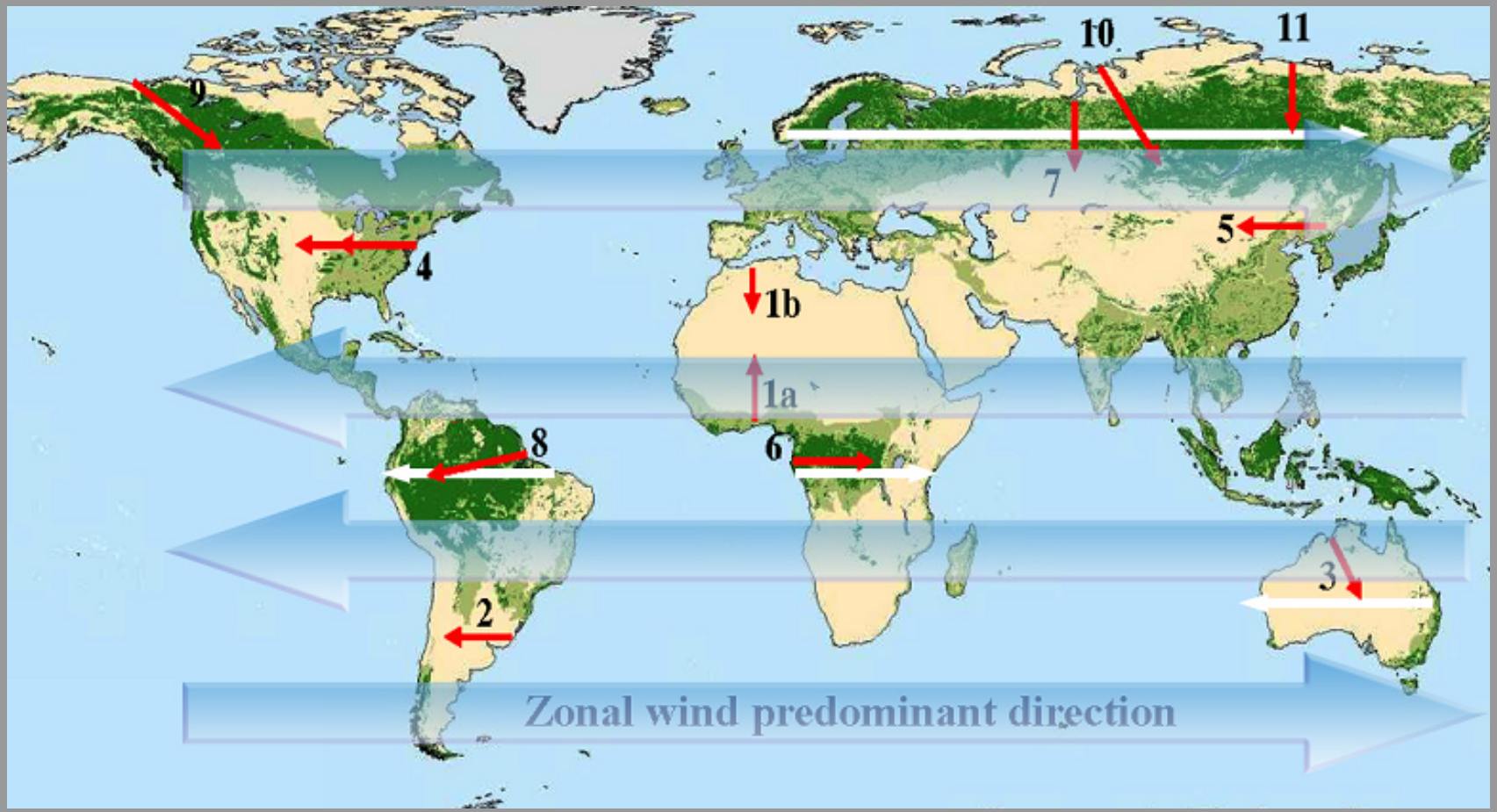
Are we unique destroying forests?



- Animals must collect biomass production over an area exceeding their body projection area by 103 by moving over this area (obligate locomotion!).
- Abundance: the animal takes all food locally, leaves an empty space and returns in 1-50 years when the vegetation regrows.
- Hurricanes and tornadoes "feeding" on water vapor act in a similar way.

Terrestrial ecosystems are inherently unstable!

How does precipitation vary in space and time in forested versus unforested regions?



In unforested regions rainfall declines exponentially with distance from the ocean, decreasing 3-fold per each 600 km on average. Forested regions enjoy spatially uniform precipitation over several thousand kilometers.

Forest moisture pump in Siberia

Kureika (Yenisey tributary), photo taken by Victor Gorshkov the year before the area was flooded to build a hydroelectric station.

Eurasian Boreal Forest Belt

Summer: Forest active

- Rainfall on land is higher than over the ocean
- Rainfall is spatially uniform over several thousand kilometers

Winter: Forest dormant

- Precipitation concentrates over the ocean
- Over land, precipitation declines with distance from the coast

Oceanic precipitation

- Small in summer
- Rises abruptly in winter despite lower temperature

The stage of forest development is crucial for biotic pump functioning

Climax stage: evergreen trees (spruce)

Evergreen trees keep their foliage ready to work year round. Immediately upon the onset of first sunny days in spring they start pumping moisture inland. They keep doing so until the first frosts late in the autumn. In the result, the moisture supply is homogeneous during the entire vegetation season. Seasonal temperature changes are gradual.

