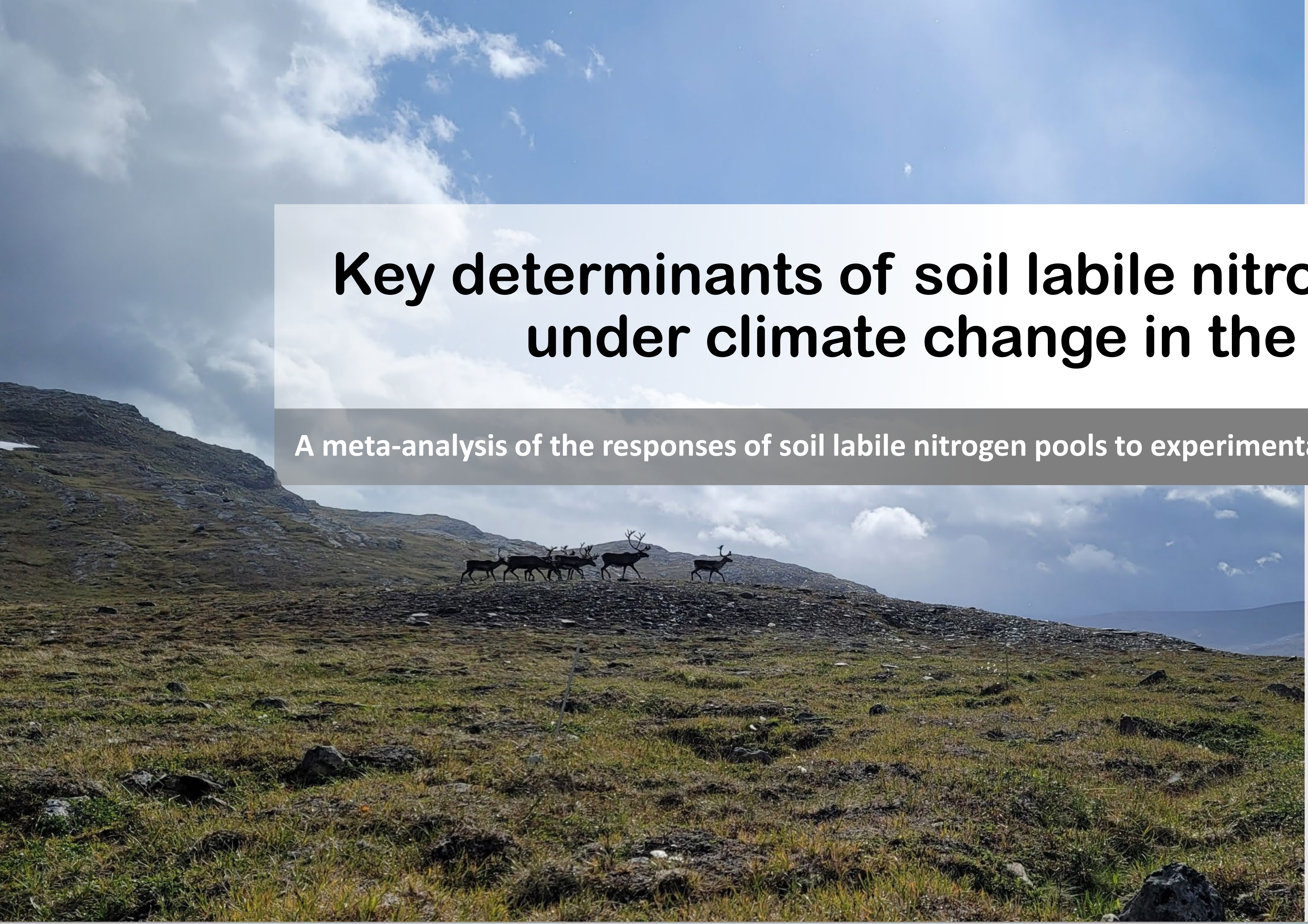


Key determinants of soil labile nitrogen changes under climate change in the Arctic

A meta-analysis of the responses of soil labile nitrogen pools to experimental warming and snow addition

<u>You Jin Kim</u> (ujin5294@kopri.re.kr)

Junge Hyun

Anders Michelsen

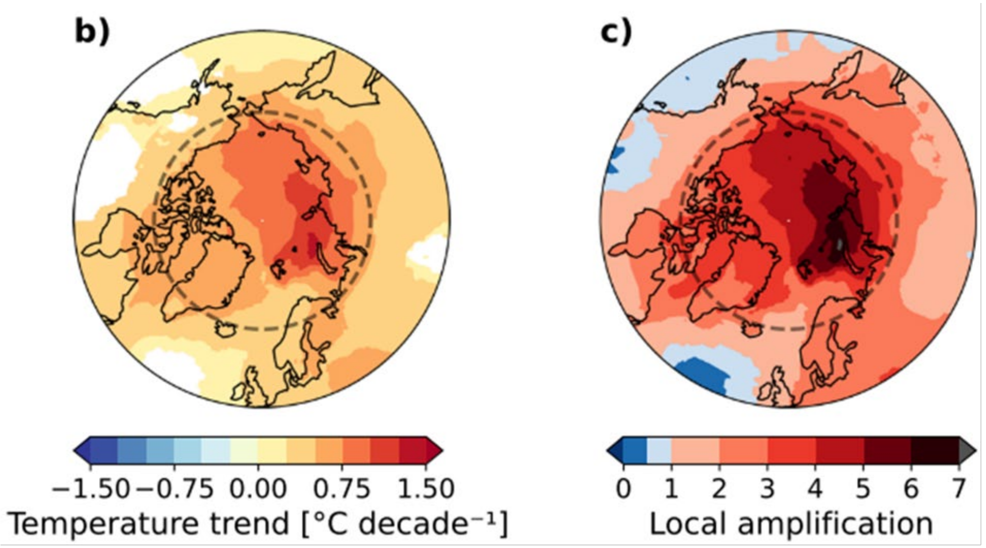
Eilhann E Kwon

<u>Ji Young Jung</u> (jyjung@kopri.re.kr)

