Spatiotemporal influence of permafrost thawing on anthrax diffusion

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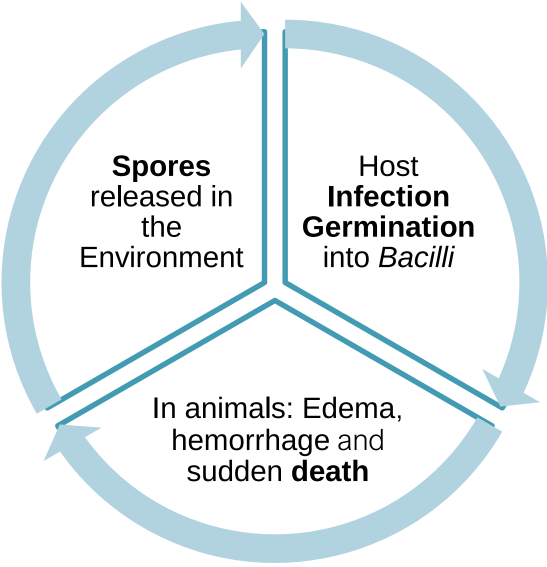
Why studying anthrax in the Arctic?

Anthrax 2016 outbreak
(EMPRES-I, source: OIE):
~2000 reindeer carcasses
110000 susceptible animals
1 reported human death

[1]
- 28.986: settlements in the Russian Federation where cases of anthrax have been reported since the end of the 19th century
- 6.688: cattle burial grounds defined "stationary adverse" to anthrax in Siberia (i.e. potential hotspots)
- 270: settlements in Yakutia where outbreaks occurred between 1906 and 2004



Anthrax is among the "**climate-sensitive**" zoonotic pathogens[2-6]

Thawing permafrost releases spores into the soil from emerging wild or domestic ruminant carcasses[6]

Increased survivability, shorter developments rates and new **chains of transmission** (e.g. insects survivability)

Modification of **the migration routes and shift of animals habitat** closer to humans

Anthrax suitability is predicted to expand and increase within the next 30 years

Host species could be more stressed and vulnerable

[1] International Office of Epizootics., World Health Organization. & Food and Agriculture Organization of the United Nations. *Anthrax in humans and animals.* (World Health Organization, 2008).

[2] Walsh, M. G., de Smalen, A. W., & Mor, S. M. (2018). Climatic influence on anthrax suitability in warming northern latitudes. Scientific reports, 8(1), 9269.

[3] Kangbai, J. B., and E. Momoh. "Anthropogenic Climatic Change Risks a Global Anthrax Outbreak: A Short Communication." J Trop Dis 5.244 (2017): 2.

[4] Bradley, Michael J., et al. "The potential impact of climate change on infectious diseases of Arctic fauna." International Journal of Circumpolar Health 64.5 (2005): 468-477.

[5] Parkinson, Alan J., et al. "Climate change and infectious diseases in the Arctic: establishment of a circumpolar working group." International journal of circumpolar health 73.1 (2014): 25163.

[6] Revich, Boris, Nikolai Tokarevich, and Alan J. Parkinson. "Climate change and zoonotic infections in the Russian Arctic." International journal of circumpolar health 71.1 (2012): 18792.

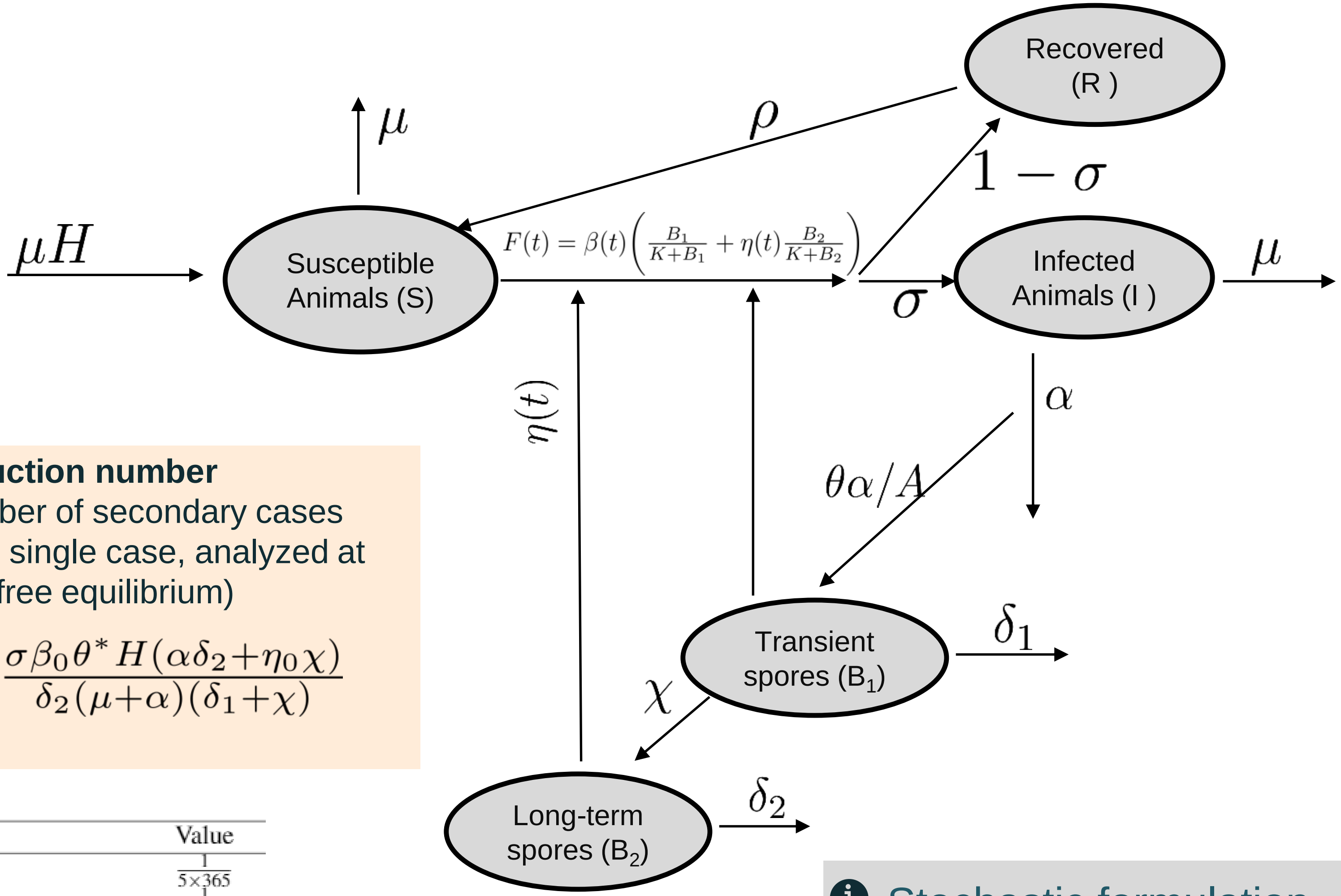
Mathematical model of Anthrax transmission

