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The albedo-climate penalty of hydropower

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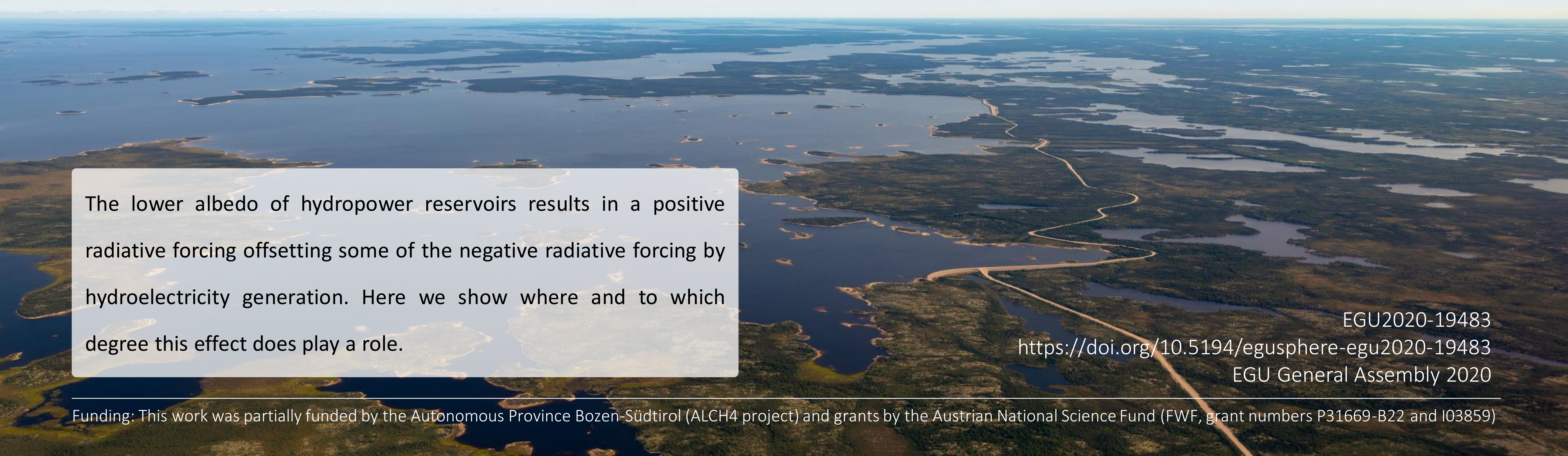

The lower albedo of hydropower reservoirs results in a positive radiative forcing offsetting some of the negative radiative forcing by hydroelectricity generation. Here we show where and to which degree this effect does play a role.

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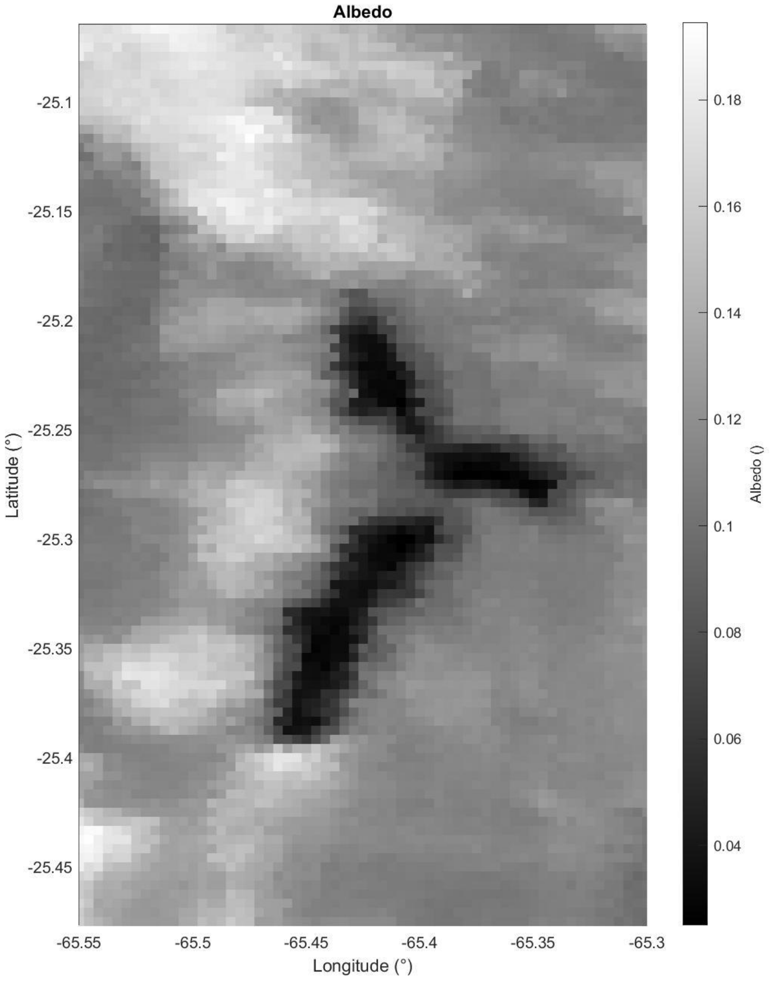
Can you tell where the lakes are located?

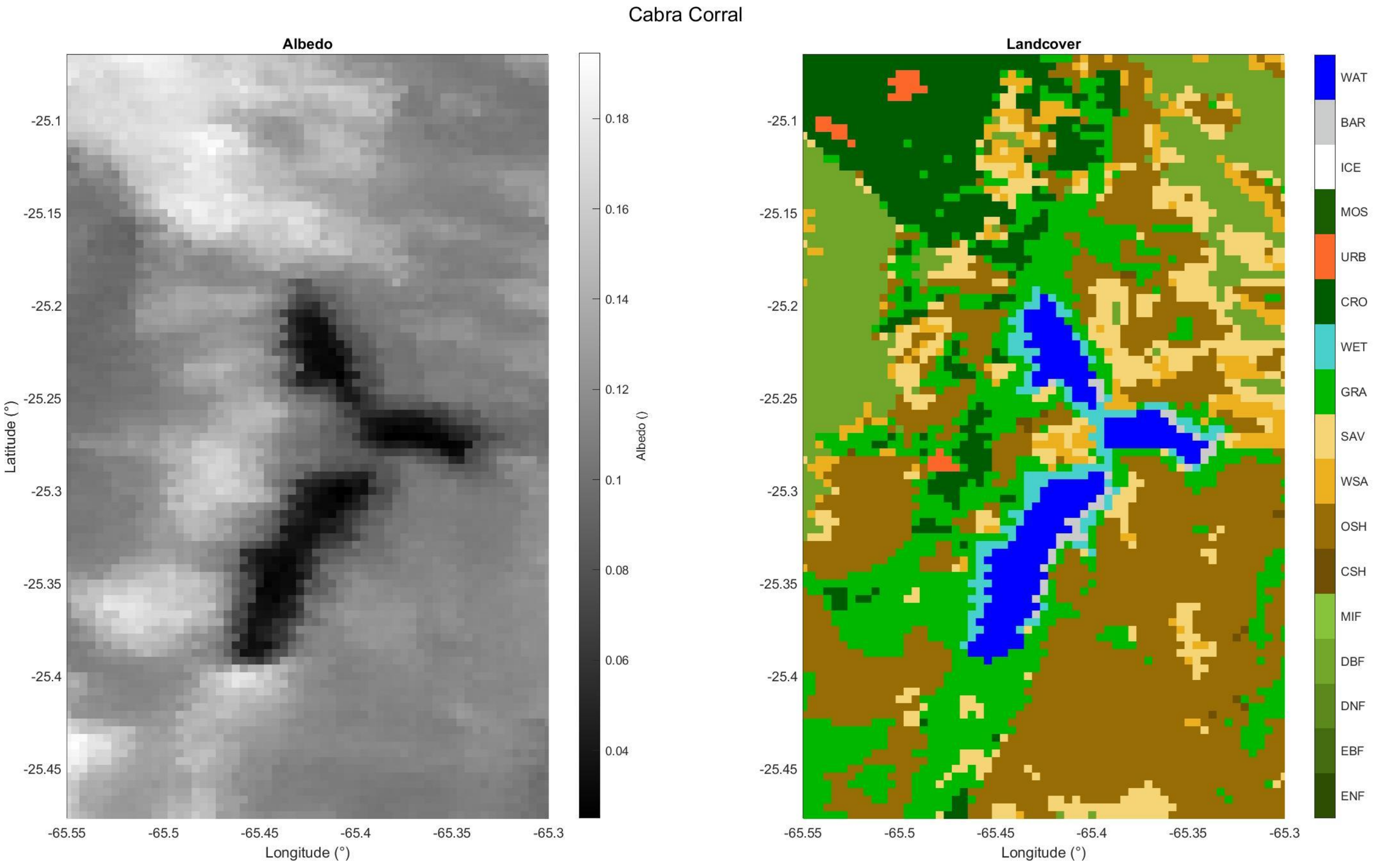
See the Albedo values for the given land surface section and guess where we can find lake covered areas in this scene …

Cabra Corral

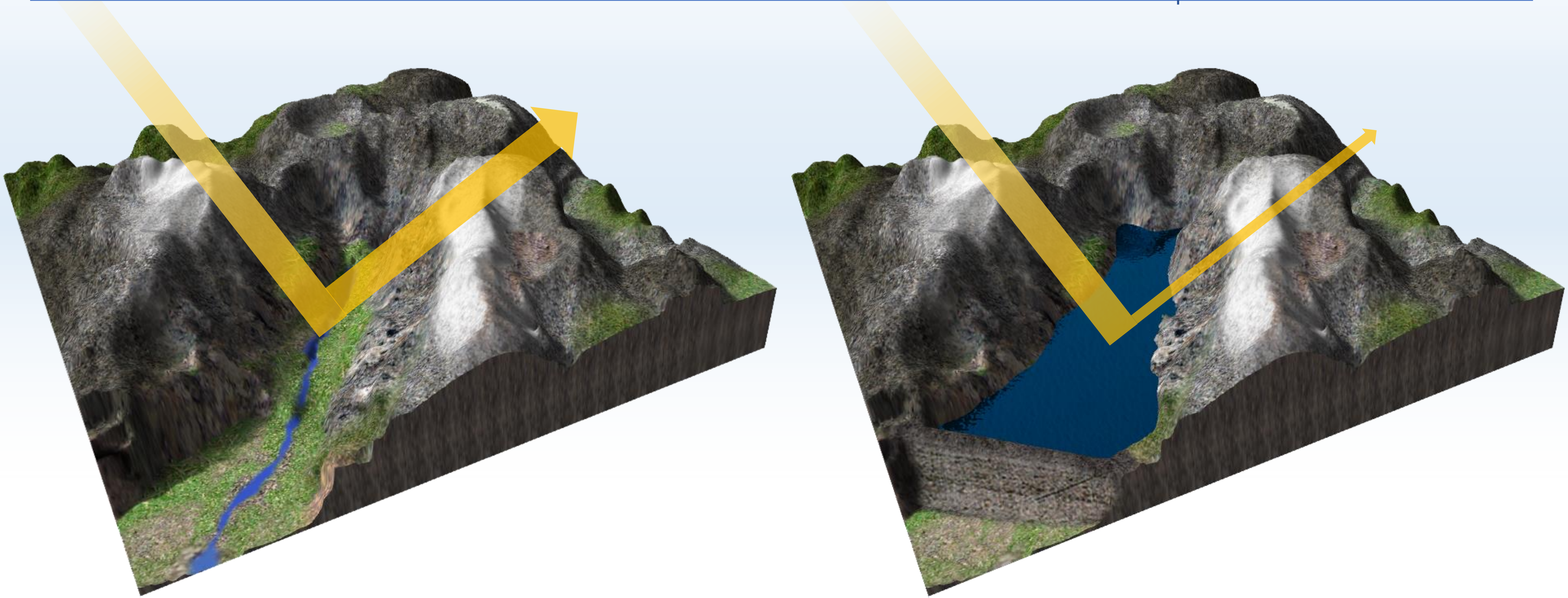


Can you tell where the lakes are located?

… right! It is the „dark spots“ with low Albedo values. Clearly separating from the “brighter” surrounding land cover.