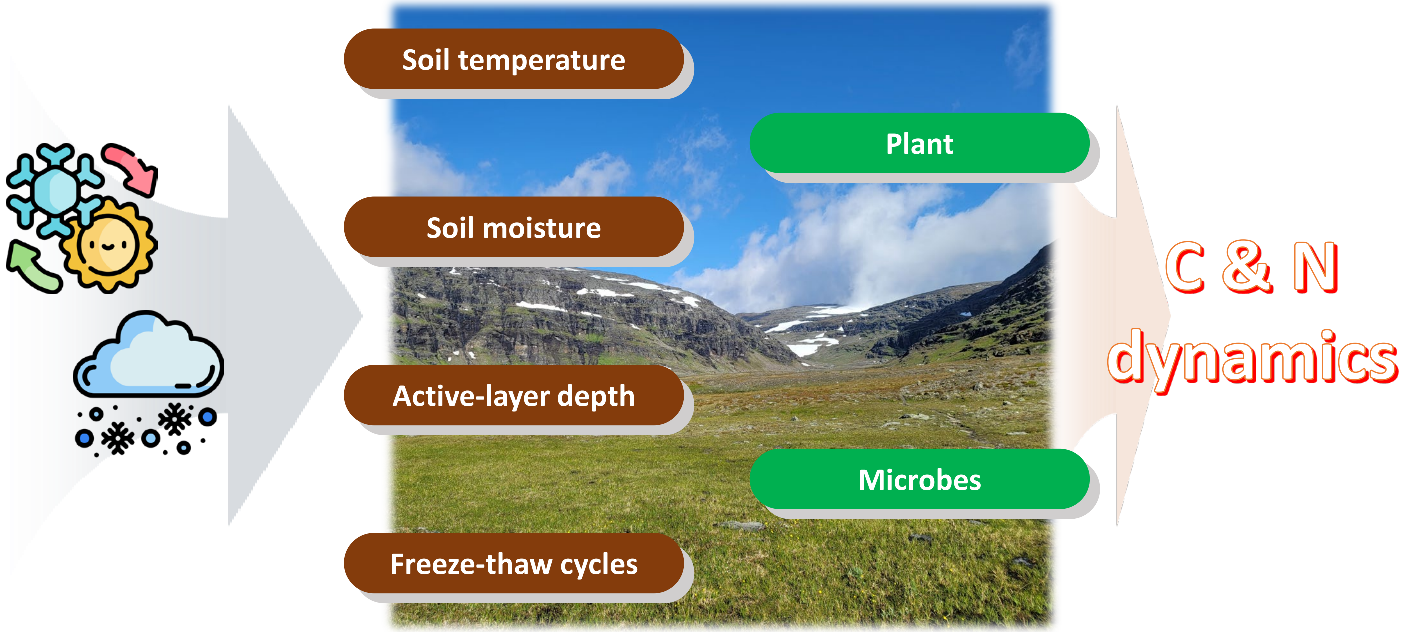
Contents

The Accelerating Warming in the Arctic

- **Unprecedented warming**: The Arctic has warming **four times faster** than the global average in recent decades.
  - Noticeable **shifts in seasonal patterns**: earlier snowmelt and soil thaw & shorter snow-cover duration
  - In some areas, **more snow** due to increased cloud formation and winter snowfall
- **Changes in Arctic terrestrial ecosystems**: Warming affects soil conditions, such as temperature, moisture, active-layer depth, and freeze-thaw cycles, leading to changes in the composition and function of Arctic plant and microbial communities.
  - **Impacts on soil biogeochemical processes**: The biotic and abiotic changes significantly influence essential soil processes, especially **carbon (C) and nitrogen (N) dynamics**.

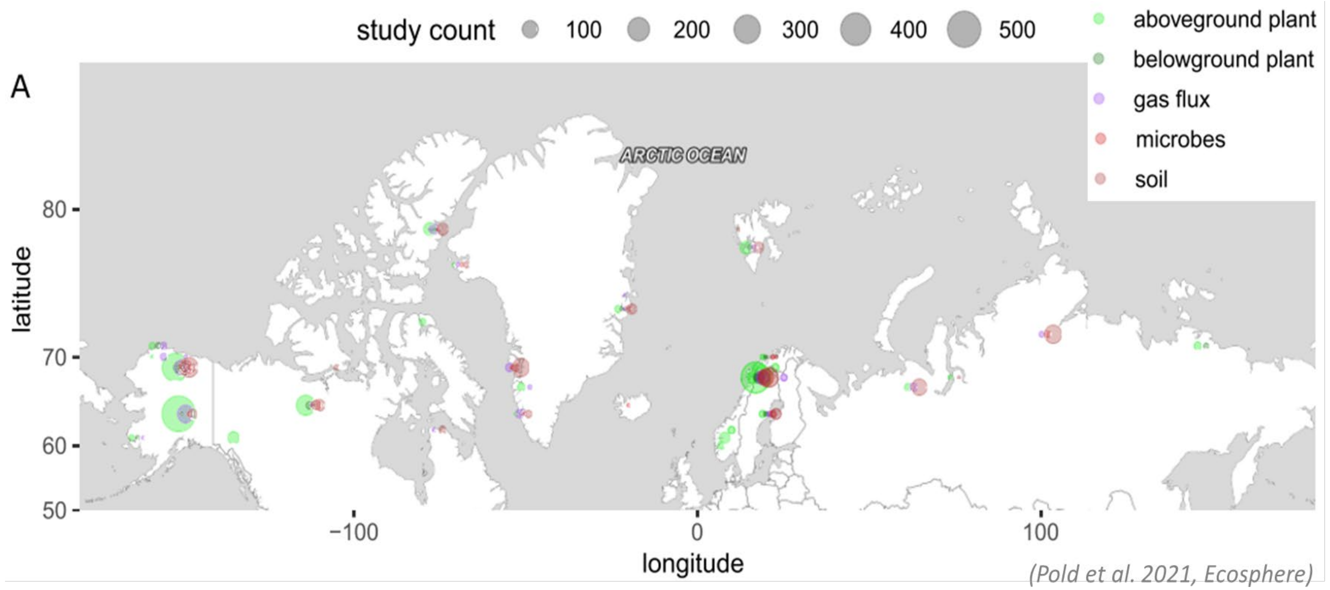


(Rantanen et al. 2022, Communications Earth and Environment)

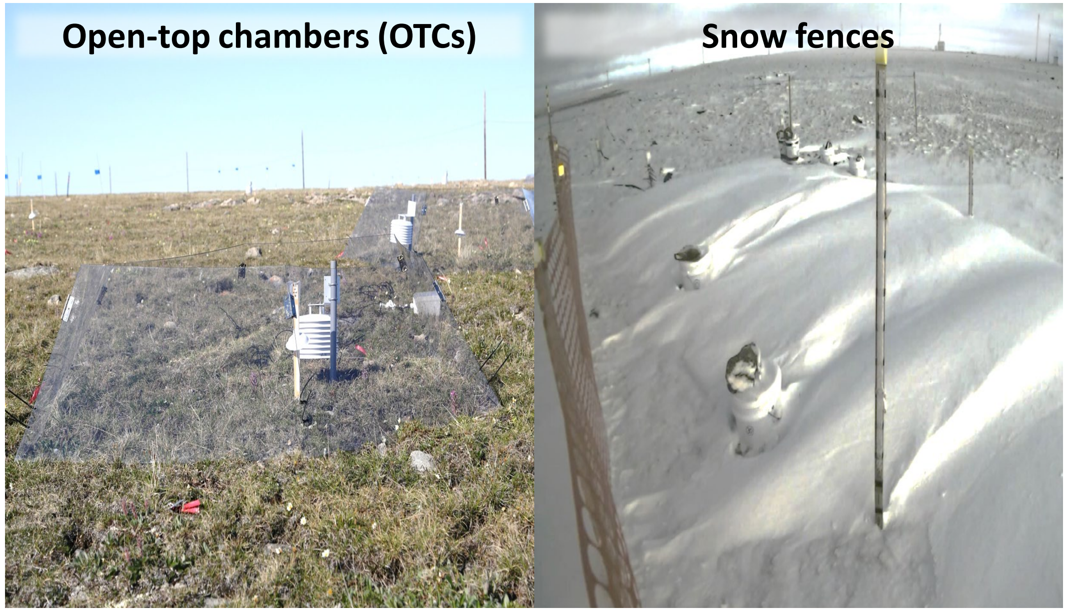


Climate Manipulation Experiments Across the Arctic

- Experimental approaches
  - **Open-top chambers (OTCs)**: To elevate soil and air temperatures by reducing wind and trapping solar energy
  - **Snow fences**: To simulate increased or decreased snow cover that affects soil insulation and meltwater availability
- Key findings from experimental warming and snow manipulations
  - Modification of soil temperature, active-layer depth, snow-free periods, and soil moisture conditions
  - Changes in the growth, structure and functions of vegetation and microorganisms
  - Significant shifts in soil C and N dynamics