Deterministic (continuous variables)
and
Stochastic (discrete variables)
formulations

$$\frac{dS}{dt} = \mu(H - S) - F(t)S$$
$$\frac{dI}{dt} = F(t)S - (\mu + \alpha)I$$
$$\frac{dR}{dt} = (1 - \sigma)F(t)S - (\mu + \rho)R$$
$$\frac{dB_1}{dt} = \theta\alpha\frac{I}{A} - (\delta_1 + \chi)B_1$$
$$\frac{dB_2}{dt} = \chi B_1 - \delta_2 B_2$$

Reproduction number
(i.e. number of secondary cases from one single case, analyzed at disease-free equilibrium)

$$R_0 = \frac{\sigma\beta_0\theta^* H(\alpha\delta_2+\eta_0\chi)}{\delta_2(\mu+\alpha)(\delta_1+\chi)}$$



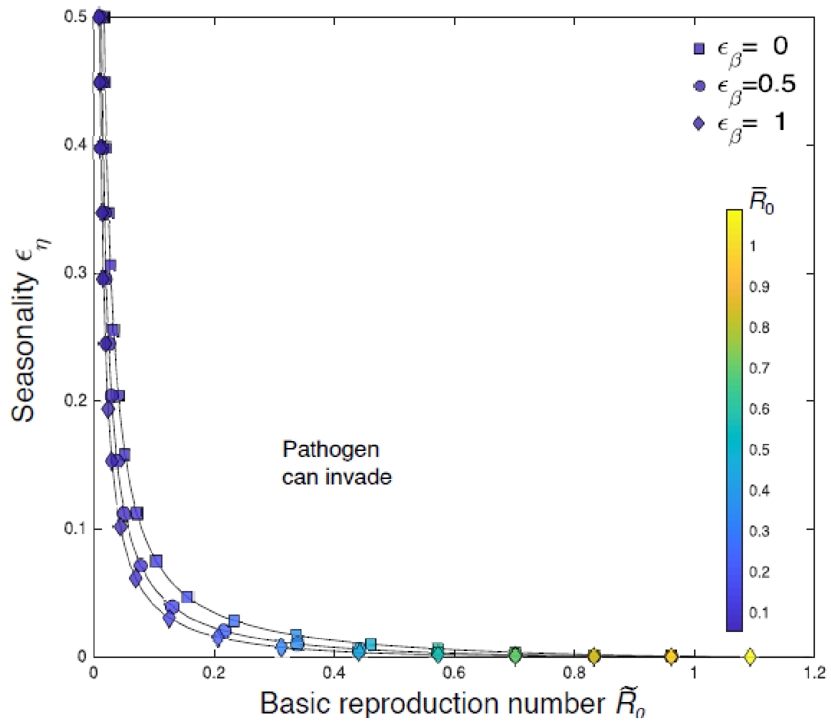
Parameter	Units	Definition	Value
μ	[days^{-1}]	baseline mortality rate	$\frac{1}{5\times365}$
α	[days^{-1}]	disease-related mortality rate	$\frac{1}{14}$
ρ	[days^{-1}]	immunity loss	$\frac{1}{6\times30}$
$\delta_1 = \delta_2$	[days^{-1}]	spore decay rate	$\frac{1}{10\times365}$
χ	[days^{-1}]	removal rate of freshly released spores	$\frac{1}{10}$
σ	[-]	fraction of symptomatic infected	0.7
η_0	[-]	probability of exposure to thawing-released spores	(0-1)
β_0	[days^{-1}]	(average) exposure rate	-
θ	[spores carcass^{-1}]	environmental spore released from infected carcasses	-

Stochastic formulation

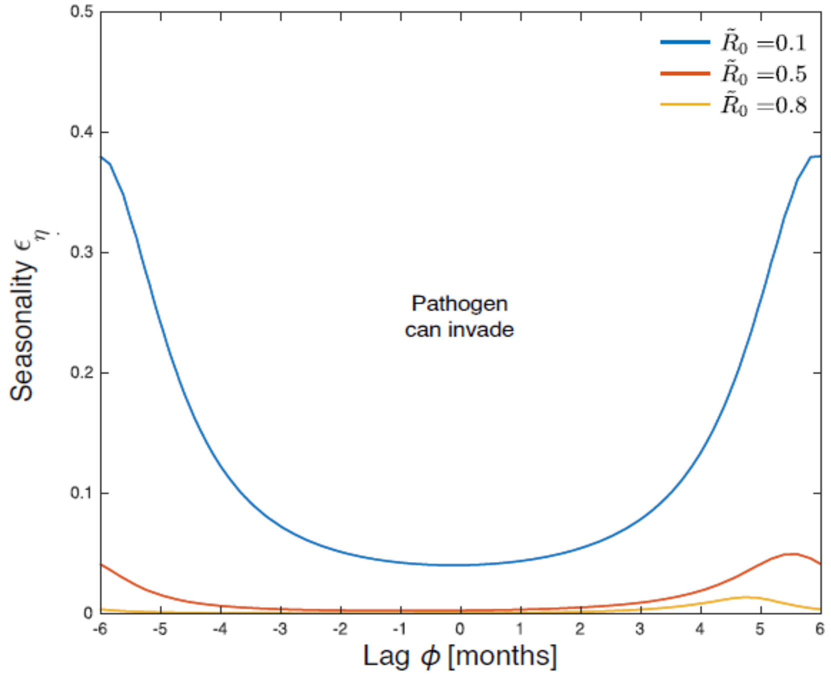
- **S** and **I discrete** variables
- **B_1** and **B_2 real continuous**
- **Occurrence of stochastic events**

Stochastic Simulator Algorithm SSA (Gillepsie, 1977)

Conditions for endemic disease transmission



Synchronous fluctuations of the probability of exposure to permafrost-released spores can **sustain anthrax transmission.**



Lagged fluctuations of the probability of exposure to permafrost-released spores may hinder pathogen establishment in the population **slowing or reducing anthrax transmission**