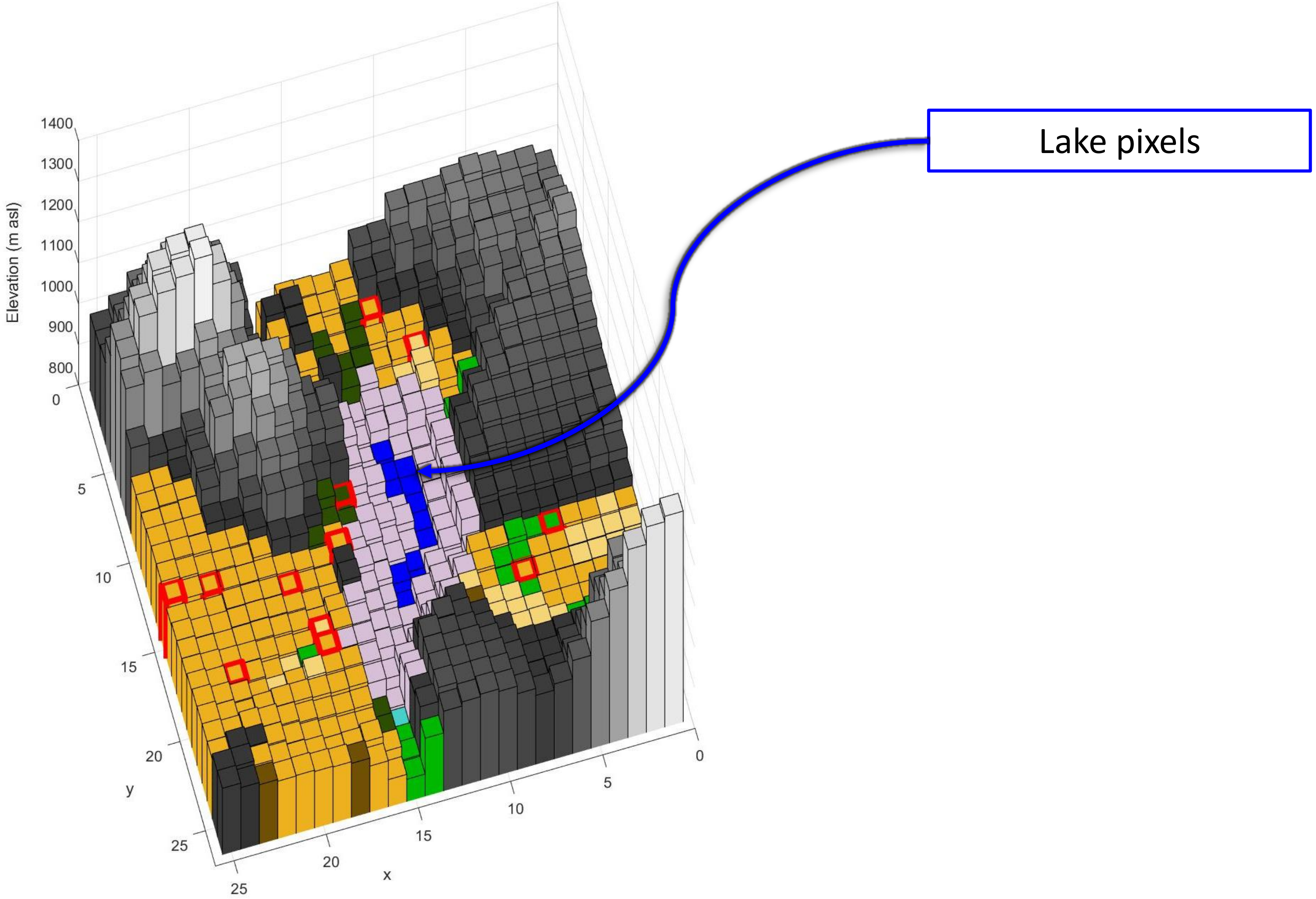


Water reservoirs reduce the Albedo of the natural landscape



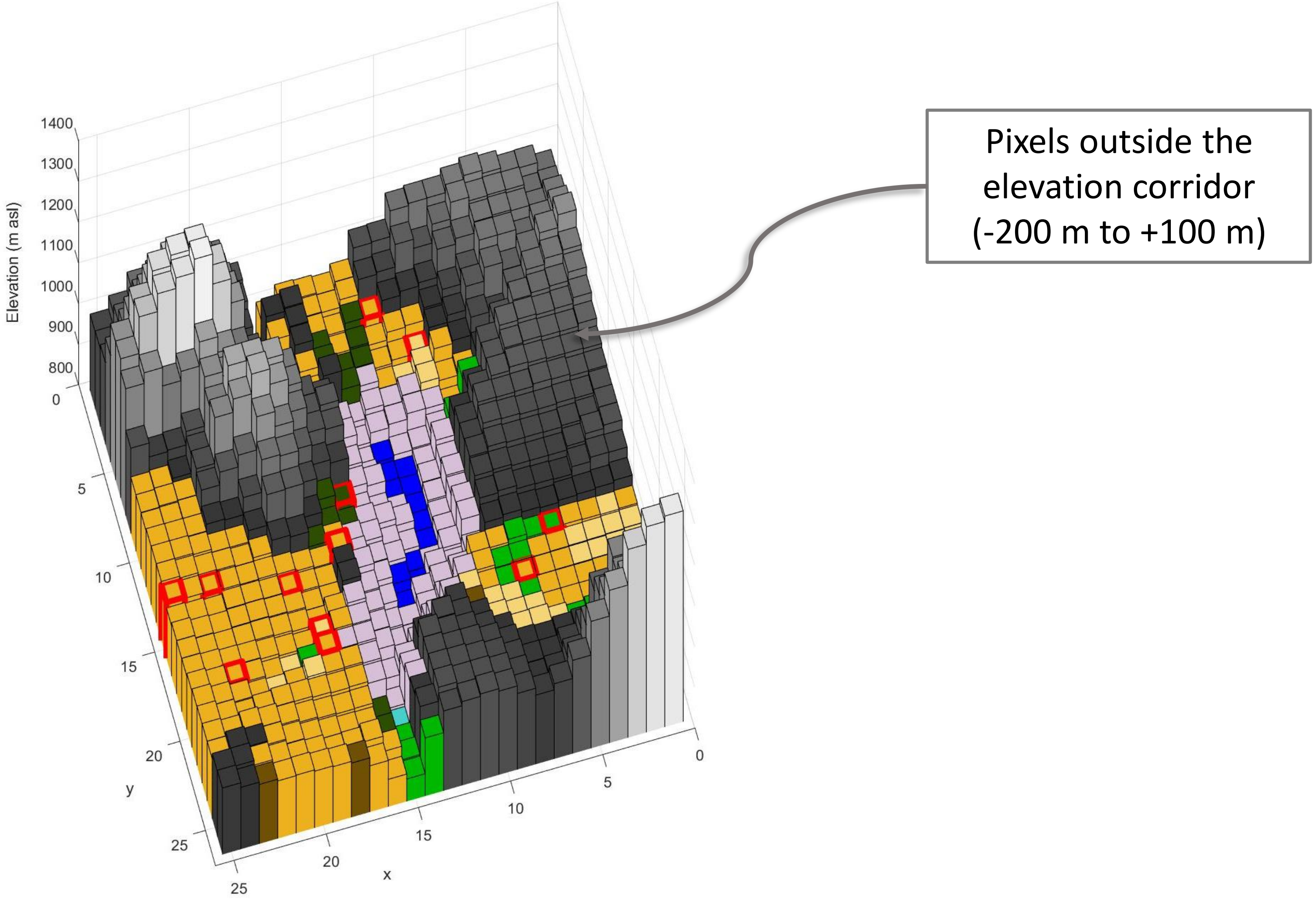
Land-use change → decrease in surface albedo → positive radiative forcing (RF) → offsets negative RF from fossil fuel displacement

Methods - Comparing reservoir and no-reservoir scenarios



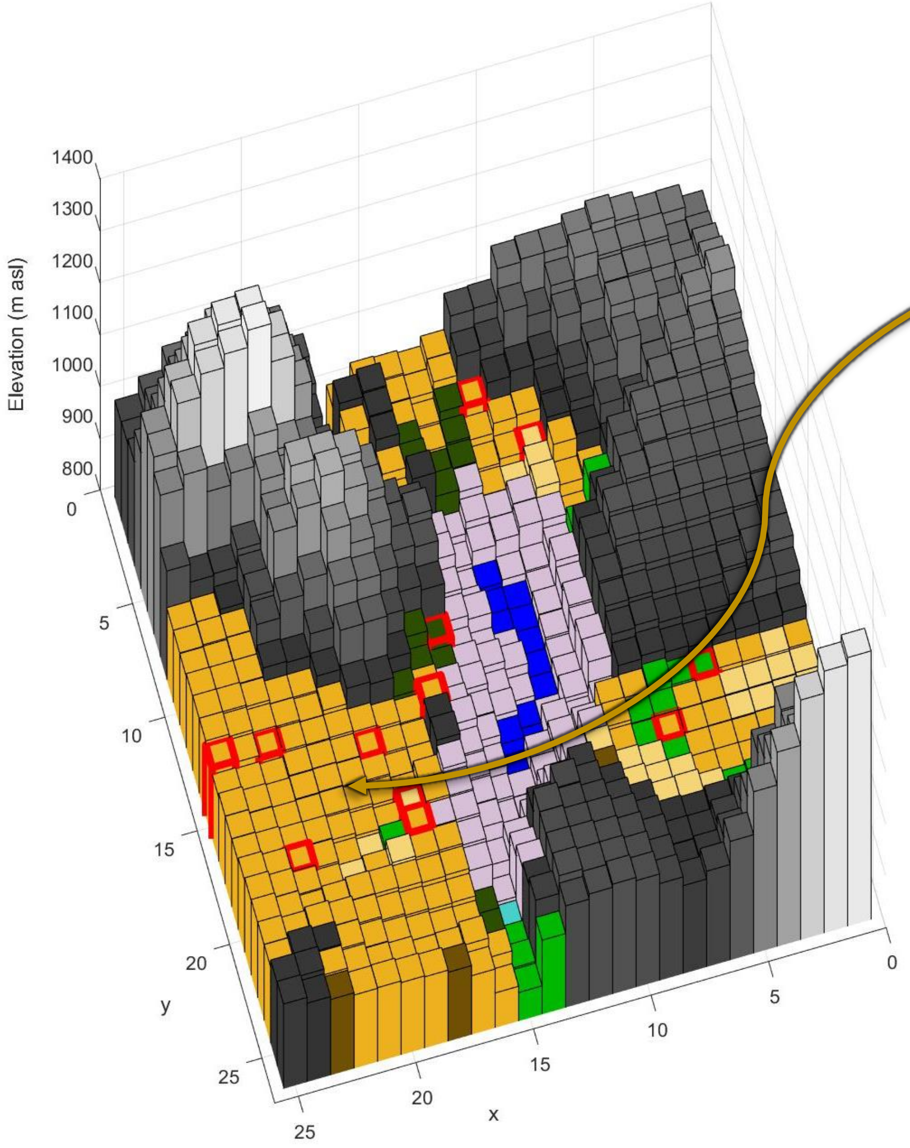
These pixels represent the actual lake/water reservoir

Methods - Comparing reservoir and no-reservoir scenarios



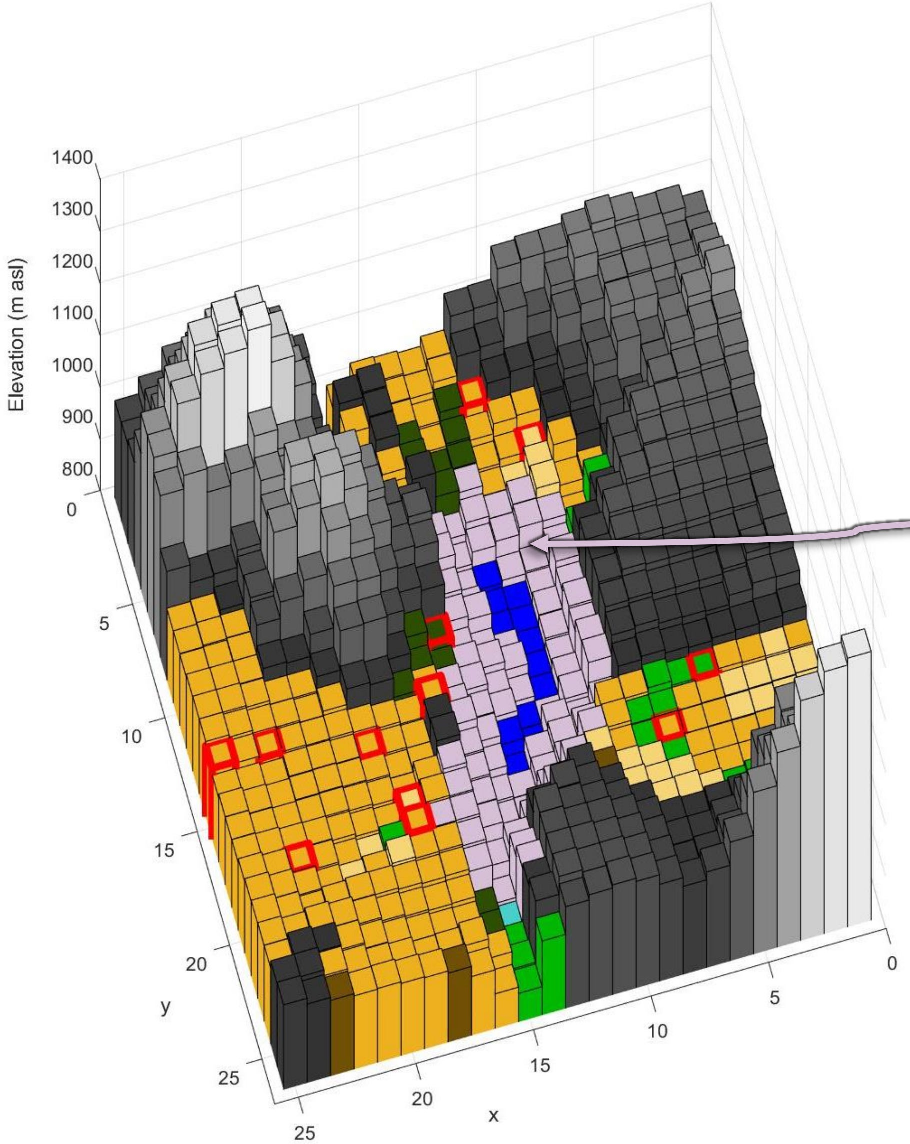
These pixels were not excluded as potential lake replacement pixels due to their elevation, and thus potentially different land cover types