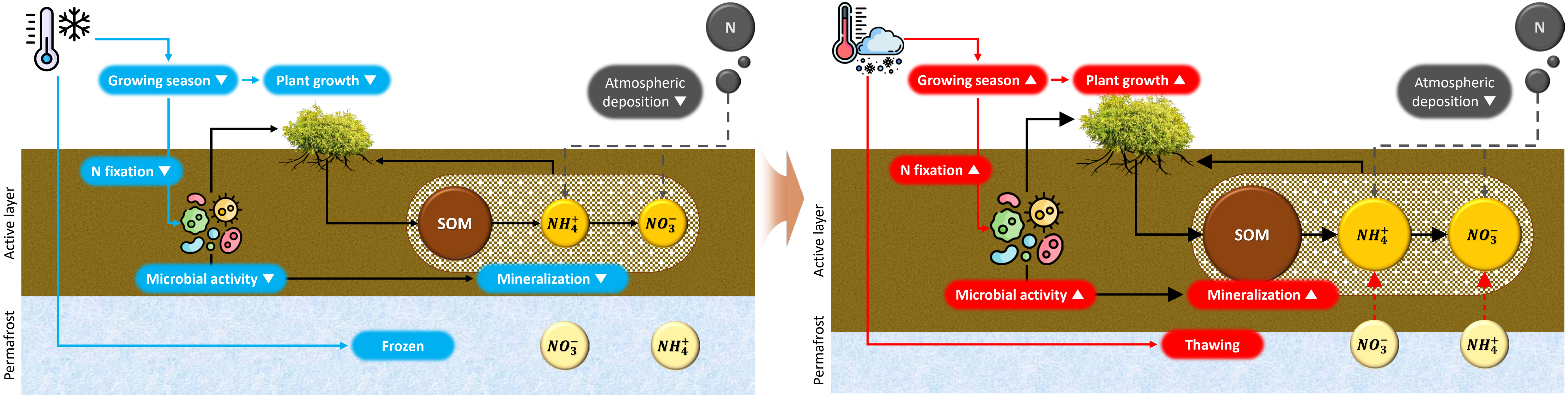


(Pold et al. 2021, Ecosphere)



Meta-analyses of Climate Manipulation Experiments

- **Meta-analyses**, synthesizing data from climate manipulation experiments, have attempted to generalize the complex responses of Arctic terrestrial ecosystems to rapid climate change, **mainly focusing on soil C stocks and dynamics**.
- **Soil N pools and their changes in Arctic terrestrial ecosystems**
  - Although a tight coupling between C and N cycling is generally believed to occur, their dynamics do not always align.
  - **Arctic N limitation**, caused by slow N transformation processes in cold climates and slow N input from deposition/fixation, is likely to intensify plant-microbe and interplant competition for N uptake, complicating the assessment of soil labile N pools.
  - **Climate manipulation experiments (experimental warming and snow manipulation) have attempted to reveal how Arctic climate change affects soil labile N pools, including dissolved-organic N (DON) and inorganic N (NH_4^+ and NO_3^-).**



Research Gap & Objectives

- Despite these efforts, **previous results from climate manipulation experiments were fragmented and controversial**.
  - Due to **the intensity, frequency, and duration of climate manipulations, influenced by specific local climates, soil conditions, vegetation types, and experimental methodologies**
- Future meta-analyses should integrate findings from diverse experiments across broad spatial and temporal scales to better understand soil labile N dynamics within Arctic terrestrial ecosystems under climate change.

In this study,

- ✓ **Data compilation**: 391 observations from 37 peer-reviewed publications to synthesize the responses of soil labile N pools in various Arctic regions to climate manipulation experiments, with a focus on experimental warming and snow addition
- ✓ **Decision tree analysis**: to explore soil labile N pool responses varied with different settings of climate manipulation experiments, such as climates, soil environments, vegetation types, and experimental methodologies

Objectives of this study,

1. **To analyze general patterns of how soil labile N pools respond to experimental warming and snow addition**
2. **To identify the key factors driving different responses among each soil labile pools**

Data Collection

- **Literature review process**
  - Using the Web of Science (apps.webofknowledge.com) for article published within the last 30 years (1995-2023)
  - Keywords: “Arctic” AND “Tundra” AND “Soil” AND (“Warming” OR “Snow”) AND (“Nitrogen” OR “Ammonium” OR “Nitrate”)

- **Selection criteria**
  1) Climate manipulation experiments conducted within the Arctic Circle (above 66.5°N latitude)
  2) Field experiments, excluding laboratory-based studies
  3) Experimental designs with warming and/or snow-added plots compared to controls under similar climate and soil conditions
  4) Studies examining the independent effects of experimental warming or snow addition, excluding the multifactorial effects
  5) Studies reporting data on the content of DON, NH_4^+, and NO_3^- in soil

Data Collection

- **Data collection**: All data were extracted from figures, tables, or the main text of the selected articles.

	Variables	Unit or Category
Soil labile N pools	Dissolved-organic nitrogen (DON)	mg/g soil
	Ammonium (NH_4^+)	
	Nitrate (NO_3^-)	
Climate	Mean annual summer temperature (MAT_{summer})	℃
	Mean annual winter temperature (MAT_{winter})	
	Mean annual precipitation (MAP)	㎜
Soil	Soil moisture	Wet for >100%, moist for 50-100%, mesic for 25-50%, and dry for <25%
	pH	Acidic for <6.5 and non-acidic for >6.5
	Soil layer	O for organic, M for mineral, and O+M for both layers
Vegetation	Vegetation type	Tussock tundra (TT), heath-dominated tundra (HE), and non-tussock without heath dominance (NT)
Experimental methodologies	Experimental duration	Years of experiment
	Climate manipulation techniques	Experimental warming: OTCs or greenhouses Snow addition: Snow fences or natural trees/shrubs
	Sampling timing	Early summer (late Jun to early Jul), peak summer (mid-Jul to mid-Aug), late summer (mid-Aug to mid-Sep), and freezing period (for all other times)
	Warming treatment periods (only for warming simulations)	Growing, year-around, and winter seasons

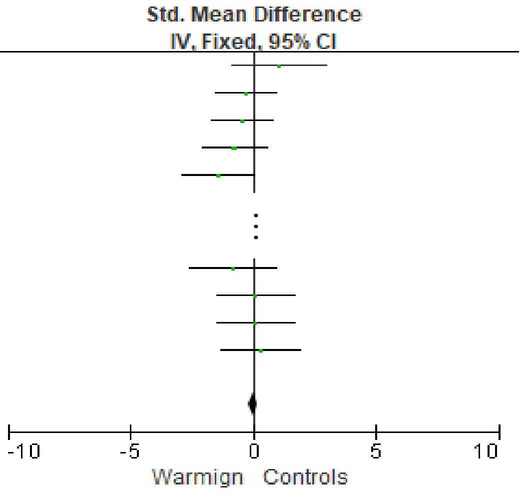
Data Analyses: Standard Mean Difference (SMD)

- Meta-analysis methodologies
  - Utilized Review Manager-5 software (RevMan-5; Cochrane Community) with a random-effects model
  - To identify the general patterns in how soil labile N pools respond to experimental climate manipulation
- **Standard mean difference (SMD)**
  - Measures the effects size of climate manipulations on soil N pools, indicating the difference between experimental and control groups relative to the pooled standard deviation in both groups
  - **The overall SMD**: weighted SMDs calculated from the means, standard deviations, and sample sizes from individual observations
- Statistical validation: p-value for significance, funnel plot analysis for literature bias, and I^2 statistics for heterogeneity