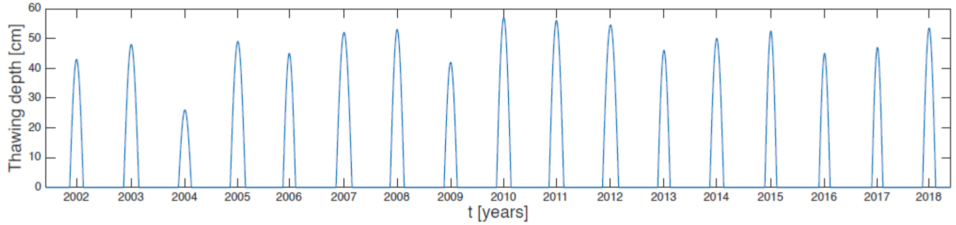
$$\beta(t) = \beta_0\left(1 + \epsilon_\beta sin\left(\frac{2\pi}{365}t\right)\right)$$

$$\eta(t) = \begin{cases} \epsilon_\eta sin(\frac{2\pi}{365}t) & \geq 0, \\ 0 & \text{otherwise} \end{cases}$$

$\tilde{R}_0$ In the absence of B_2

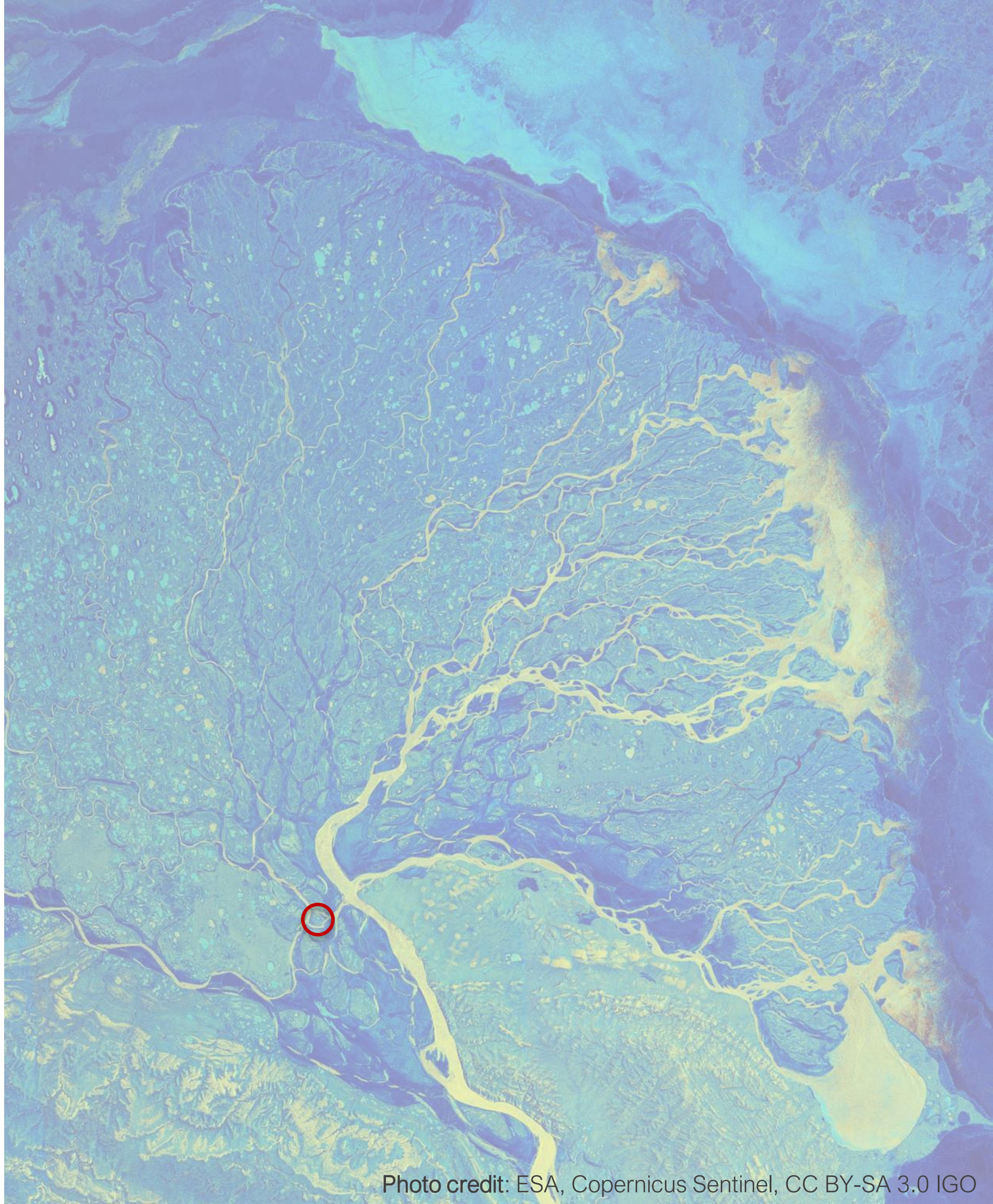
$\overline{R}_0$ $\beta(t) = \beta_{avg} = cost$, $\eta(t) = \eta_{avg} = const$

Application to a realistic Arctic environment: the Lena River monitoring site[1]