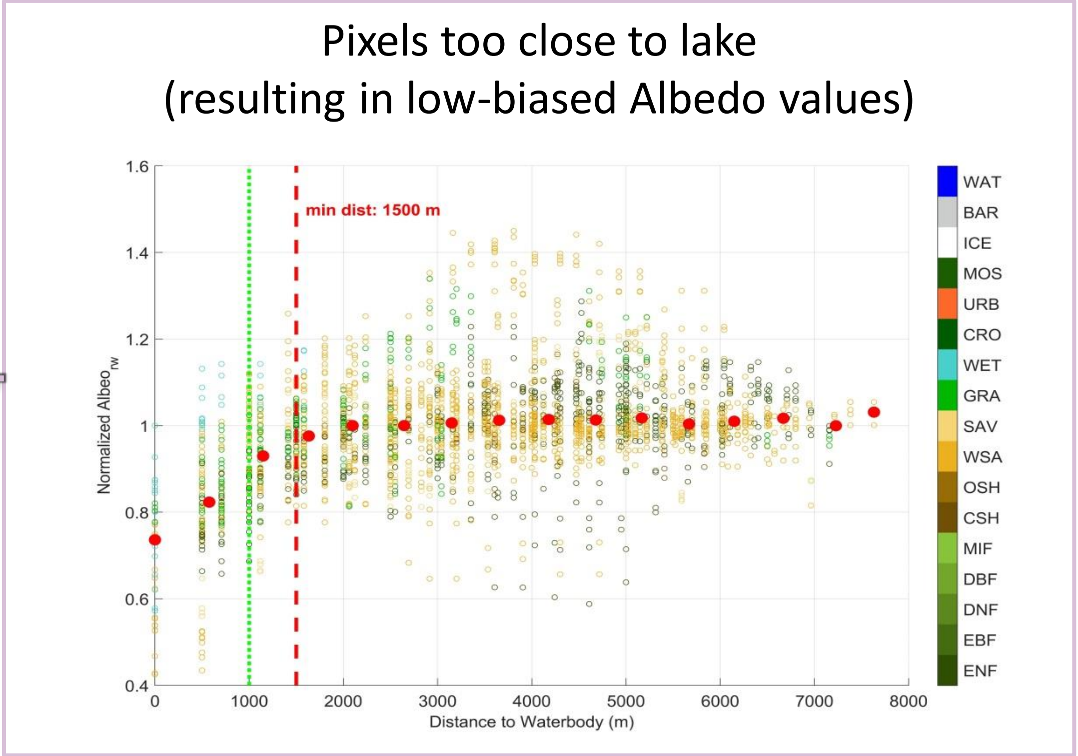
Methods - Comparing reservoir and no-reservoir scenarios



Pixels within the elevation corridor used to randomly select replacement pixels from

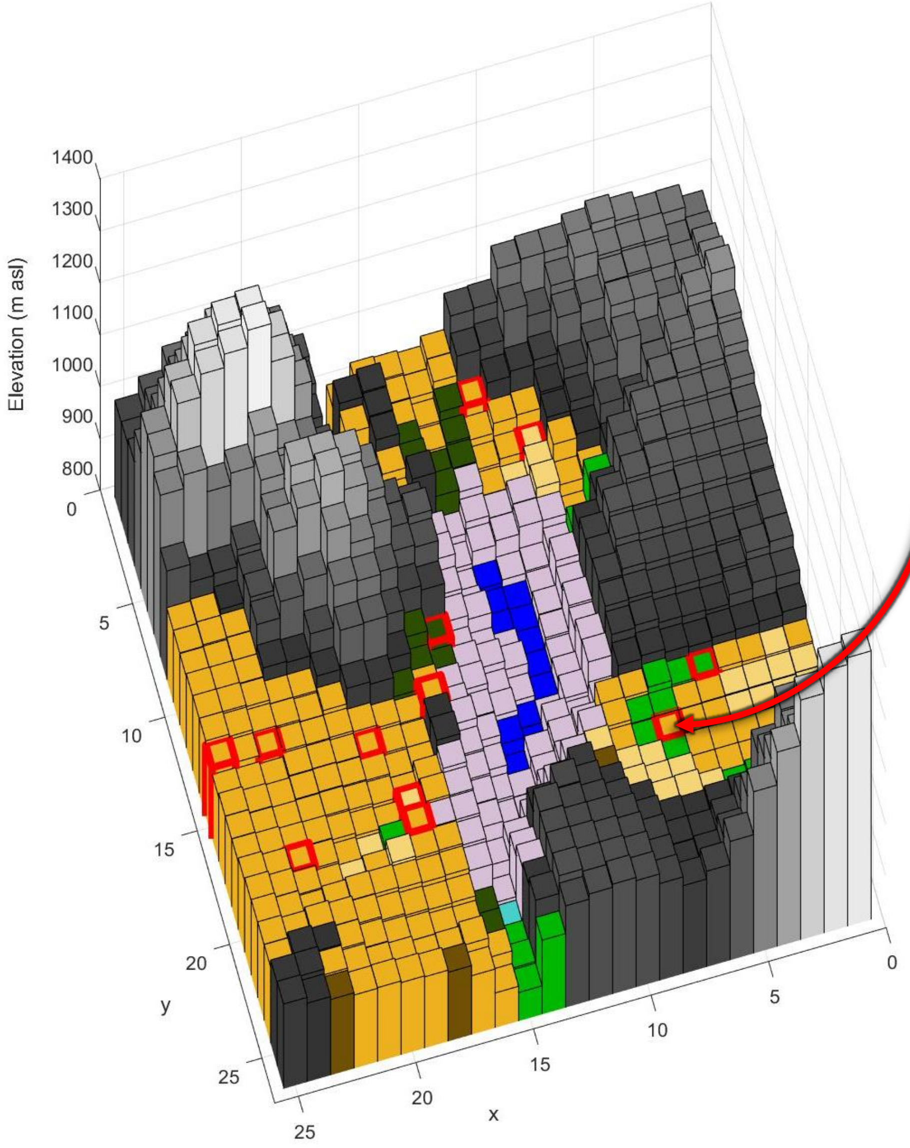
Methods - Comparing reservoir and no-reservoir scenarios





Pixels too close to any water body were excluded, as they are biased towards lower albedo values