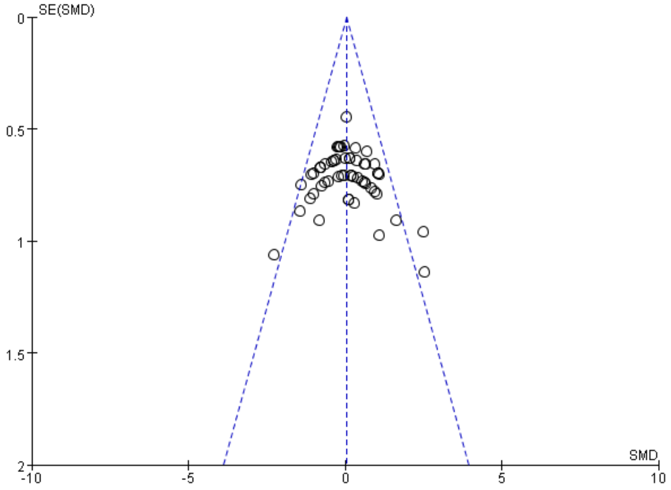
<<< Analysis results from RevMan-5 >>>

	Warming			Control				Std. Mean Difference
Study or Subgroup	Mean	SD	Total	Mean	SD	Total	Weight	IV, Fixed, 95% CI
DON01	4.883	2.94449	3	2.026	0.45033	3	0.9%	1.09 [-0.83, 3.00]
DON02	28.6	8.49706	5	36.9	35.1063	5	2.1%	-0.29 [-1.54, 0.96]
DON03	29.8	10.5095	5	44.7	41.1437	5	2.0%	-0.45 [-1.71, 0.82]
DON04	29.2	13.4164	5	76.9	77.1443	5	1.9%	-0.78 [-2.09, 0.54]
DON05	8.3	4.24853	5	41.8	30.4105	5	1.5%	-1.39 [-2.86, 0.07]
⋮								
DON56	0.26	0.0866	3	0.34	0.06928	3	1.0%	-0.82 [-2.60, 0.97]
DON57	0.29	0.22517	3	0.26	0.20785	3	1.3%	0.11 [-1.49, 1.71]
DON58	0.74	0.72746	3	0.67	0.12124	3	1.3%	0.11 [-1.50, 1.71]
DON59	0.39	0.6755	3	0.2	0.19053	3	1.2%	0.31 [-1.32, 1.93]
Total (95% CI)			**266**			**265**	**100.0%**	**0.02 [-0.16, 0.20]**

Heterogeneity: $Chi^2 = 64.89$, $df = 56$ ($P = 0.19$); $I^2 = 14\%$
Test for overall effect: $Z = 0.23$ ($P = 0.82$)



<<< Funnel plot >>>

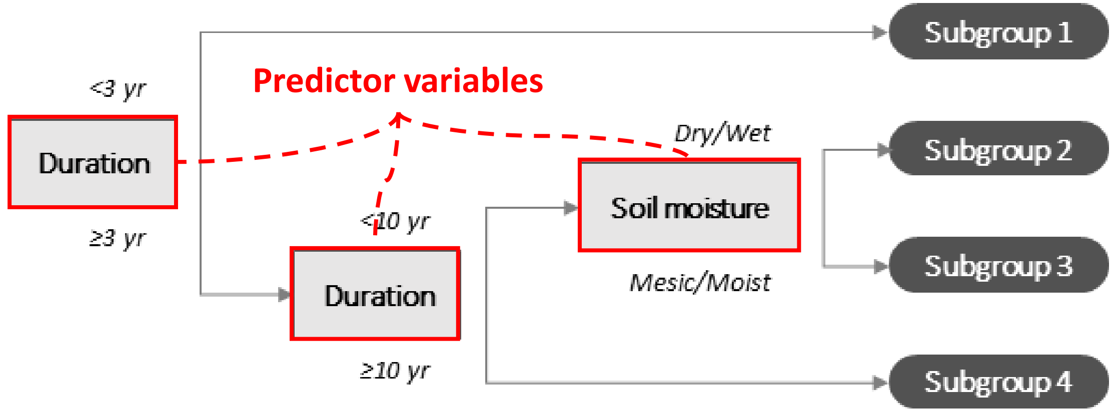


Data Analyses: Decision Tree Analysis

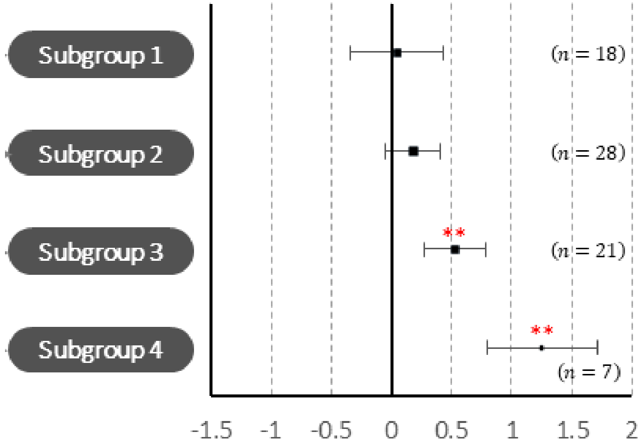
- **Decision tree analysis** = Classification & regression trees
  - Non-parametric statistical approach that segments the dataset along the predictor variables into smaller or more homogeneous subgroups through recursive partitioning
  - **To uncover factors driving the differential responses of soil labile N pools to experimental warming and snow addition, allowing the identification of meaningful subgroups**
  - Methodology
    ① The rpart package in R (version 4.2.1) for recursive partitioning and regression tree algorithm
    ⇒ “**Predictor variables = data on climates, soil conditions, vegetation types, and experimental methodologies**”
    ② A random effects model in RevMan-5 for calculating **SMD subtotals and 95% CIs for identified subgroups**

<<< Decision tree analysis >>>

For examples, **Dependent variable = $SMDs_{NH_4^+}$ from snow-added experiments**



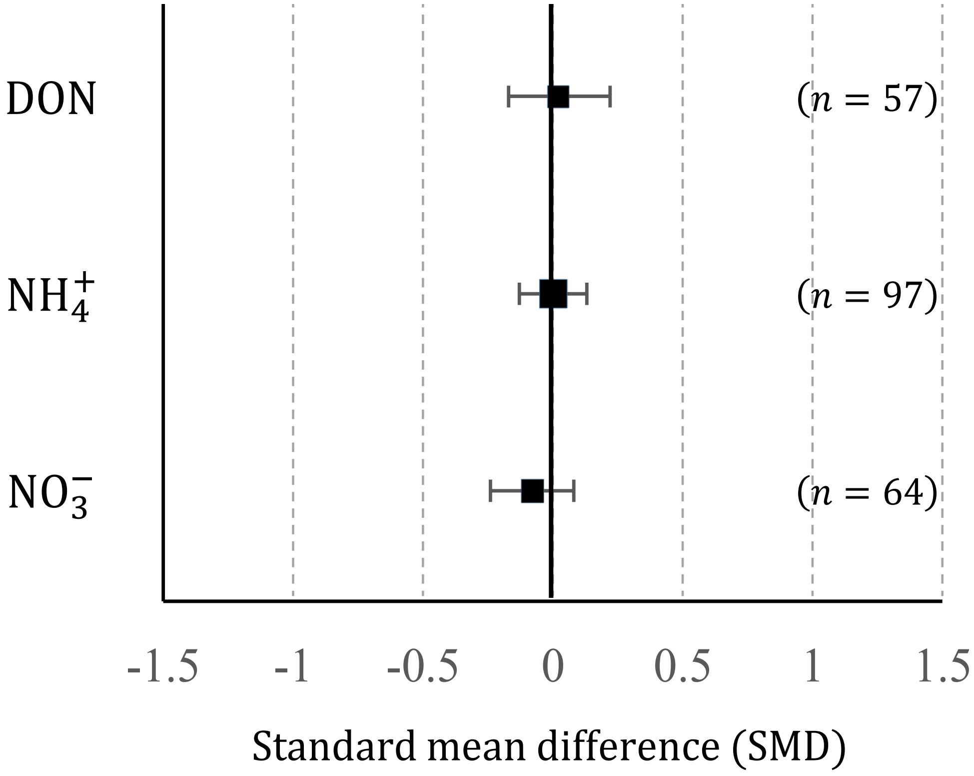
<<< SMD subtotal for identified subgroups >>>



Responses of Soil Labile N to Experimental Warming

- **No significance in the overall responses of soil labile N pools to experimental warming ≠ no impact from warming**
- **Note the diversity of the data sources**: 30 sites across seven Arctic regions, including Alaska, Canada, Finland, Greenland, Russia, Svalbard, and Sweden, leading to the variability in soil labile N pools and their responses