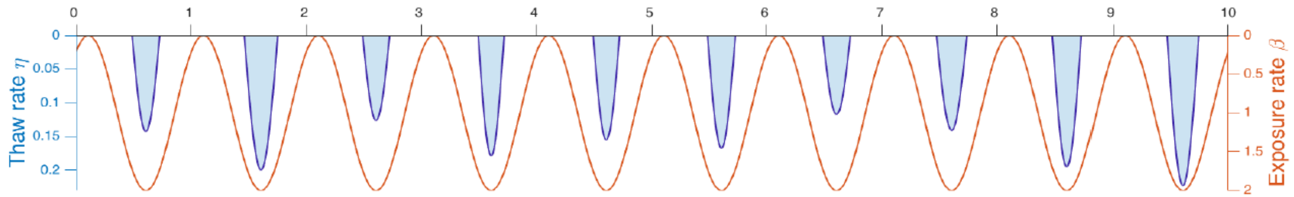


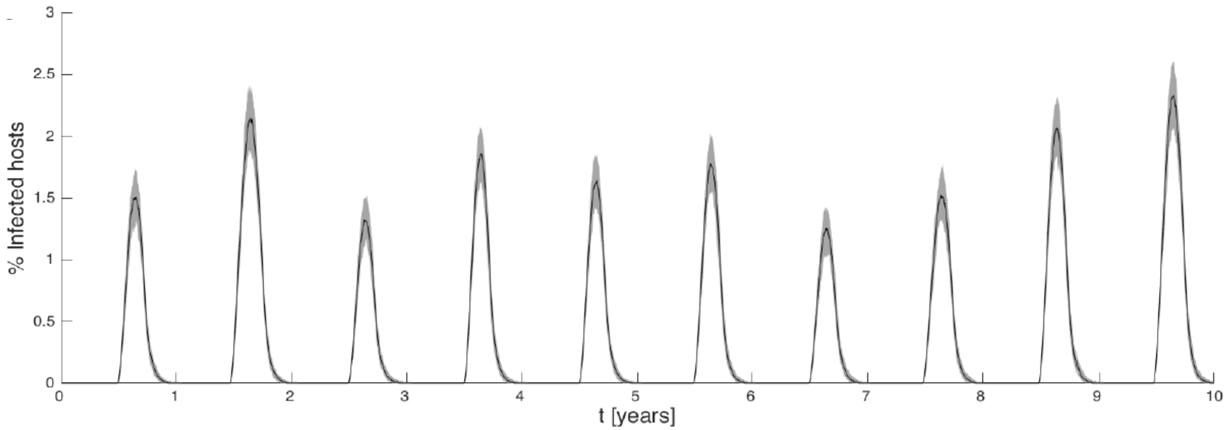
Active Layer Temperature + Active Layer Depth

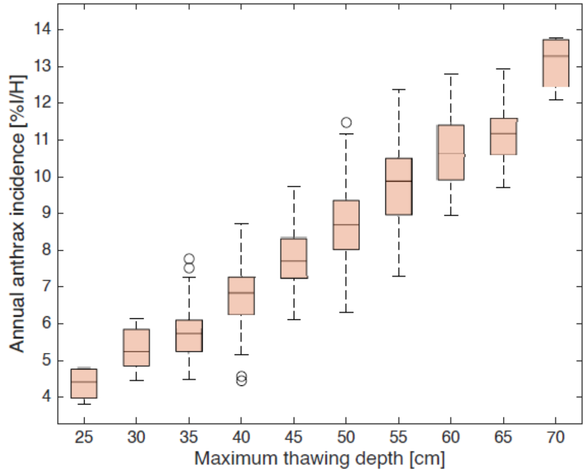
[1]Boike, Julia, et al. "A 16-year record (2002–2017) of permafrost, active-layer, and meteorological conditions at the Samoylov Island Arctic permafrost research site, Lena River delta, northern Siberia: an opportunity to validate remote-sensing data and land surface, snow, and permafrost models." *Earth System Science Data* 11.1 (2019): 261-299.

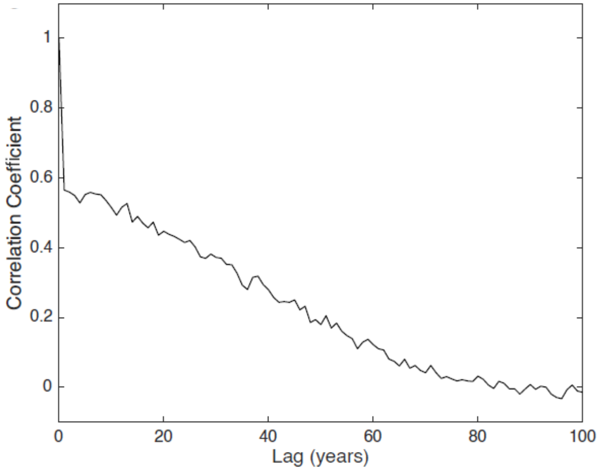


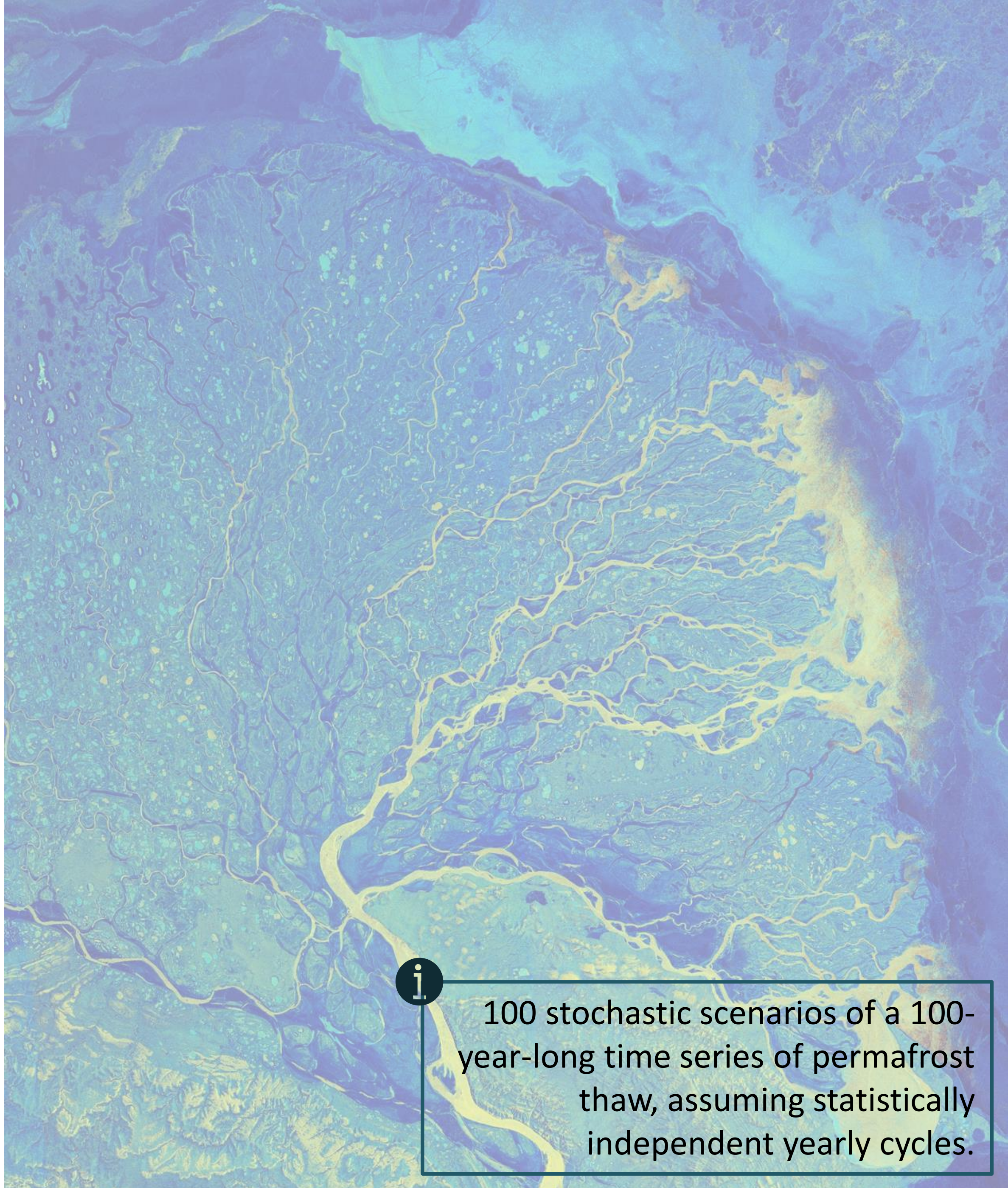
Application to the Lena River monitoring site