Methods - Comparing reservoir and no-reservoir scenarios

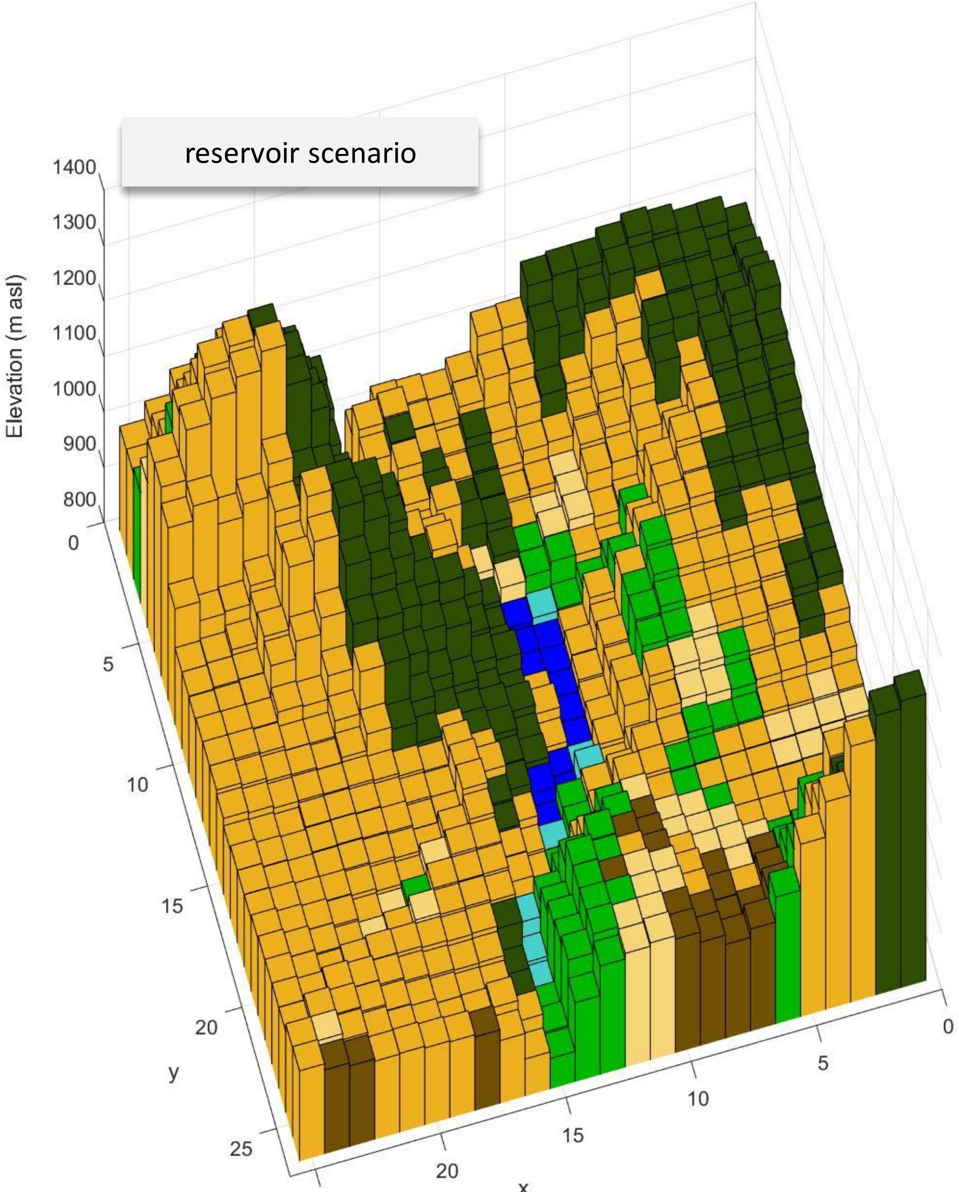


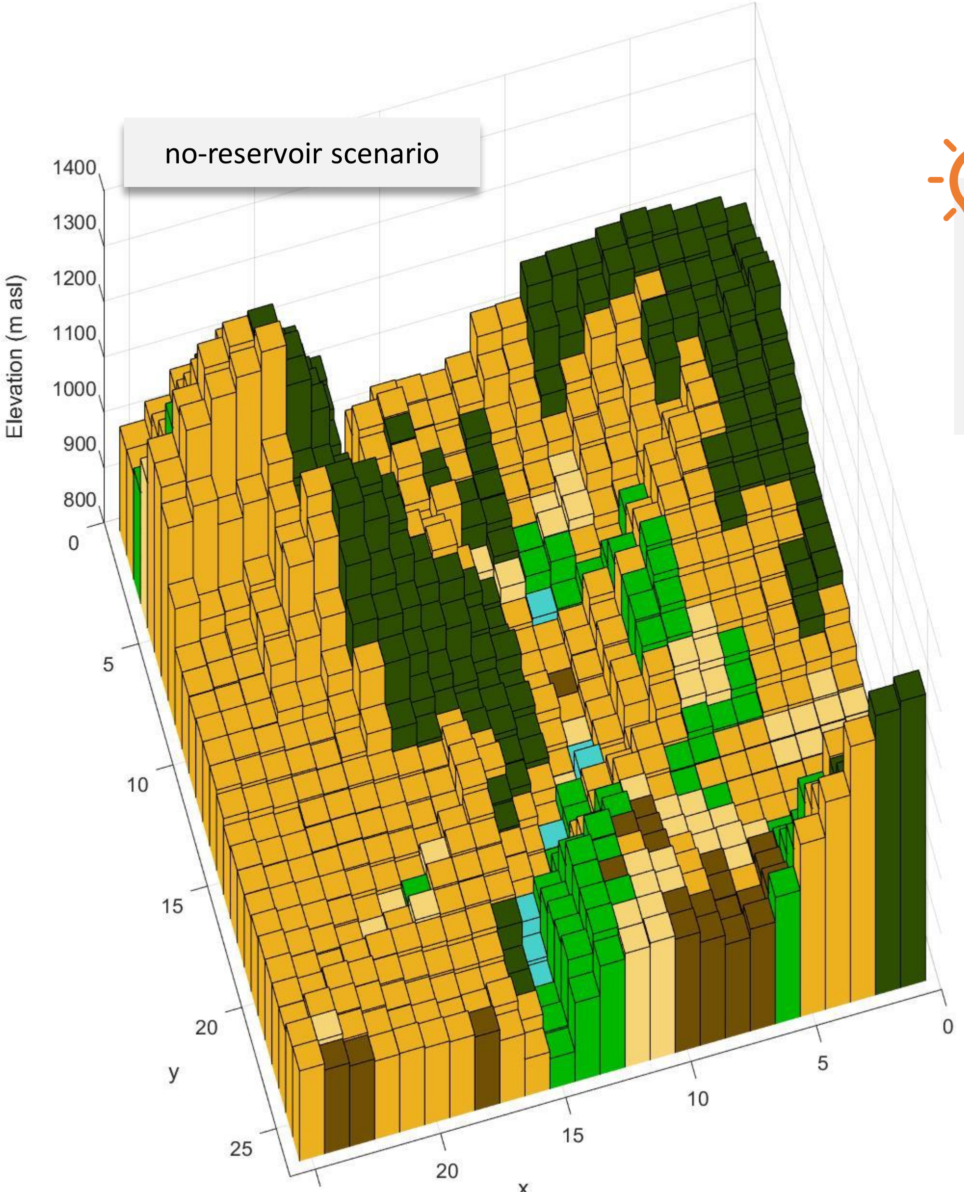
Randomly chosen pixels within corridor to replace lake

Out of these remaining pixels a weighted random sample (representing current land cover fractions) was chosen as lake replacement pixels

n replacement pixels equals n lake pixels

Methods - Comparing reservoir and no-reservoir scenarios





Calculated difference in top of atmosphere radiative forcing between both scenarios

Data used

PowerPlant database

GRanD database (v 1.0.1)

(physical attributes)

GPPD database (v 1.1.0)

(electricy generation)

Intersection of these two

Remote sensing data

MODIS MCD43A1 v6

- BRDF/albedo model parameter

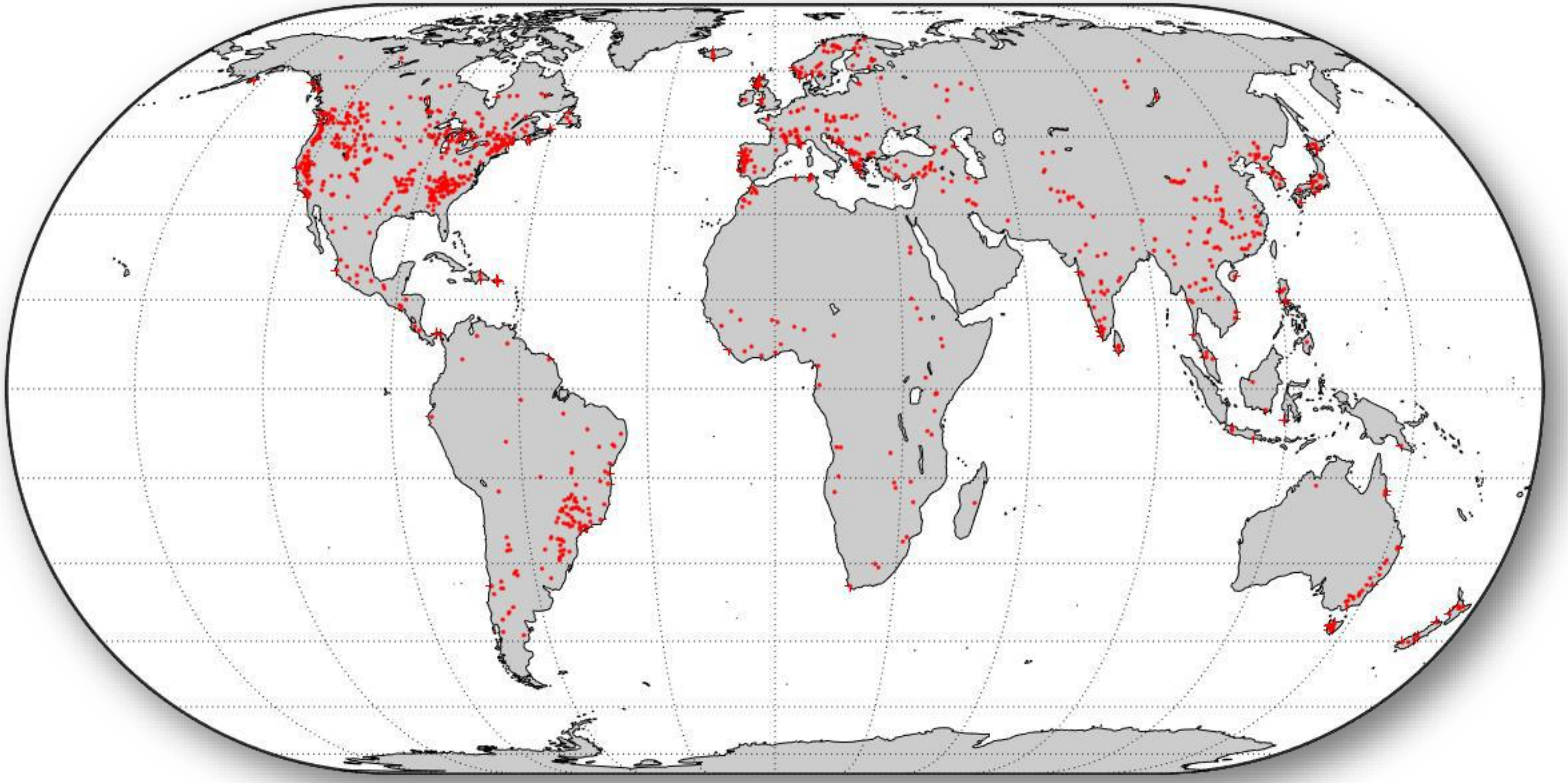
MODIS MCD12Q1 v6

- land water mask
- land cover

NASA Shuttle Radar Topography Mission v3 or ASTER DEM

- digital elevation model

World map of investigated reservoirs (n = 724)



Validation of water albedo

Water albedo (average and standard deviation) as a function of the solar zenith angle (1° bins).

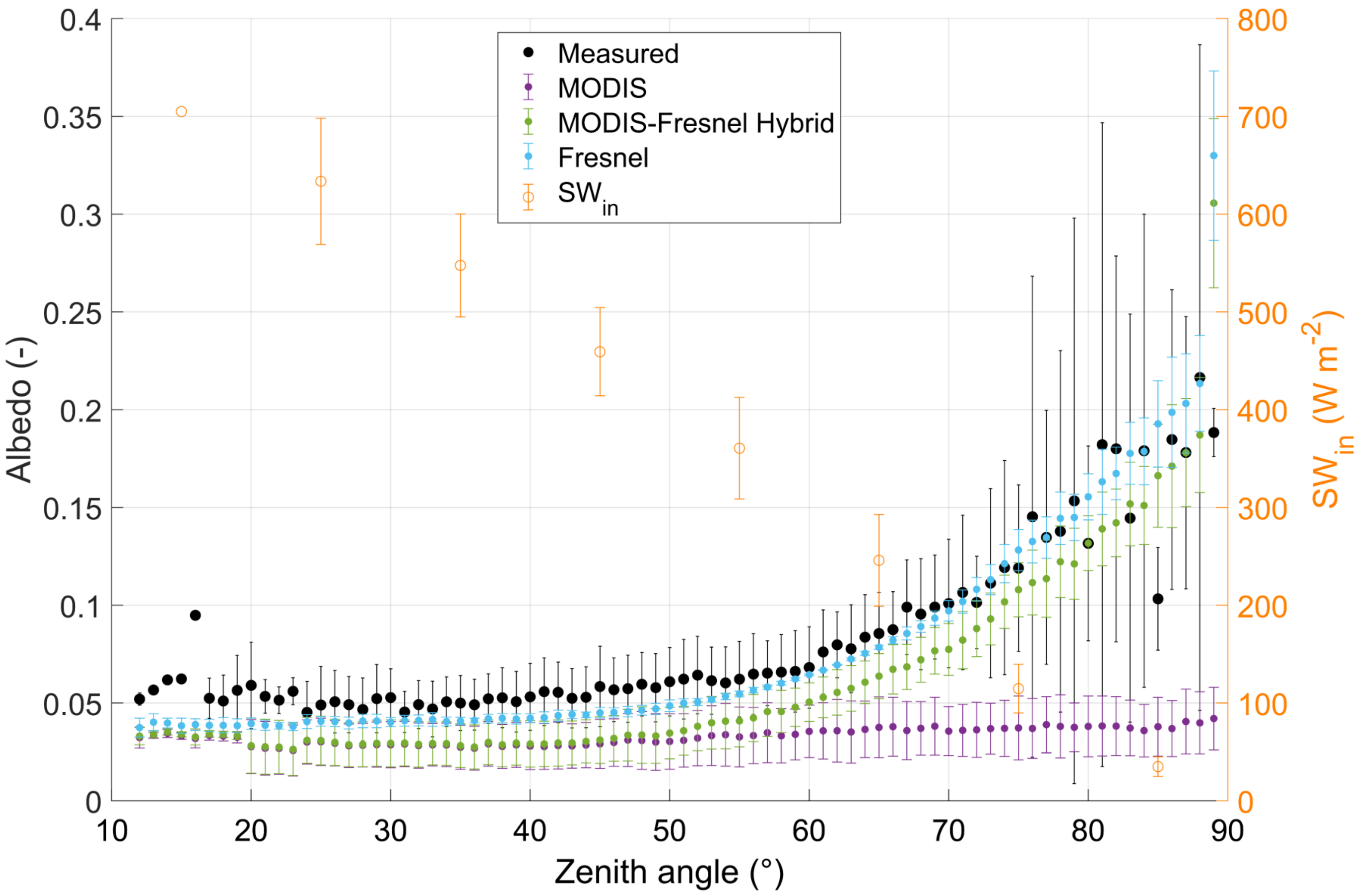
Measurements refer to the seven lakes with actual measured albedo values.

MODIS to the albedo calculated from the MCD43A1 BRDF parameters.

Fresnel refers to the Fresnel model.

MODIS-Fresnel hybrid to the combination of the latter two.

SW_{in} (right axis) refers to bin averaged shortwave radiation (10° bins).