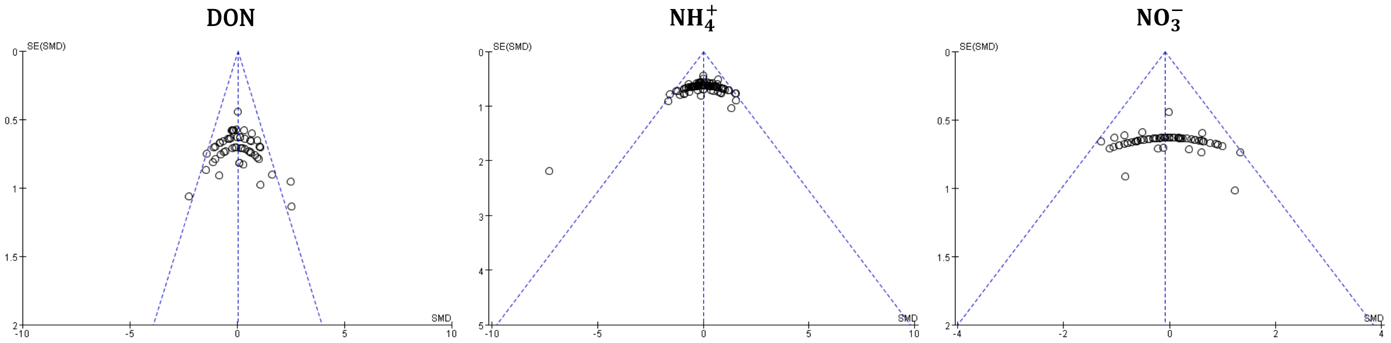
<<< Overall responses >>>



<<< Statistical validation >>>

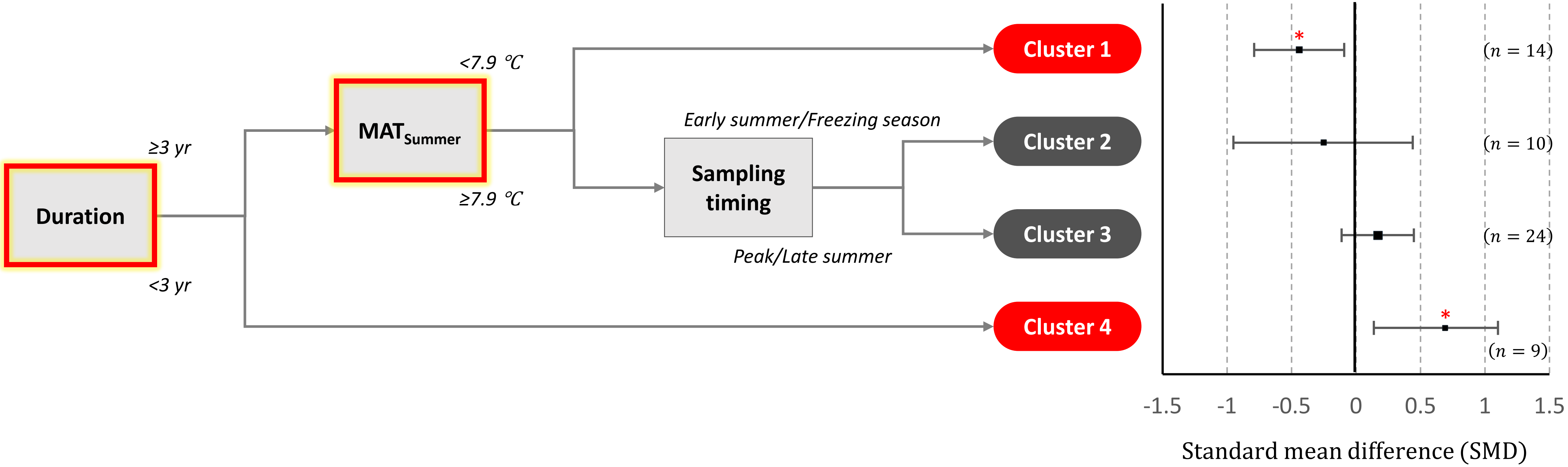
Climate manipulation	Soil N pool	I^2	P-value
Warming	DON	14%	0.81
	NH_4^+	0%	0.95
	NO_3^-	0%	0.31

- The I^2 statistic <40% is typically interpreted as low heterogeneity among the meta-data.
- The P-value represents the significance of the overall SMD at a 0.05 level.

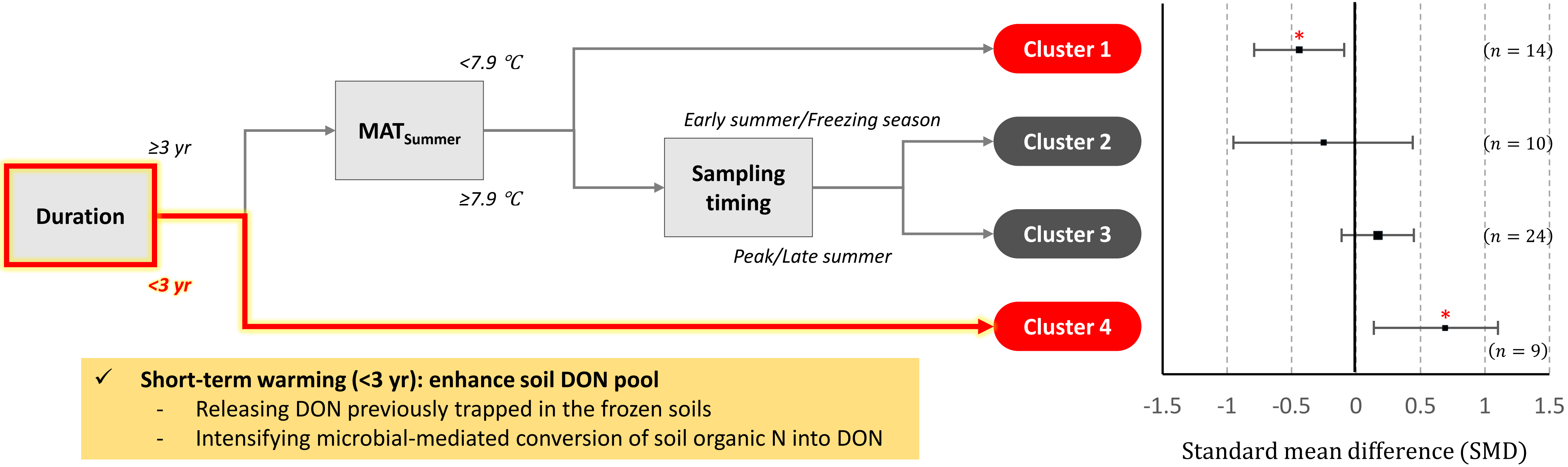


- Vertical-dashed lines = overall SMD; funnel shapes = 95% confidence level
- The presence of most observations within the funnel areas = a likely absence of literature bias