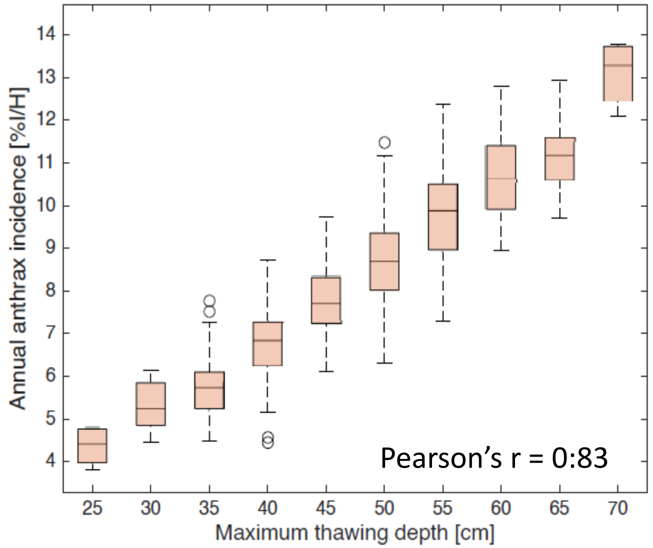




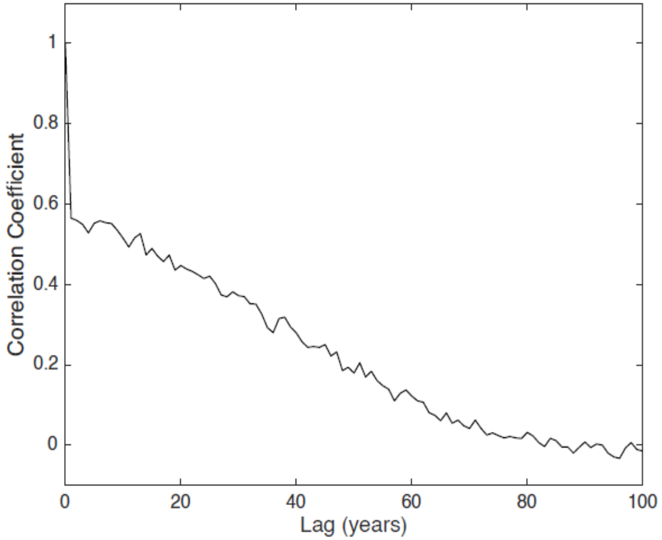


100 stochastic scenarios of a 100-year-long time series of permafrost thaw, assuming statistically independent yearly cycles.

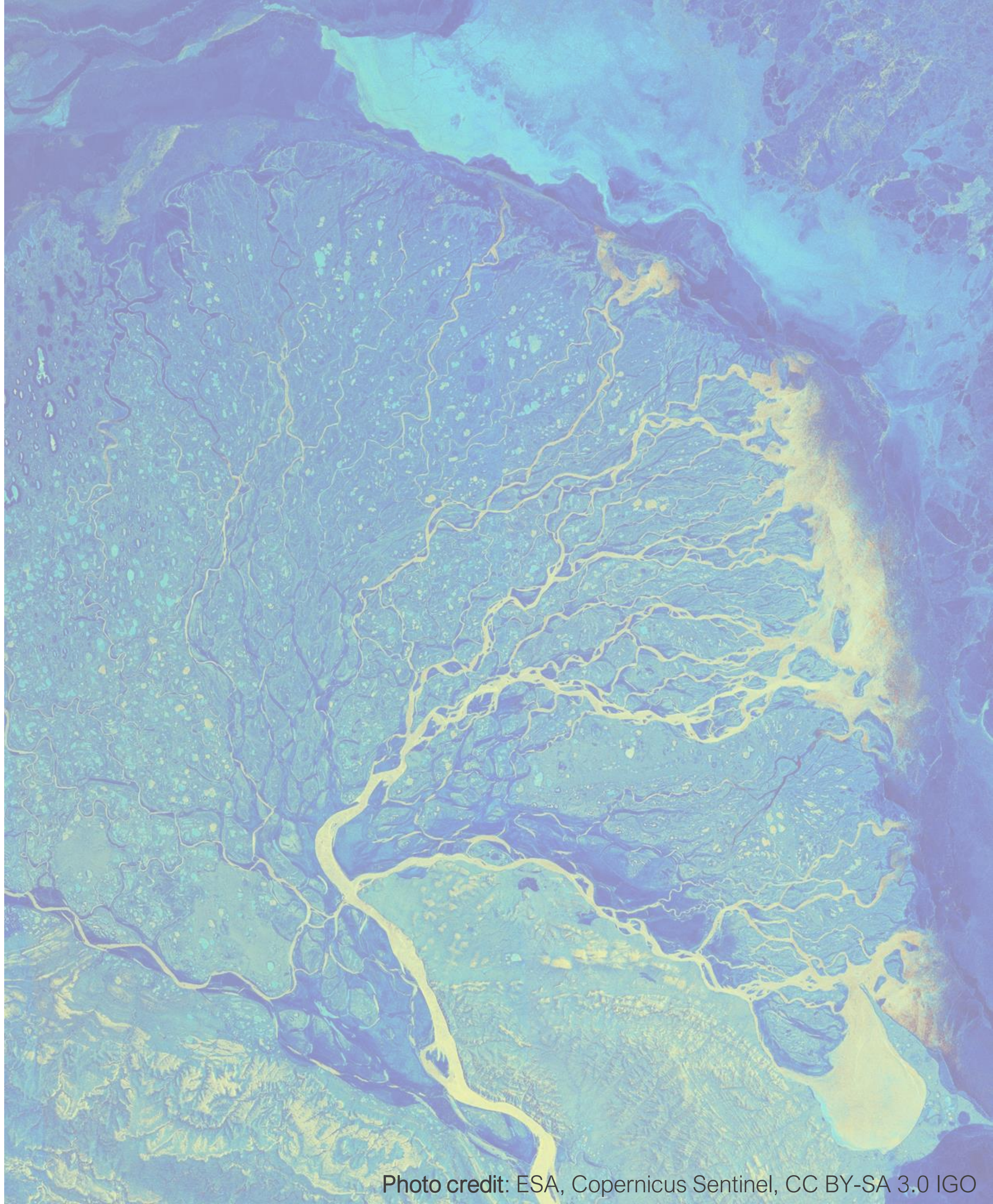
Application to the Lena River monitoring site