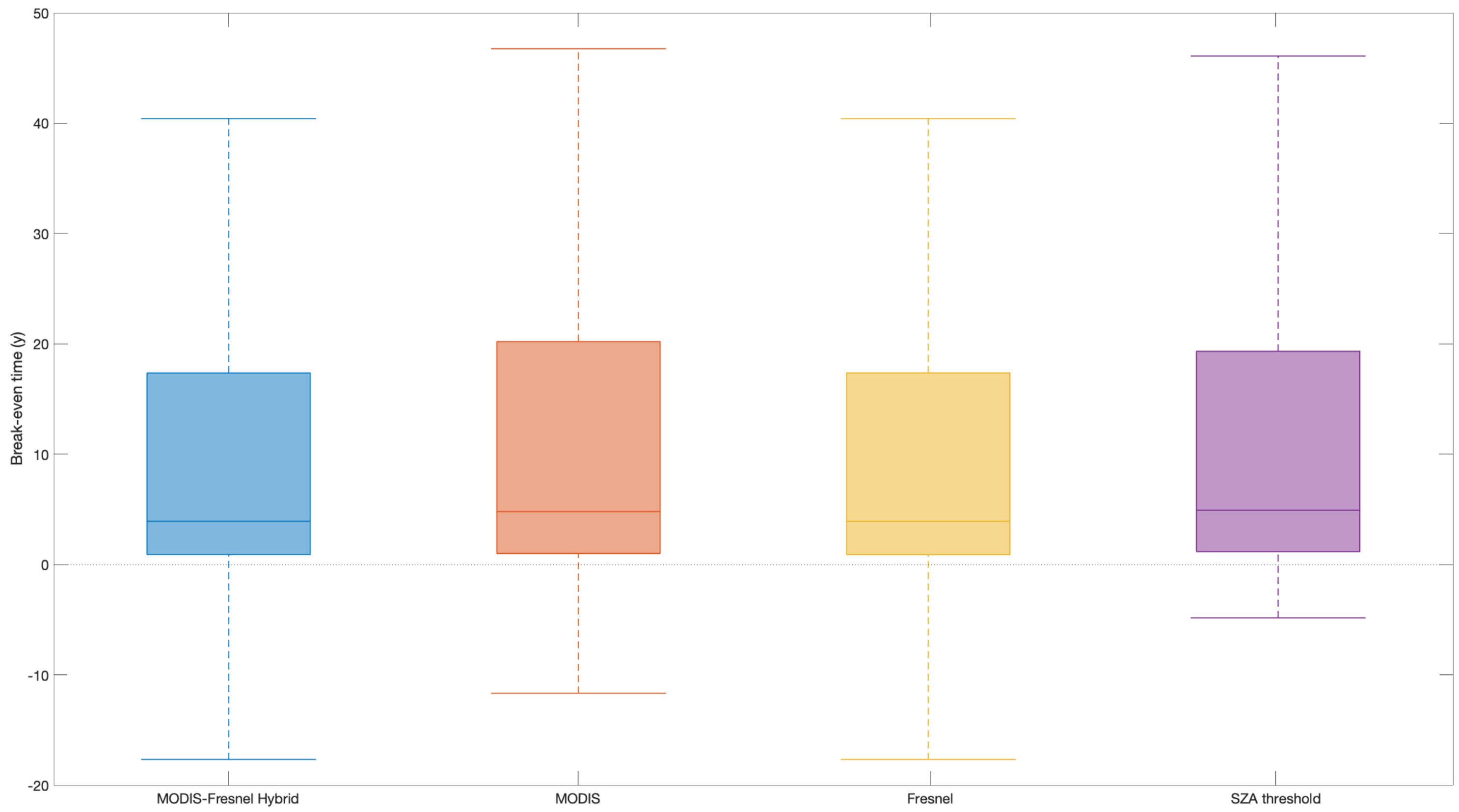
Concept of Break Even Time - BET

The time duration until which the negative radiative forcing from fossil fuel replacement by hydroelectric power outcompetes the positive radiative forcing from the albedo change

Sensitivity of BETs to albedo calculation

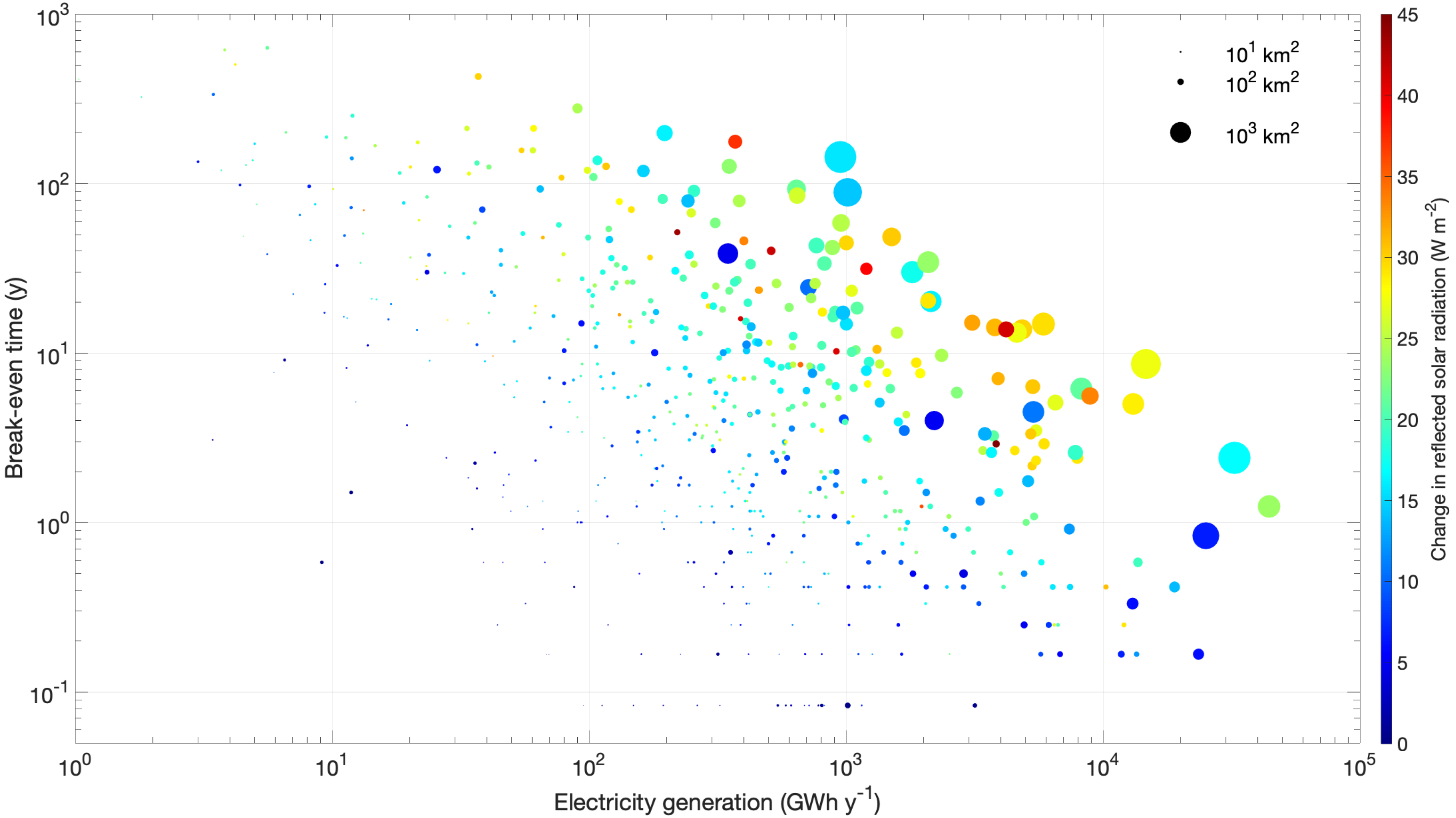
Calculated BET values were robust against different albedo modelling approaches.

All further results presented refer to the MODIS-Fresnel Hybrid approach.



BETs are highly case-specific

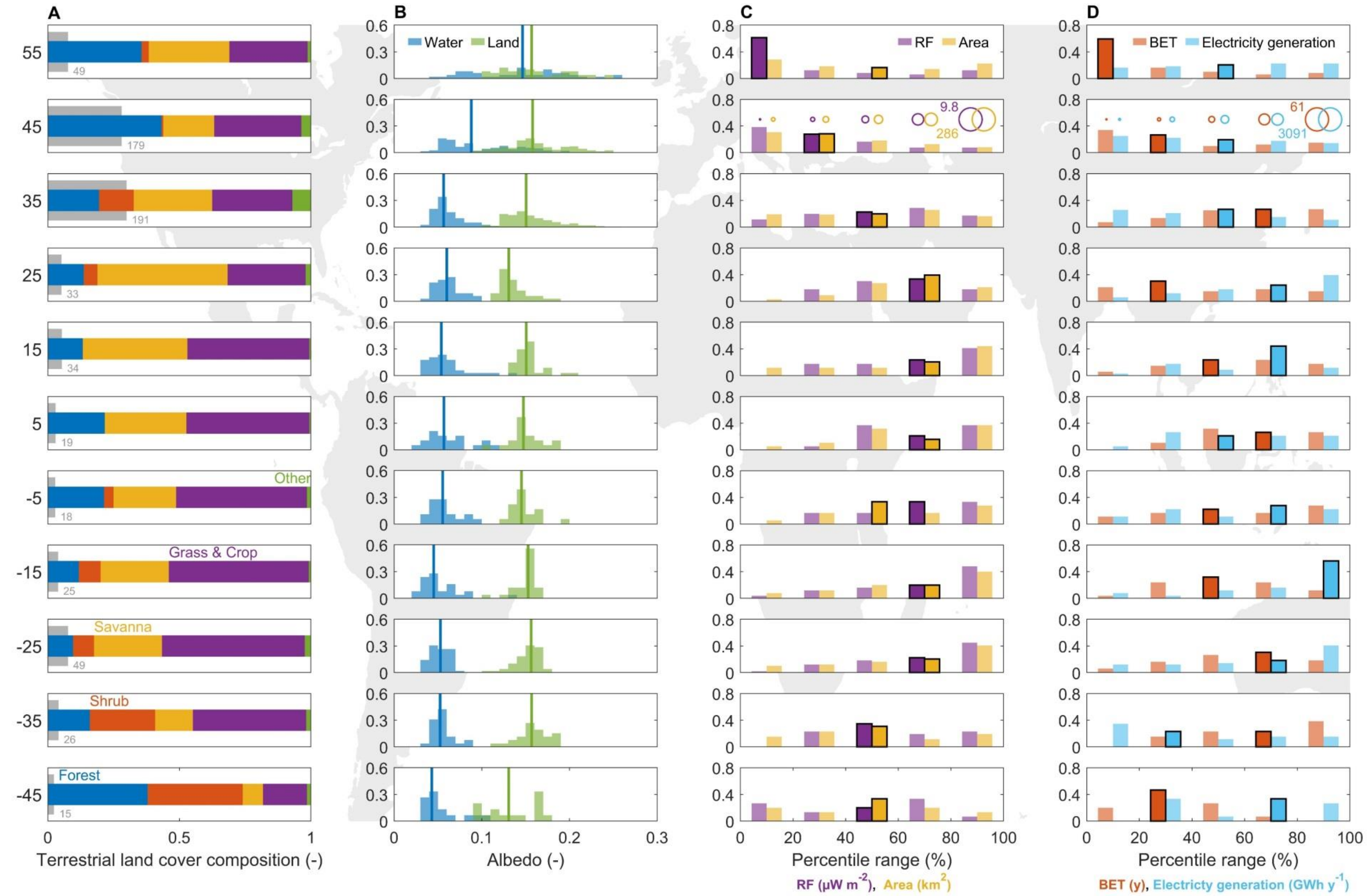
Similar BETs were reached under contrasting climatic (incident solar radiation) and environmental (albedo difference) conditions and with different hydropower plant designs (reservoir surface area and annual electricity generation).