Leafy trees and herbs must develop foliage first before they can pump moisture. Until then, there is little moisture transport from the Atlantic ocean. Thus, spring features drastic temperature changes: (1) first it is very cold, (2) then land warms rapidly in the absence of moisture transport from the Atlantics, then green leaves flush and there is cool and very wet weather that can stay until there is active photosynthesis (causing floods in June). Then leaves become inactive in September, and the moisture transport ceases.

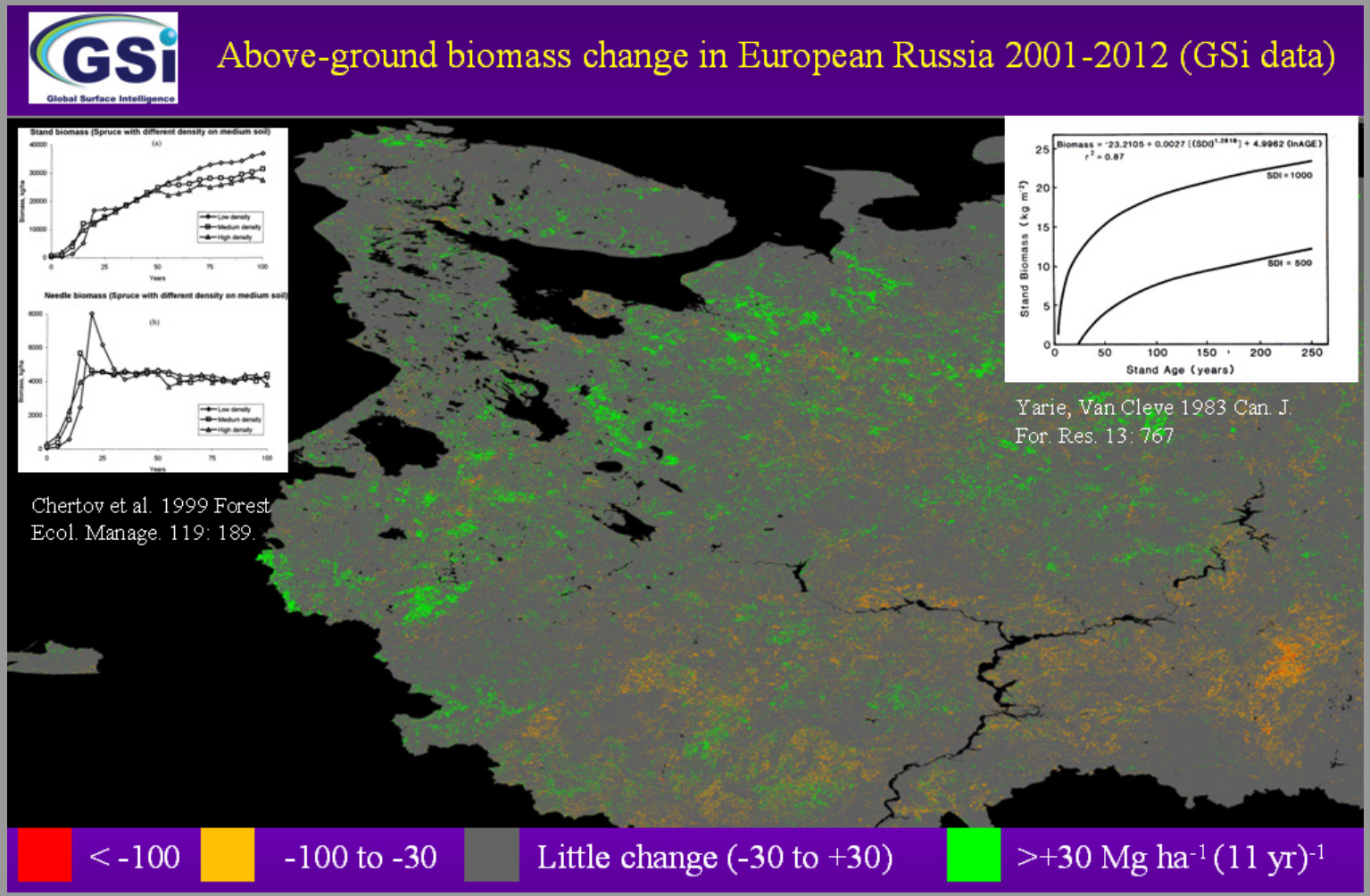
Early succession: deciduous trees

Hydrological competence versus commercial value

- The relative rate of biomass increment is highest at the earliest succession stage; then it gradually slows down to become zero in the climax forest: climax forest, as a healthy adult body, does not either gain or lose "weight" (biomass).
- Biomass grows steadily from early succession to climax. Because of these peculiarities, forestry industries are used to value most the successional stages at about 50-70 years after disturbance: the biomass is already there to harvest, while biomass increment rate is not yet zero.
- From the commercial viewpoint, it is prudent to keep all forests within 50-70 years of the last cutting. But the water regulation potential of early successional stages and even-aged stands is low.

A conflict exists between the modern commercial value of a forest and the forest's abilities to regulate the regional water cycle and to be self-sustainable: these parameters cannot be maximized simultaneously.

Eurasian forest pump: A common legacy



Large areas in the North-West have been recently disturbed and are re-growing. In the South forest loss dominates over re-growth. Deforestation in Russia threatens water security in EU and China.

Deforestation consequences: destabilization followed by desertification

Conclusions

1. **Forests keep condensation going by moistening the atmosphere**

2. **Condensation drives winds**

3. **Winds bring moisture to land to compensate for runoff water losses**

The biotic pump should be urgently taken into serious consideration by all concerned about continental water security