High values of the **thawing rate** have a **major** impact on the **risk** of anthrax transmission, which proportionally is higher in warmer years, as the probability to be exposed to permafrost-released spores increases.



Current transmission risk at a given point in time is expected to **affect** the magnitude of **future anthrax** outbreaks, because the **spores** released by infected carcasses may remain **available** on the soil for decades before being removed or stored.

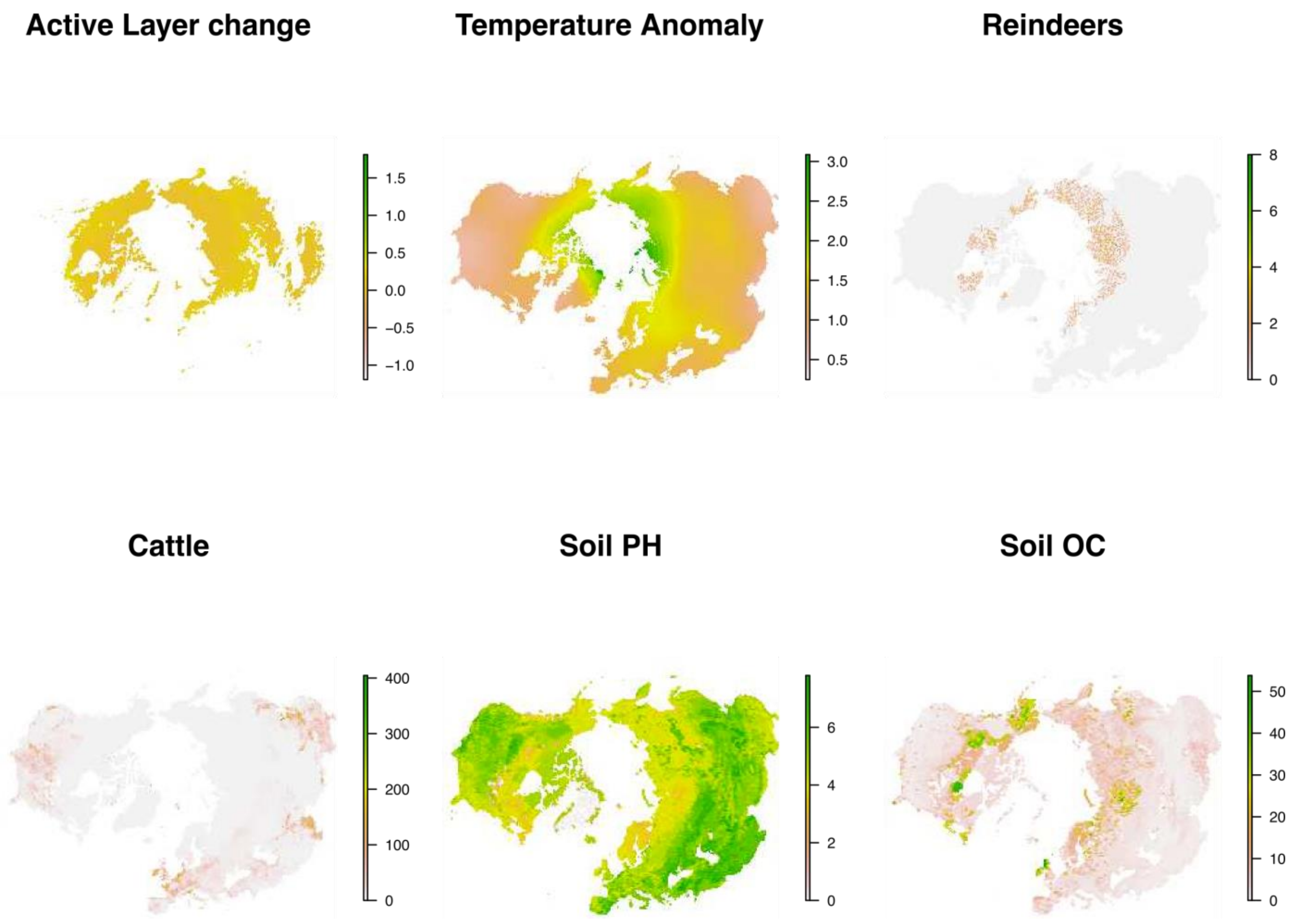


Mapping anthrax suitability

Ecological Niche Model

MaxEnt applied to the coastal Arctic region[1]