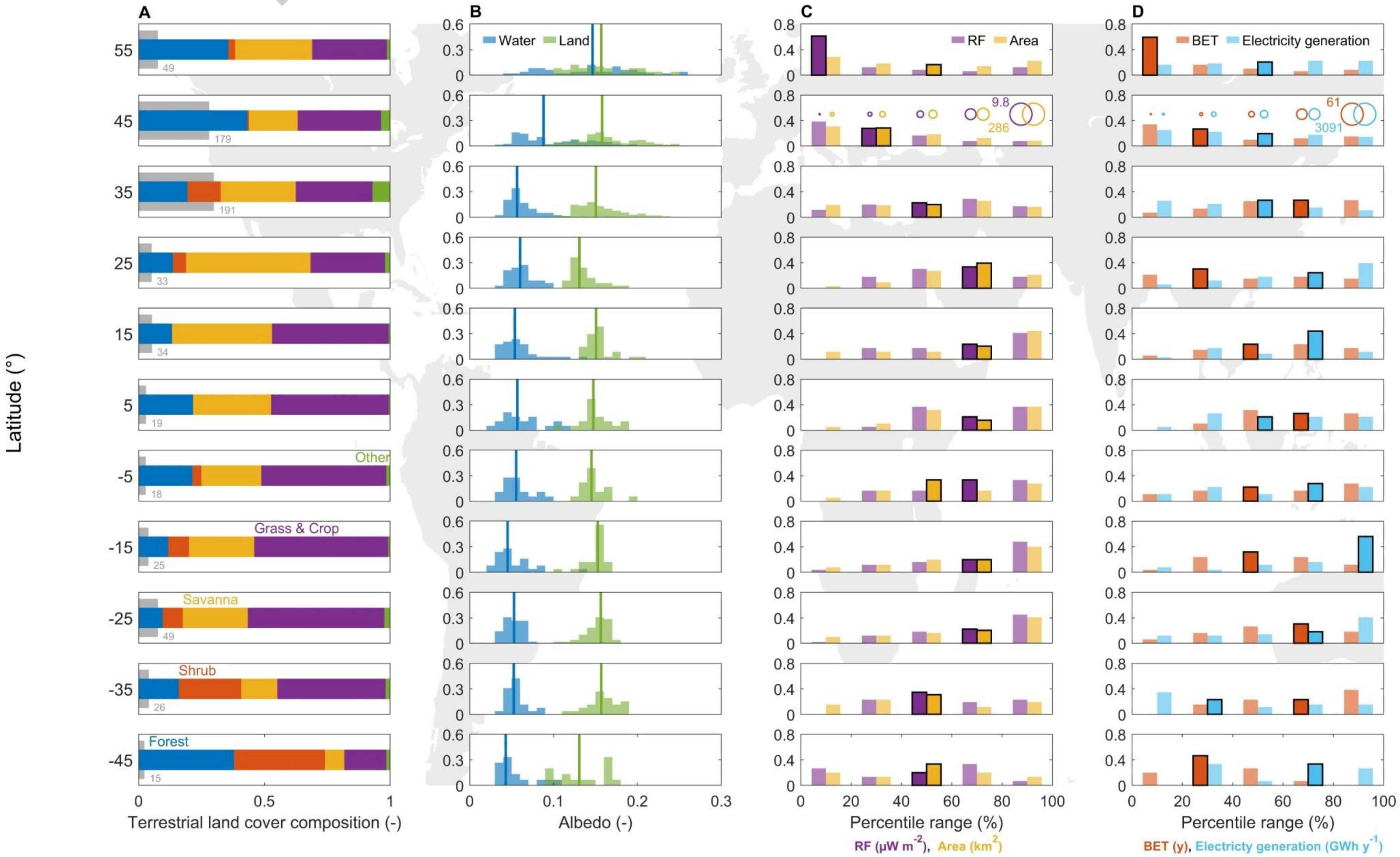
Results

Latitudinal distribution of investigated parameters

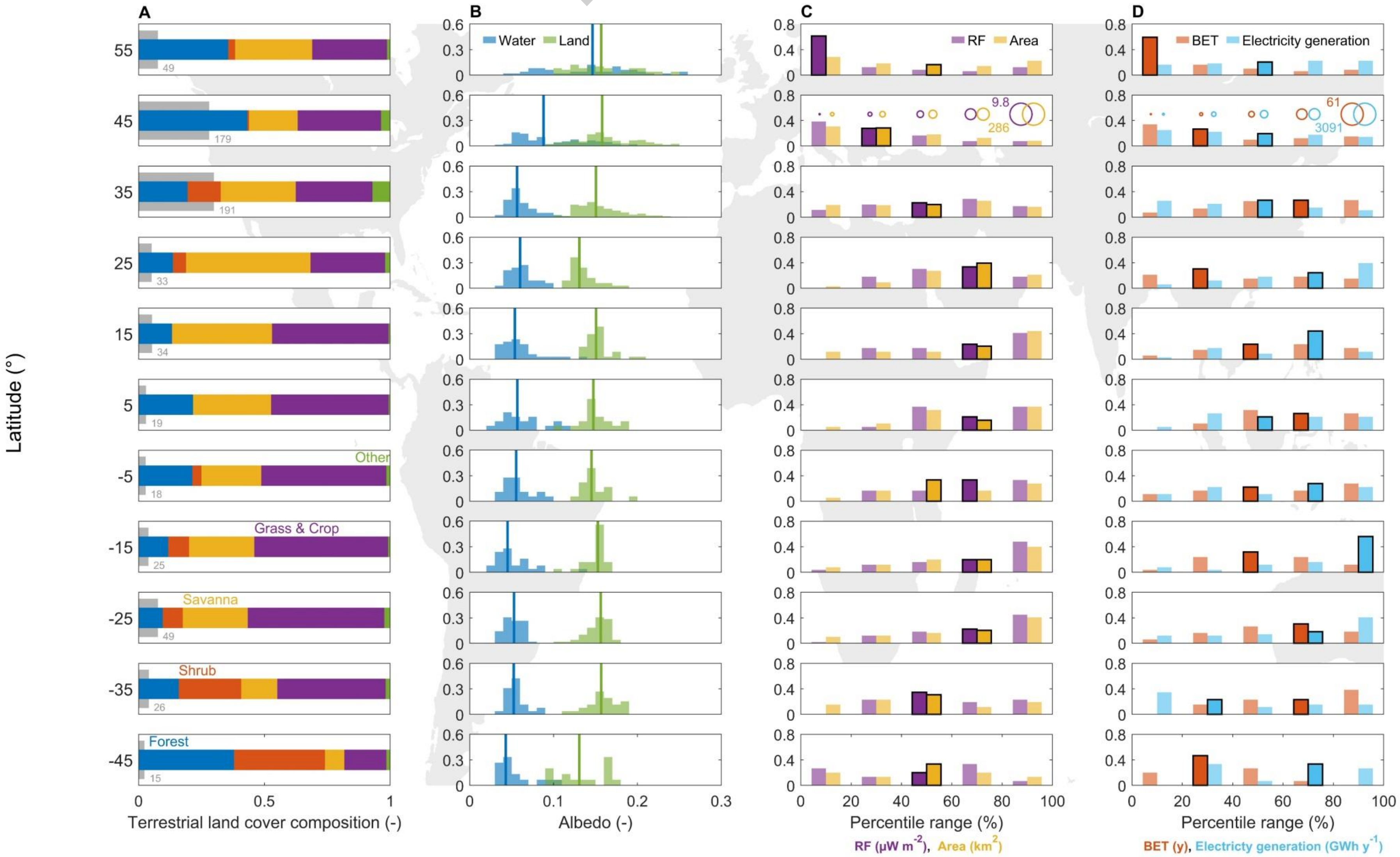
Latitude (°)



Land cover composition surrounding hydropower reservoirs (color coded) and number of investigated hydropower reservoirs (grey bars and associated numbers)

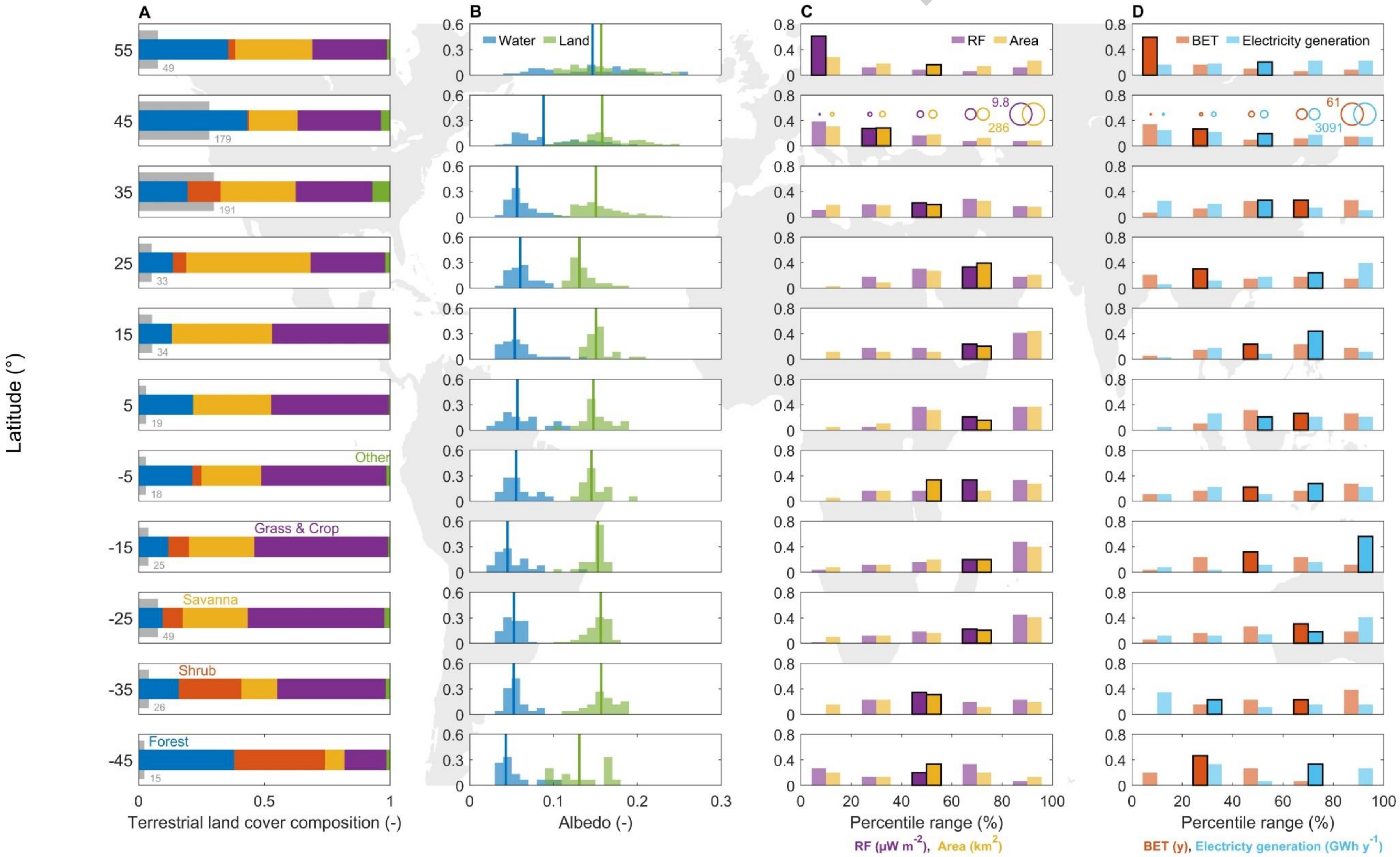


Hydropower reservoir (blue) and terrestrial (green) albedo (medians are indicated by vertical colored lines) being significantly different from each other, except for the highest latitudes. Here snow/ice cover and large solar zenith angles increased the hydropower reservoir albedo during the cold season more than that of the surrounding terrestrial landscape.



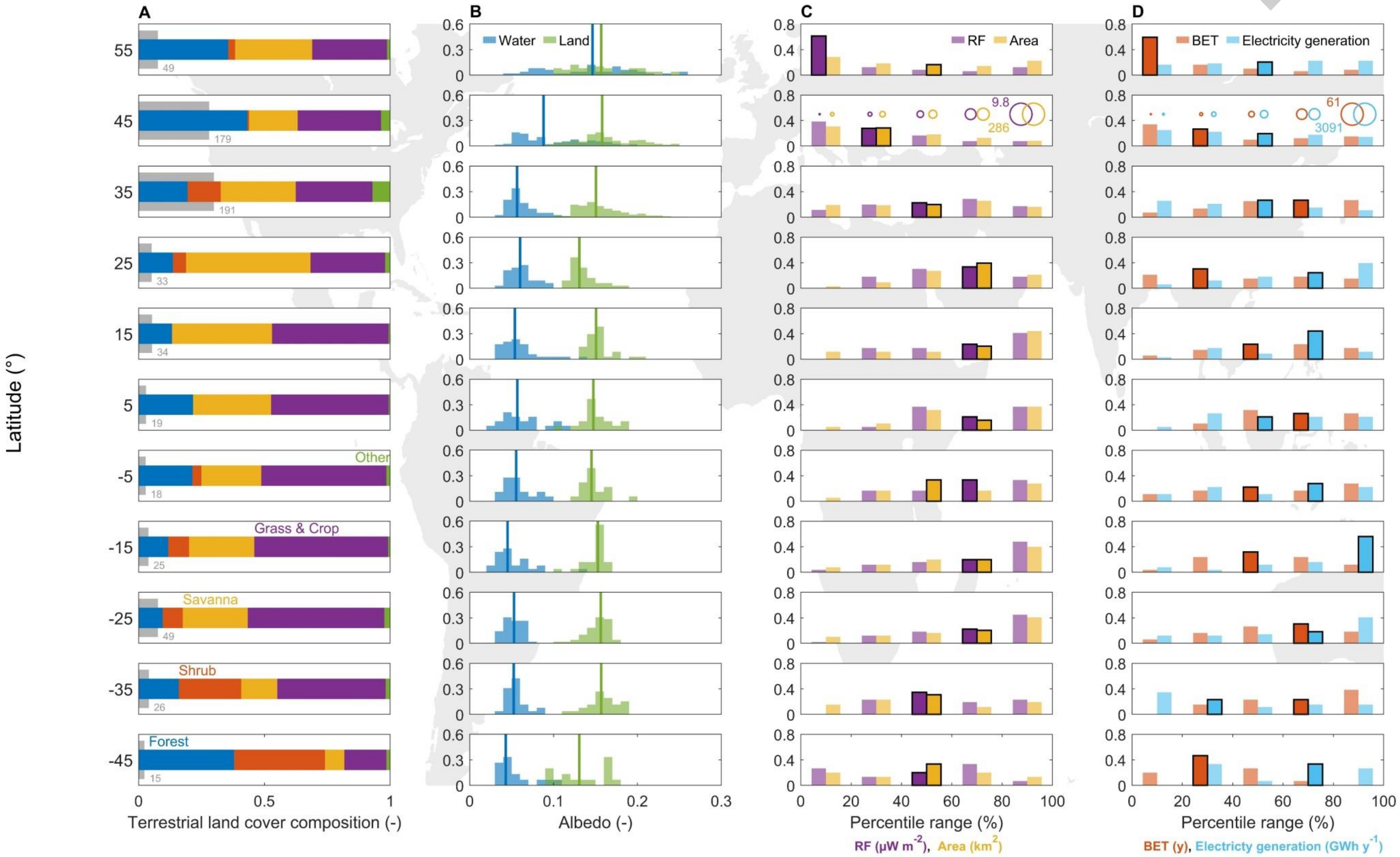
Fractional occurrence in 20 % percentile groups. Groups containing the respective latitudinal medians being indicated by bold bars.