Responses of Soil DON to Experimental Warming



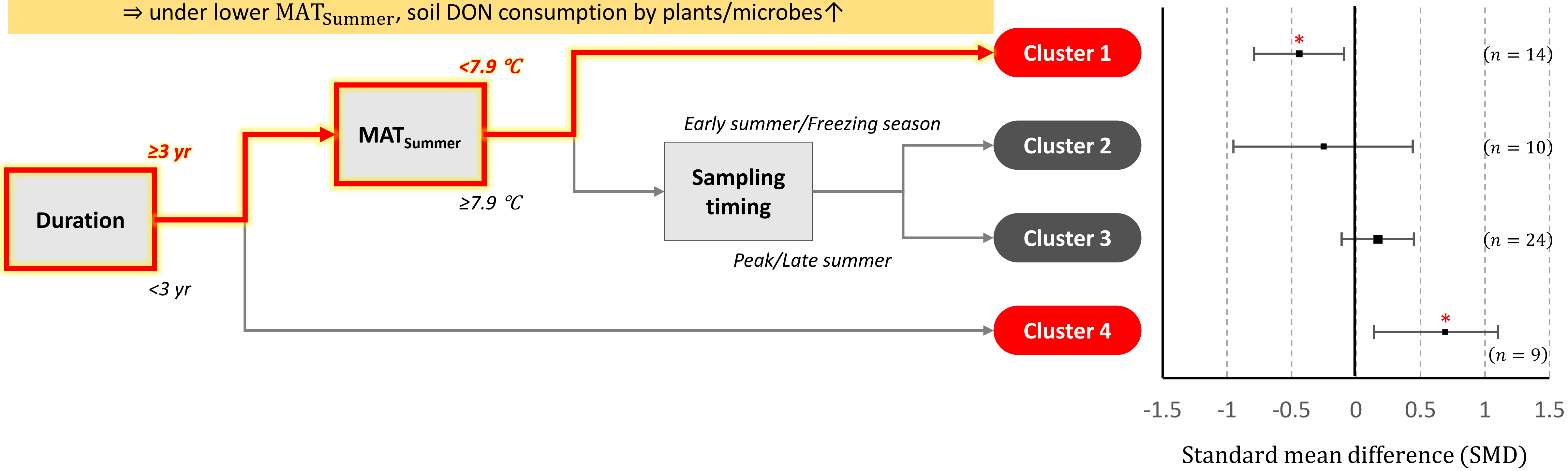
Responses of Soil DON to Experimental Warming



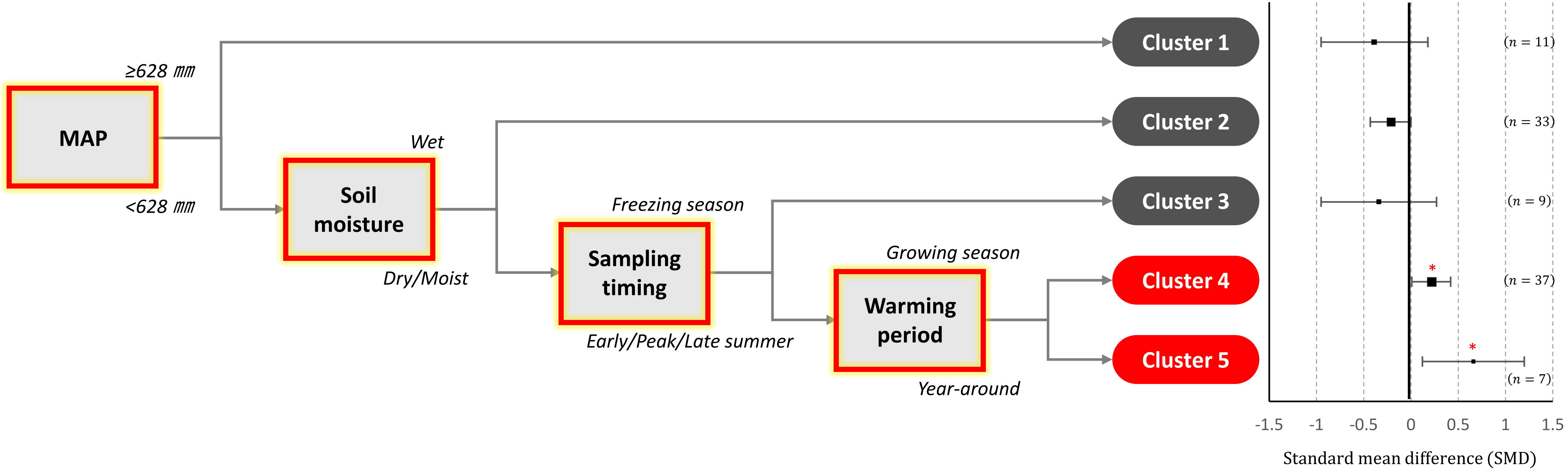
- ✓ **Short-term warming (<3 yr): enhance soil DON pool**
  - Releasing DON previously trapped in the frozen soils
  - Intensifying microbial-mediated conversion of soil organic N into DON

Responses of Soil DON to Experimental Warming

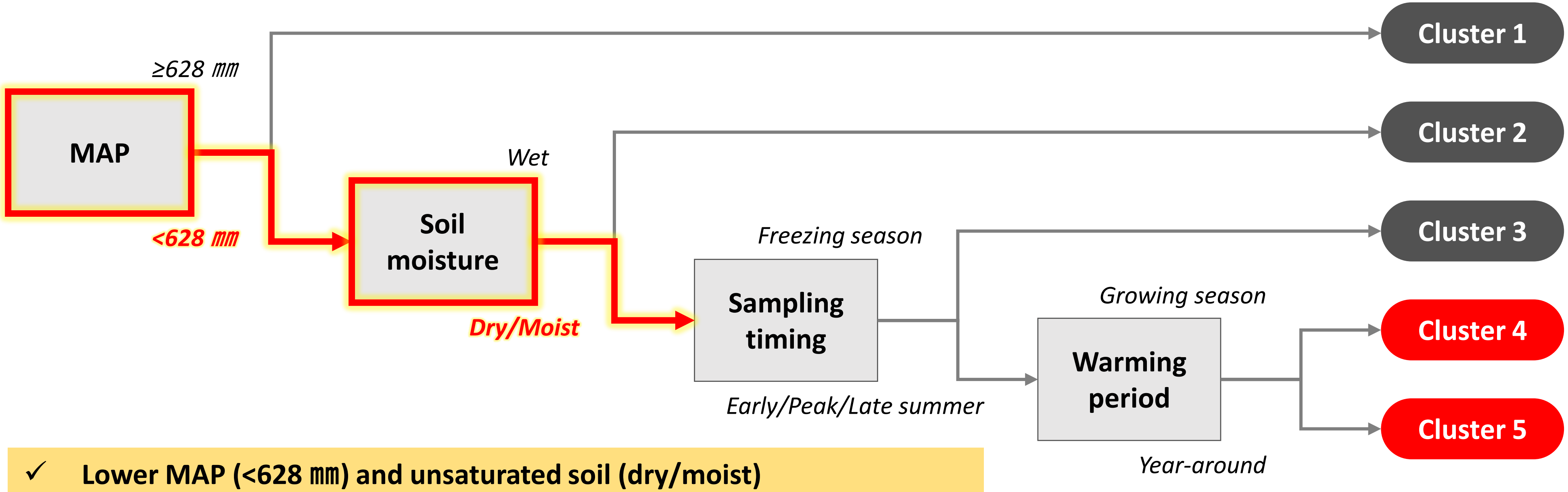
✓ **Prolonged warming (≥3 yr) & lower MAT_{Summer} (<7.9 ℃): decrease soil DON pool**
- Long-term warming ⇒ Growing season↑ ⇒ soil labile N uptake and mineralization↑
- In colder regions, plant and microbes: sensitive to temperature increases
  ⇒ under lower MAT_{Summer}, soil DON consumption by plants/microbes↑