Anthrax outbreaks locations + Spatial Environmental variables

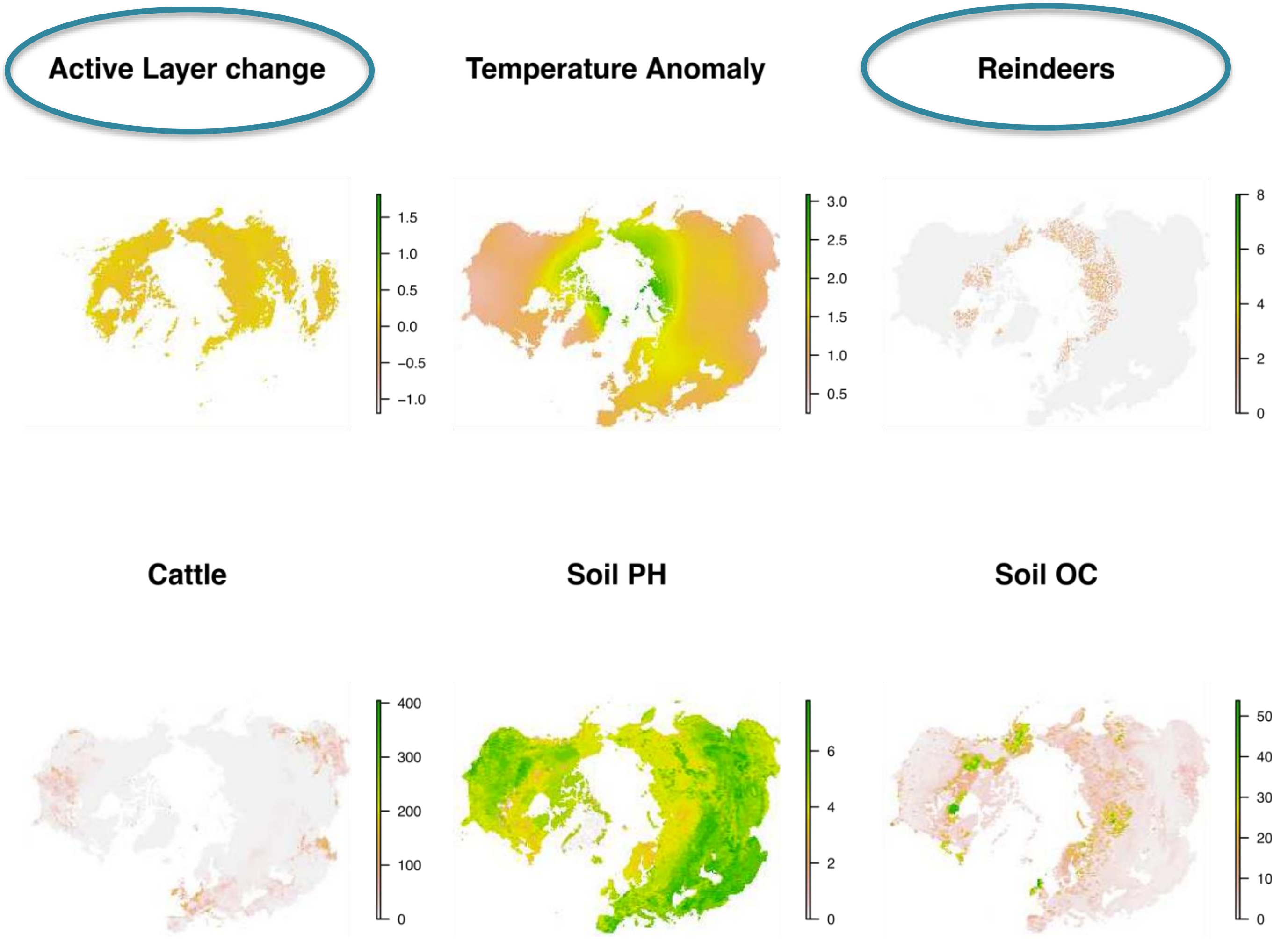


[1]Walsh, Michael G., Allard W. de Smalen, and Siobhan M. Mor. "Climatic influence on anthrax suitability in warming northern latitudes." *Scientific reports* 8.1 (2018): 9269.

Mapping anthrax suitability

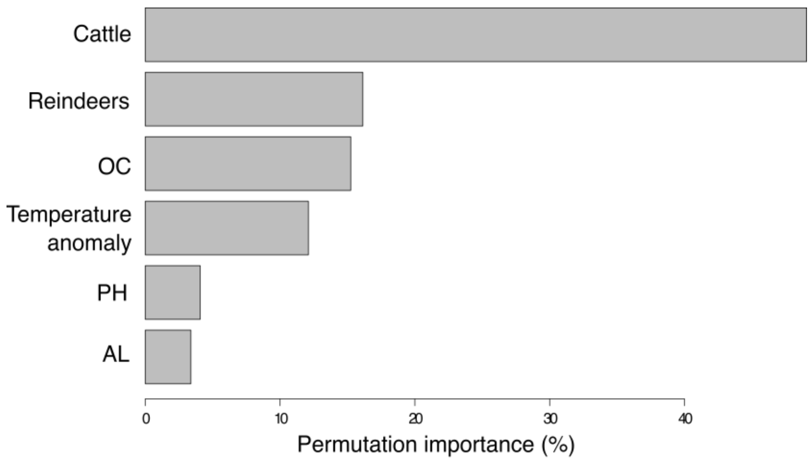
Additional sites to account for old infected burial sites (not available, sampled randomly)

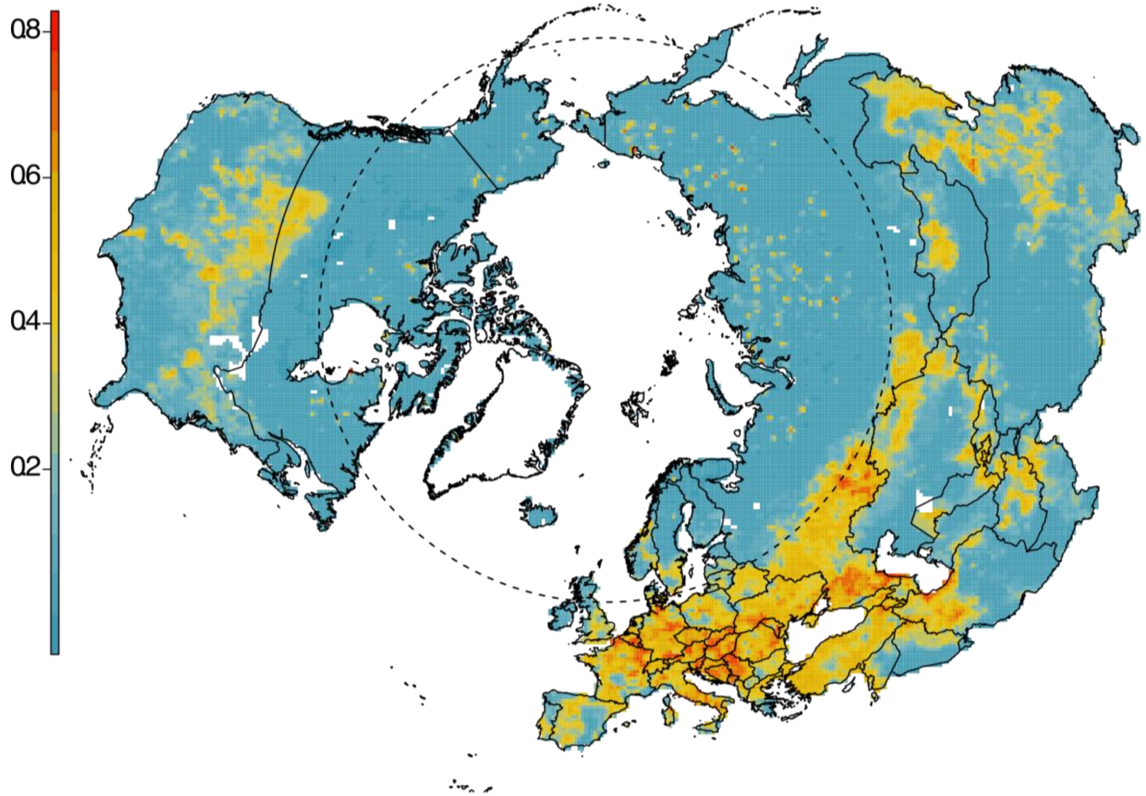
Herders+wild densities: probability ditributions