Top of atmosphere radiative forcing (RF) from albedo change (purple) and reservoir surface area (yellow). Variability in RF was largely explained by the hydropower reservoir surface area that also drove the increase of the TOA RF around the tropics.

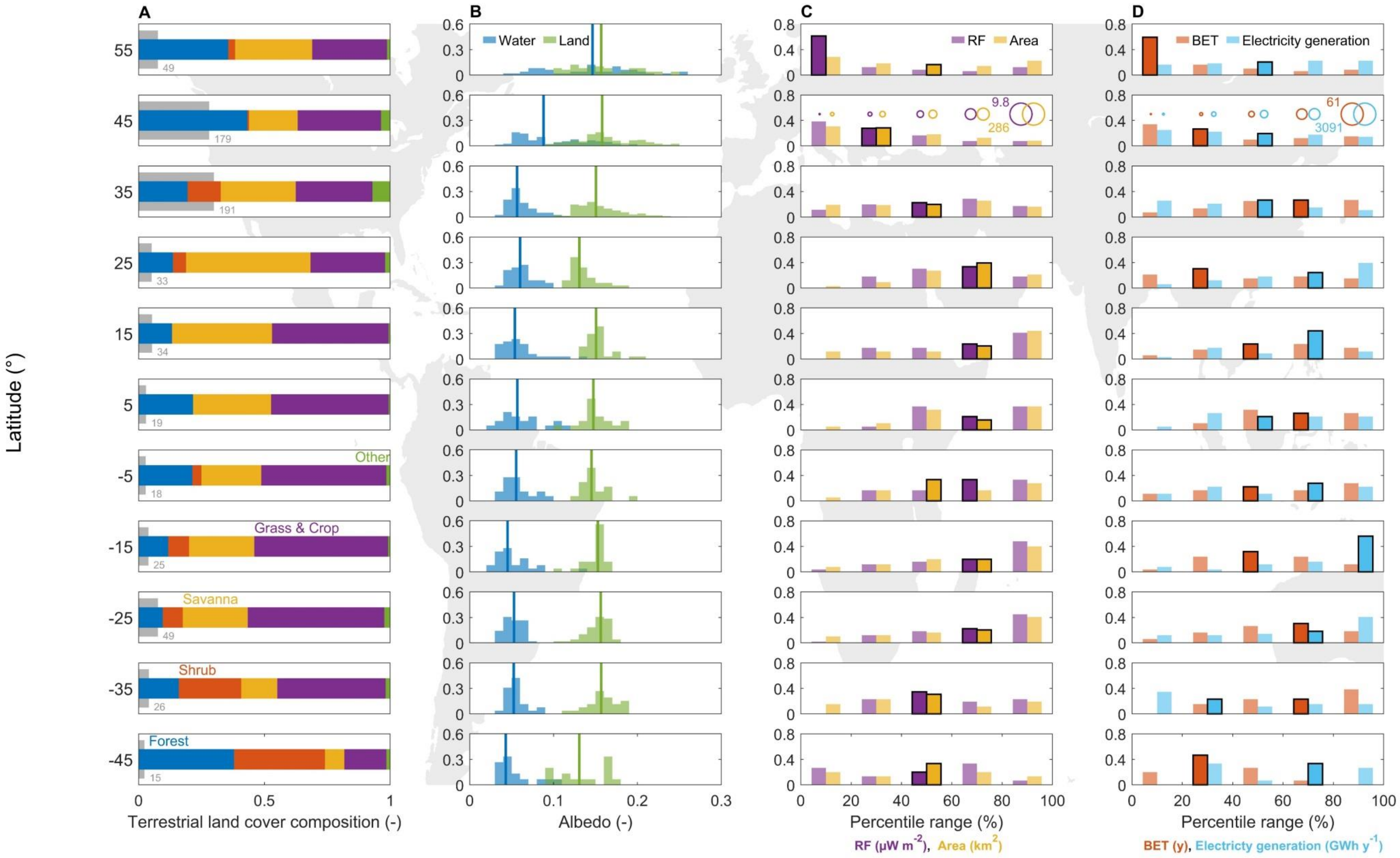


Fractional occurrence in 20 % percentile groups. Groups containing the respective latitudinal medians being indicated by bold bars.

Break-even time (BET; red) and electricity generation (blue). BETs amounted to <= 4 year, i.e. 5 % of an estimated 80 year lifetime of hydropower plants, for 45 % of all hydropower reservoirs, exceeded 30 years in 16 % and in 7 % of all cases 80 years.



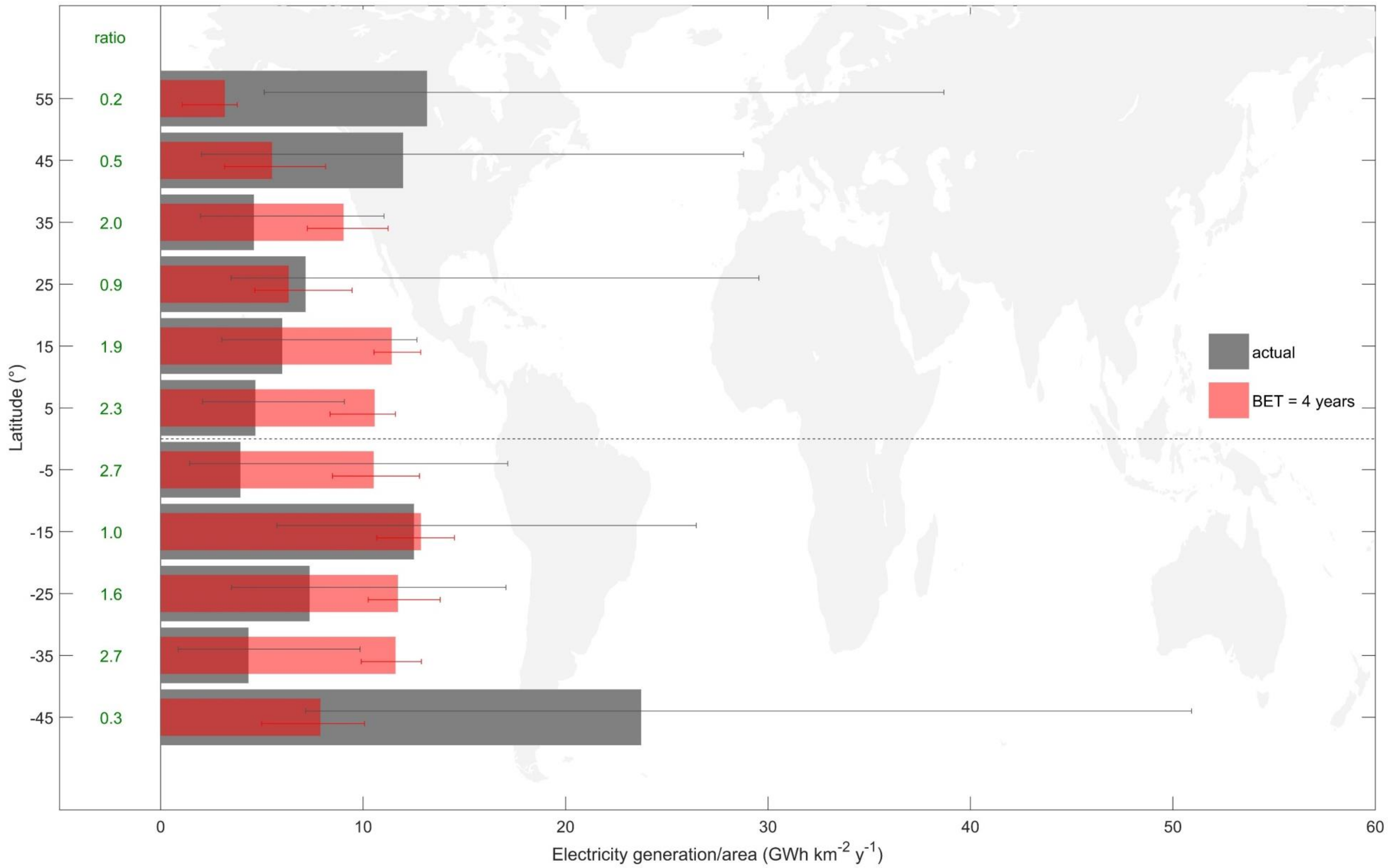
Results



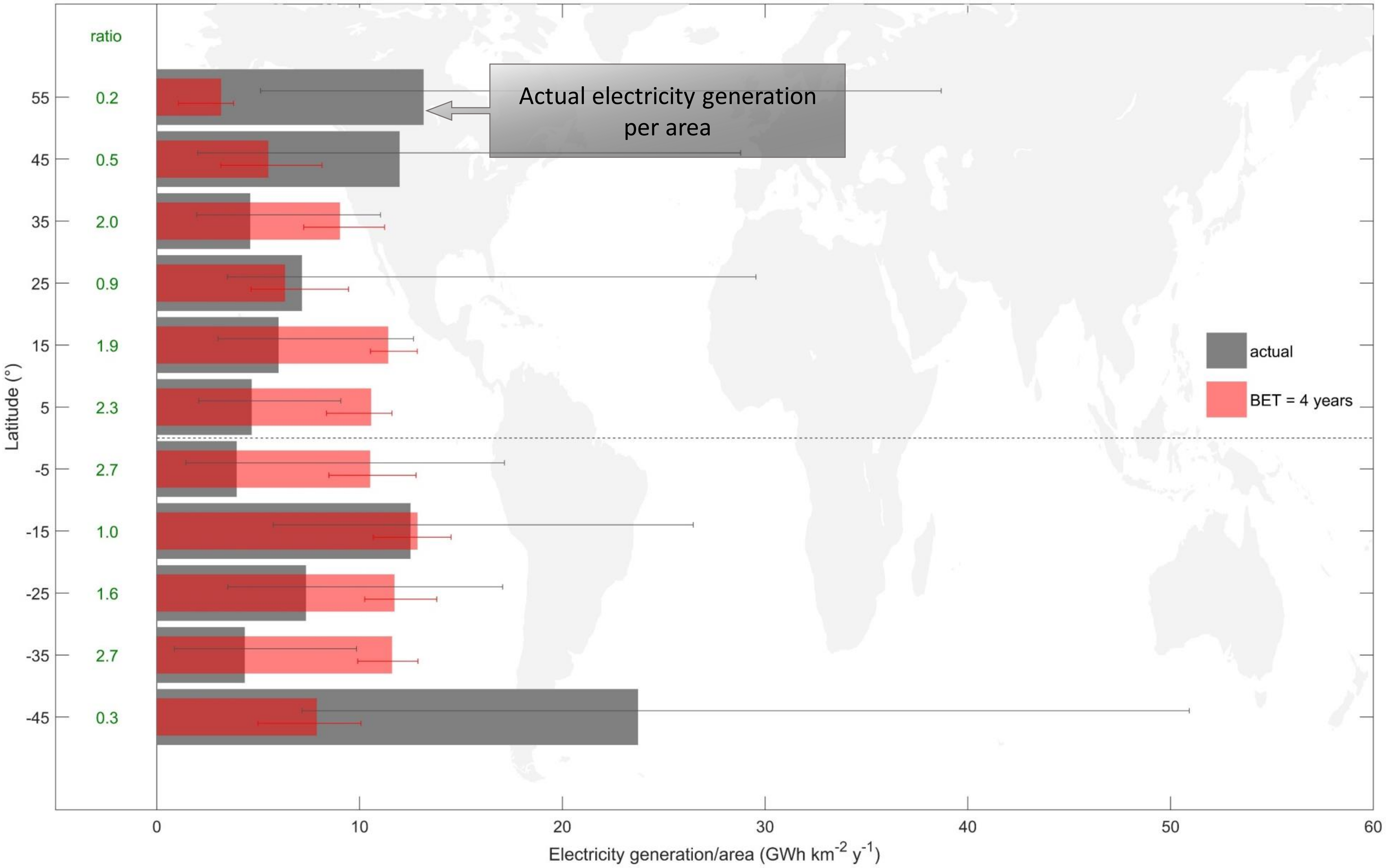
medians of the percentiles in absolute units

Results

Latitudinal distribution of the electricity generation to hydropower reservoir surface area (EA) ratio