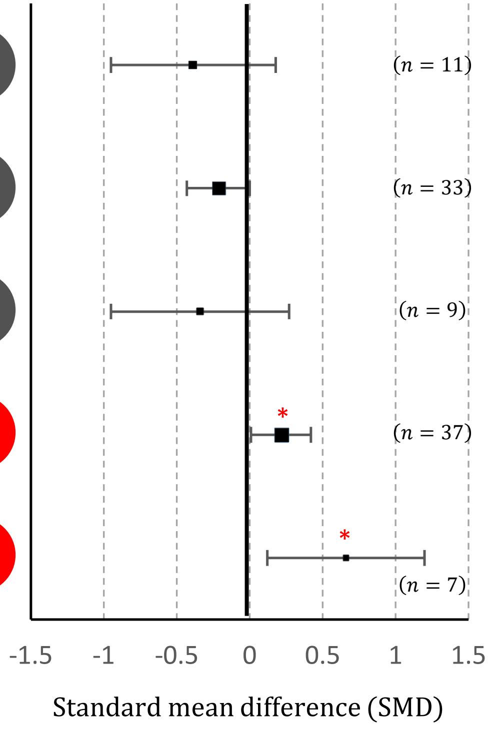


Responses of Soil NH_4^+ to Experimental Warming



Responses of Soil NH_4^+ to Experimental Warming

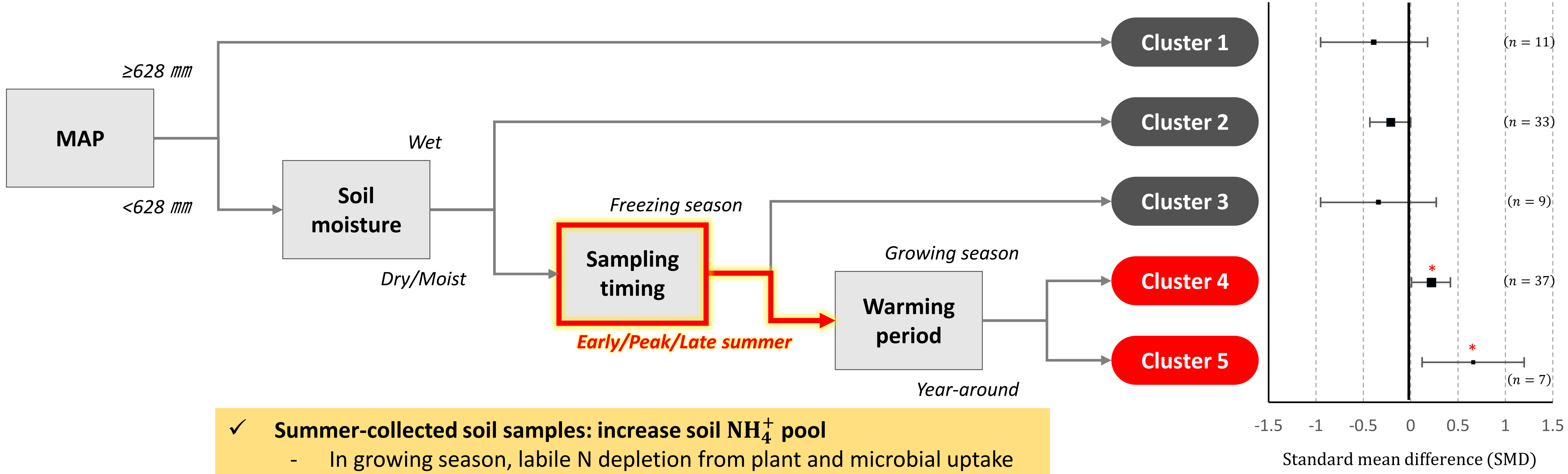




✓ **Lower MAP (<628 ㎜) and unsaturated soil (dry/moist)**

- Aerobic conditions favored for ammonification
  ⇒ possible to increases in soil NH_4^+ production owing to warming

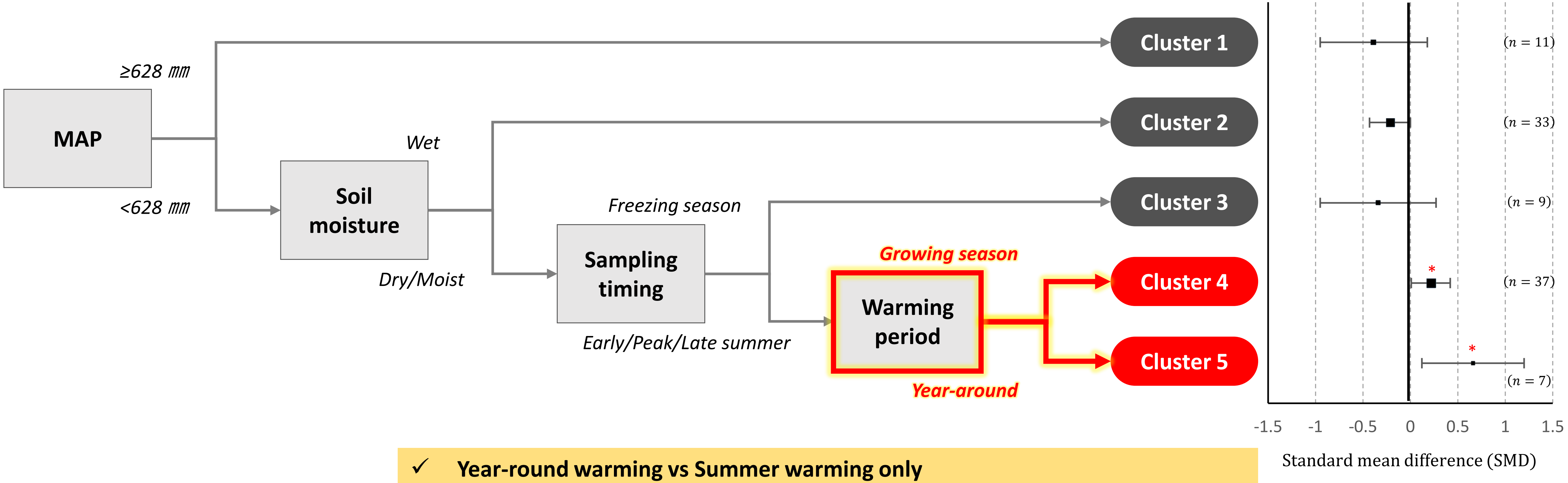
Responses of Soil NH_4^+ to Experimental Warming



✓ **Summer-collected soil samples: increase soil NH_4^+ pool**

- In growing season, labile N depletion from plant and microbial uptake ⇒ easily detectable even minor changes in NH_4^+ during summer

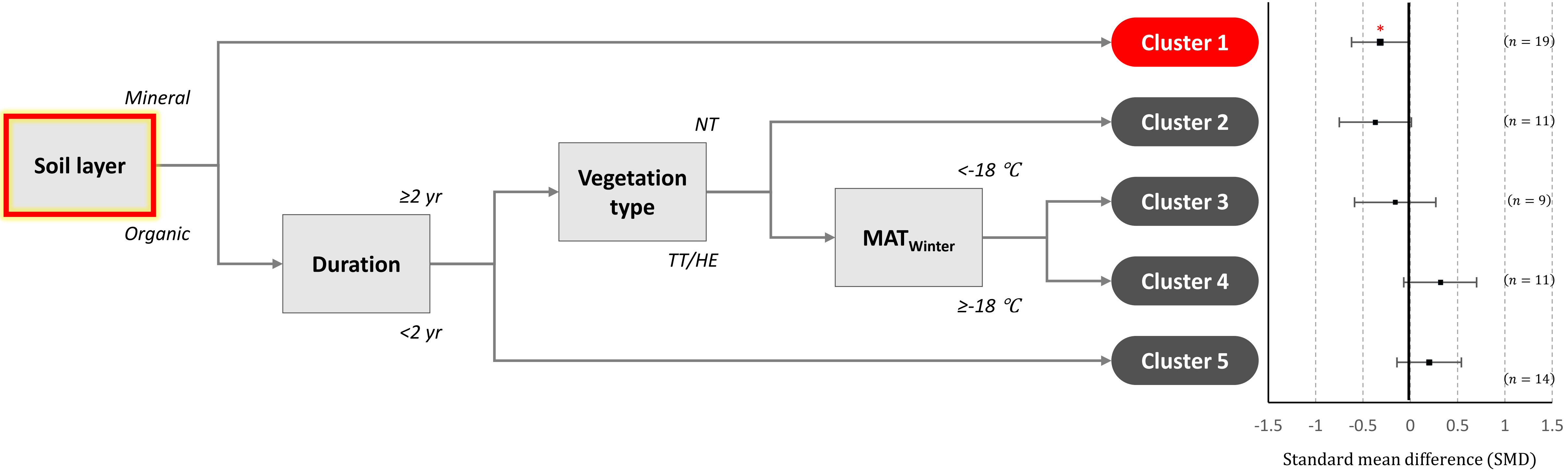
Responses of Soil NH_4^+ to Experimental Warming