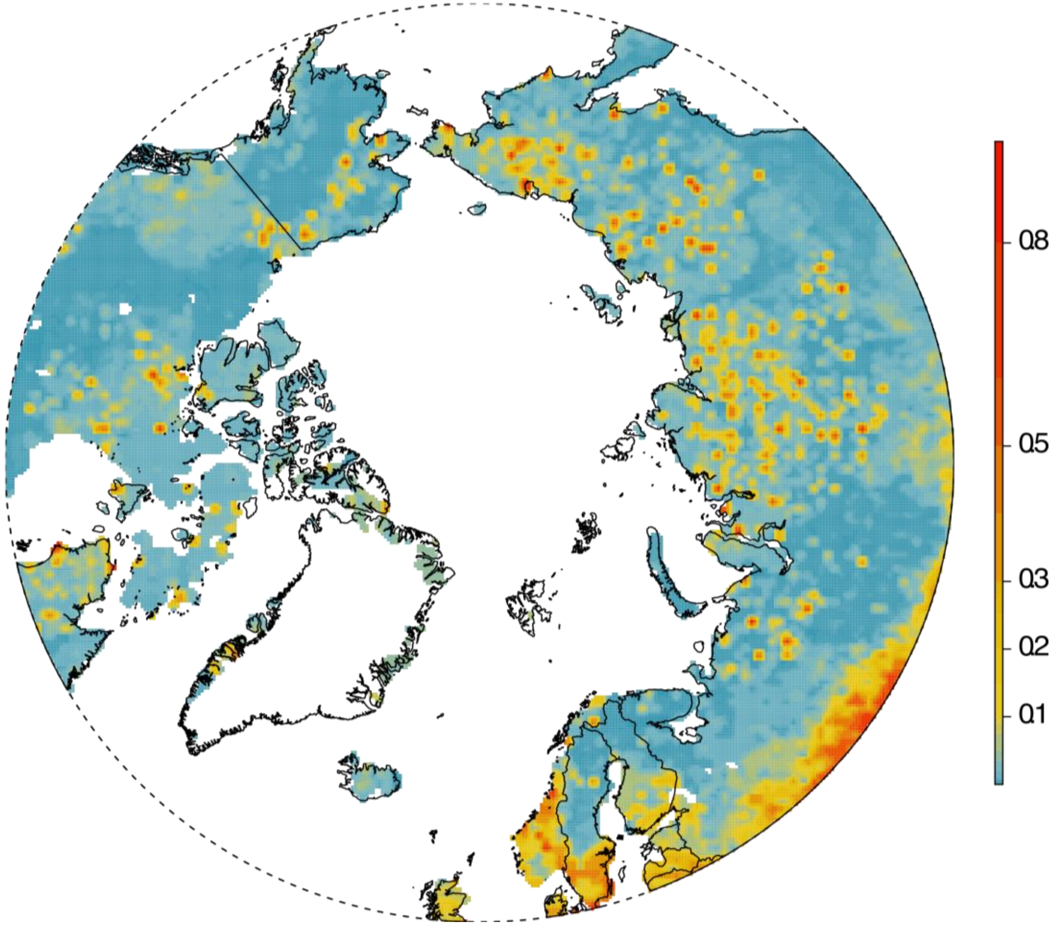


Mapping anthrax suitability

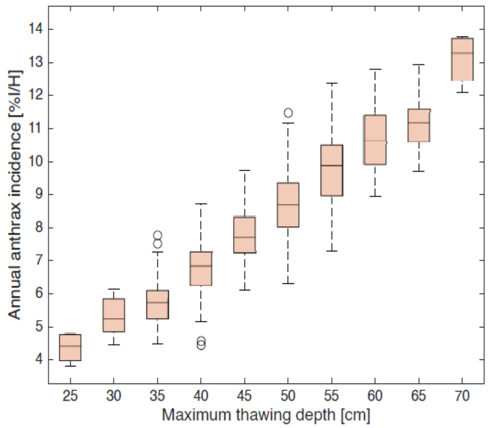
The exact detection of areas potentially at risk is still difficult to determine, since more detailed data are needed.

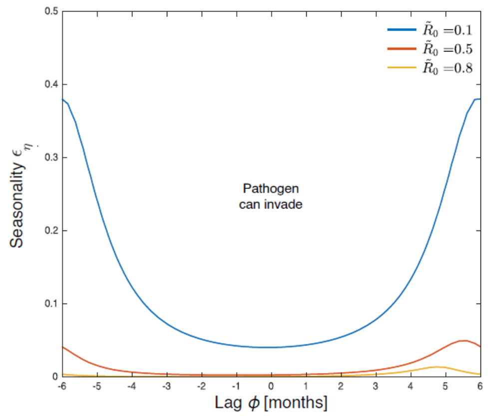






Conclusions





- Seasonal thawing -> increased risk of sustained disease transmission.
- Prolonged periods of warming temperatures -> major risk of endemic dynamics
- One measure to decrease the risk of infection associated to herding practices: in accordance to local (e.g. by moving earlier or later animals to seasonal migration routes or transhumance sites).
- In order to map anthrax risk in the Arctic more detailed data are needed. Summer grazing areas or migration routes should be identified in order make reindeer information more focused. Also, if possible, exact locations of infected burial sites could help to improve precision of anthrax risk prediction. More detail could help herding communities to outline areas potentially at risk, and hence, to prevent eventual infections

To account also:

- Low awareness of local populations
- Permafrost degradation combined with anthropogenic drivers (e.g. oil and gas exploitation) -> increase probability to cross hazardous areas.

THANK YOU!