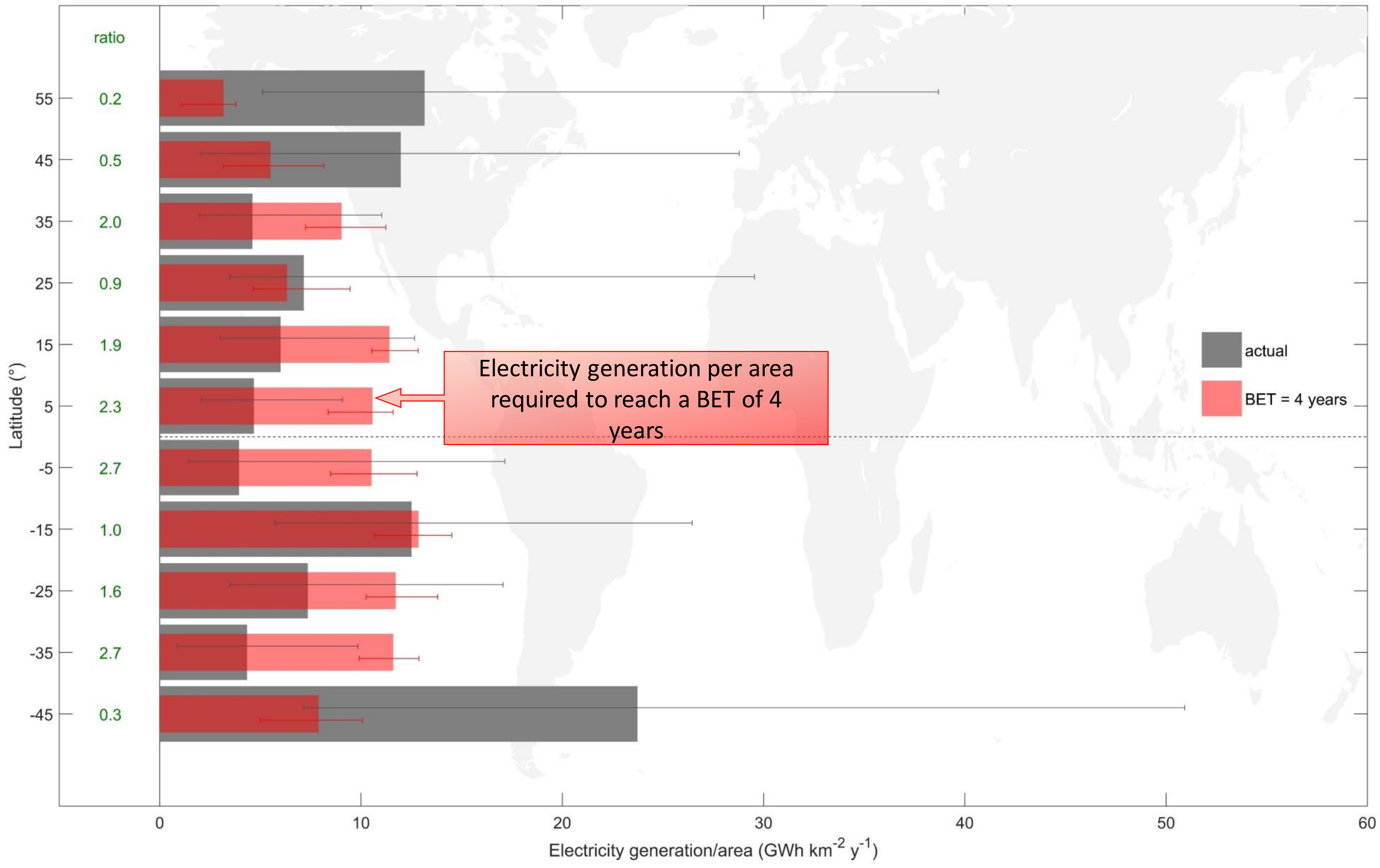


Results



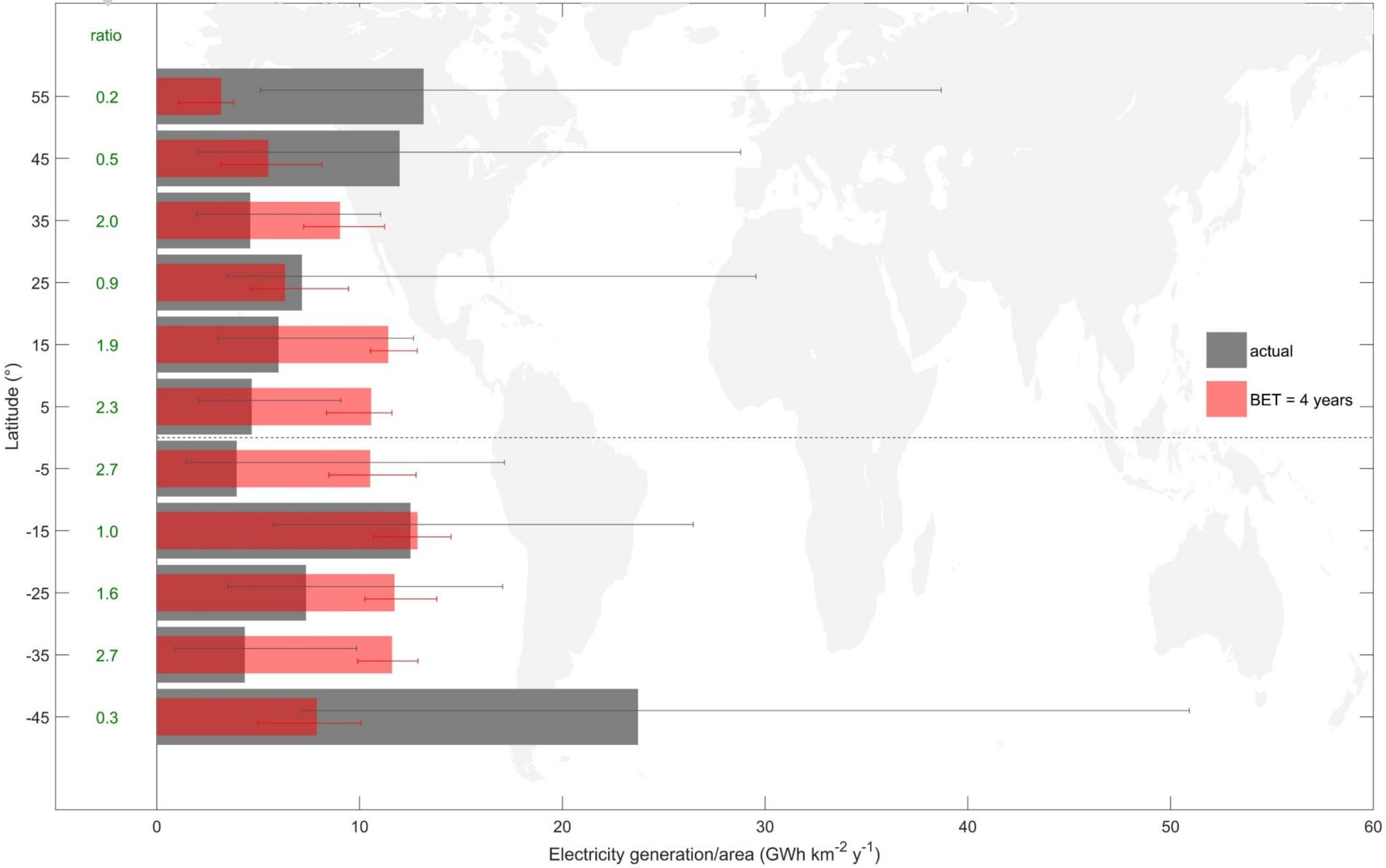
ratio
Actual electricity generation per area
55
45
35
25
15
5
-5
-15
-25
-35
-45
0.2
0.5
2.0
0.9
1.9
2.3
2.7
1.0
1.6
2.7
0.3
Latitude (°)
actual
BET = 4 years
0
10
20
30
40
50
60
Electricity generation/area (GWh km^{-2} y^{-1})

Results


ratio
55
45
35
25
15
5
-5
-15
-25
-35
-45
0.2
0.5
2.0
0.9
1.9
2.3
2.7
1.0
1.6
2.7
0.3
Latitude (°)
Electricity generation per area required to reach a BET of 4 years
actual
BET = 4 years
0
10
20
30
40
50
60
Electricity generation/area (GWh km-2 y-1)

Results

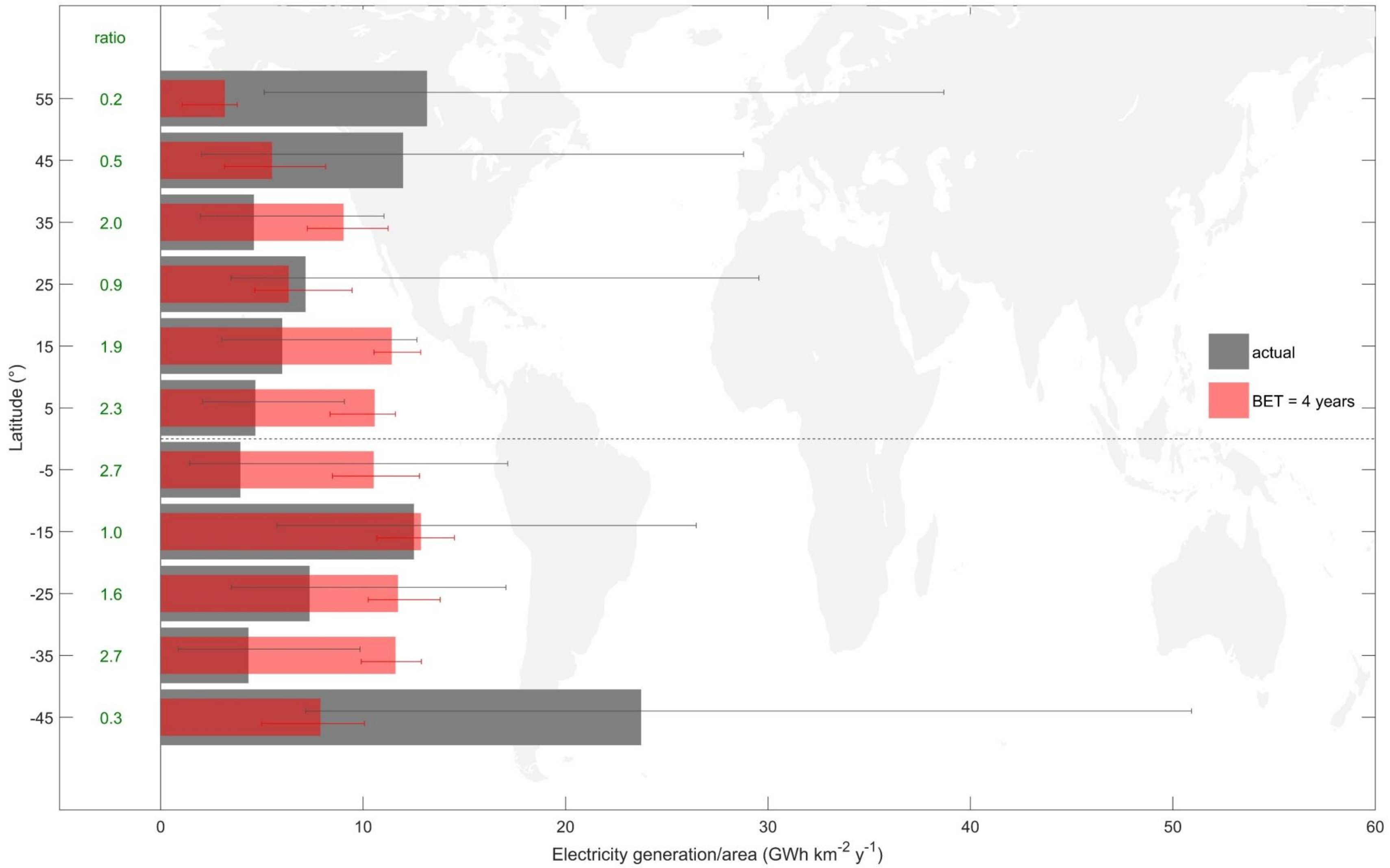
Ratio between these two



Results

Low values of incident solar radiation, partially combined with small albedo differences, above/below 40° North/South resulted in low EA ratios required for achieving a BET of 4 years. At these latitudes, actual EA ratios were by up to a factor of 5 higher (and actual BETs thus lower than 4 years).

Conversely, large EA ratios required for achieving a BET of 4 years, which exceeded actual ones by up to a factor of 2.7, were inferred for the temperate and tropical latitudes in between.



Conclusions

- BETs depend on specific combination of climatic (solar radiation), ecological (albedo difference) and powerplant design (electricity generation to surface area ratio) characteristics.

- In 16 % of all investigated cases, BETs exceeded 30 years – way too long to make a meaningful contribution towards decarbonization required for limiting warming to <1.5°C by the end of this century.

- Reaching meaningful BETs between +/- 40° latitude, where 90 % of the hydropower capacity that is globally under construction/planned is located, requires a much more favorable electricity to water surface area ratio compared to Northern latitudes.

- The albedo penalty of hydropower needs to be taken into account in order to avoid no-win situations for both climate and environment.

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