✓ **Year-round warming vs Summer warming only**

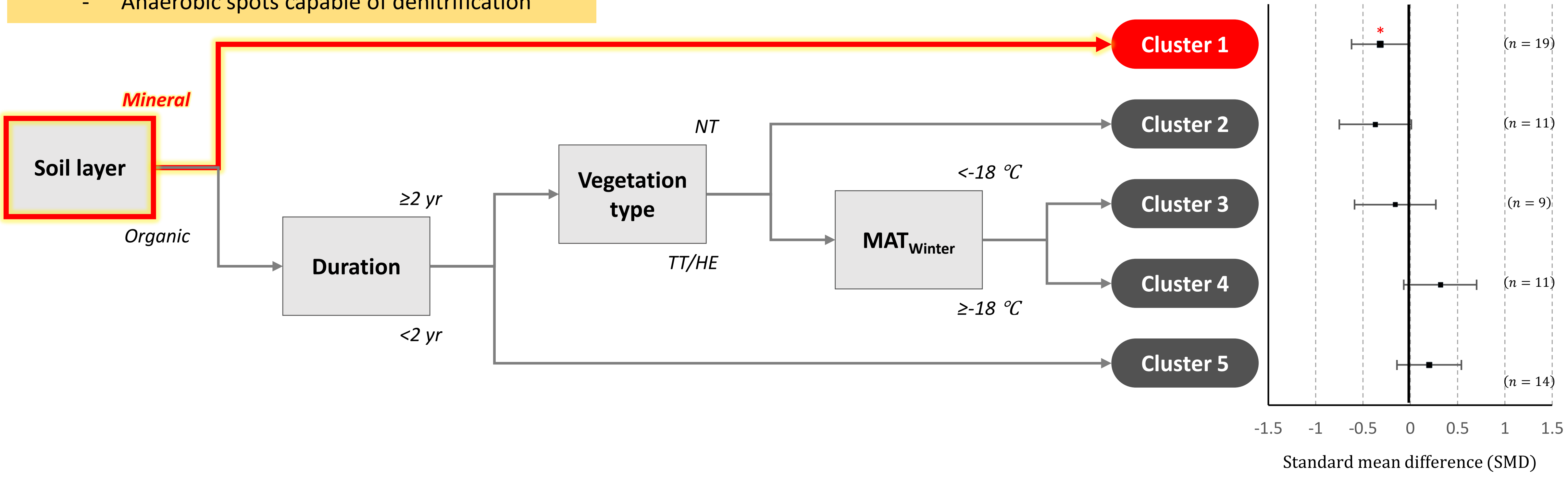
- Year-round > Summer warming: probably due to winter warming effect
- But, careful discussion on the limited data and broad confidence intervals

Responses of Soil NO_3^- to Experimental Warming



Responses of Soil NO_3^- to Experimental Warming

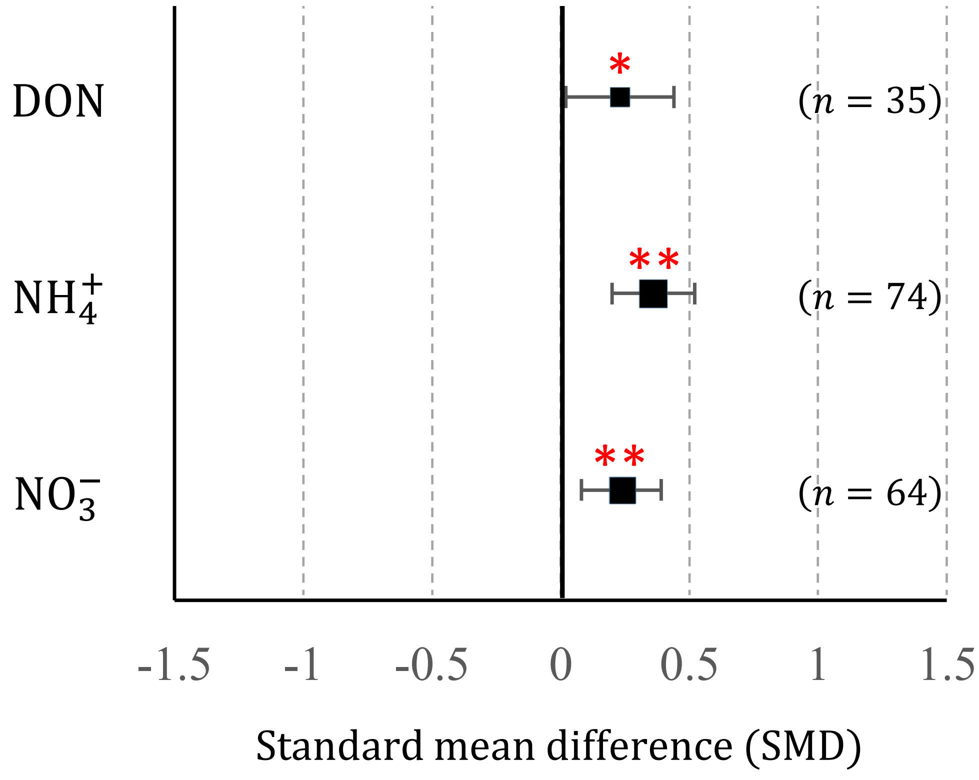
✓ **Soil M layer: decrease soil NO_3^- pool**
- Plant uptake by deepening roots with warming
- Microbial immobilization
- Anaerobic spots capable of denitrification



Responses of Soil Labile N to Snow Addition

- **Significance in the overall responses of soil labile N pools to snow addition**
- Should not overlook their responses to snow addition, as it can vary depending on the experimental and environmental conditions

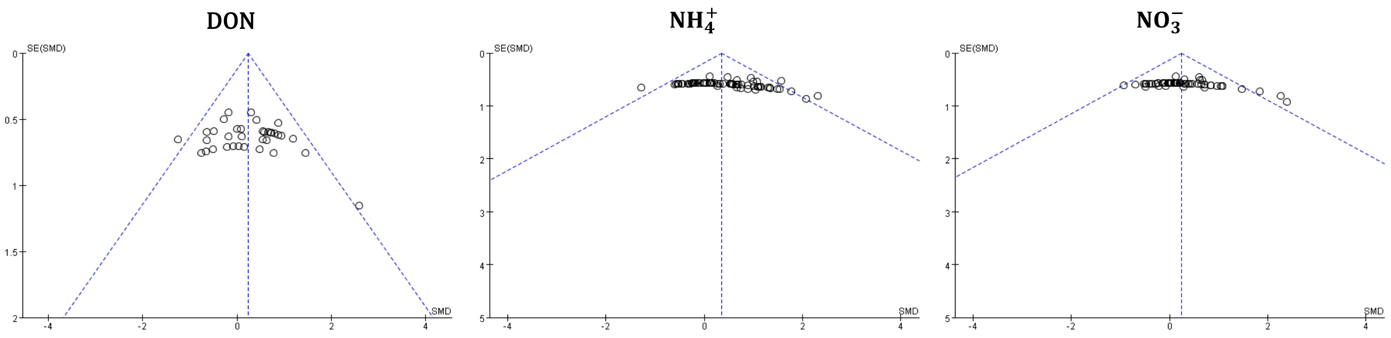
<<< Overall responses >>>



<<< Statistical validation >>>

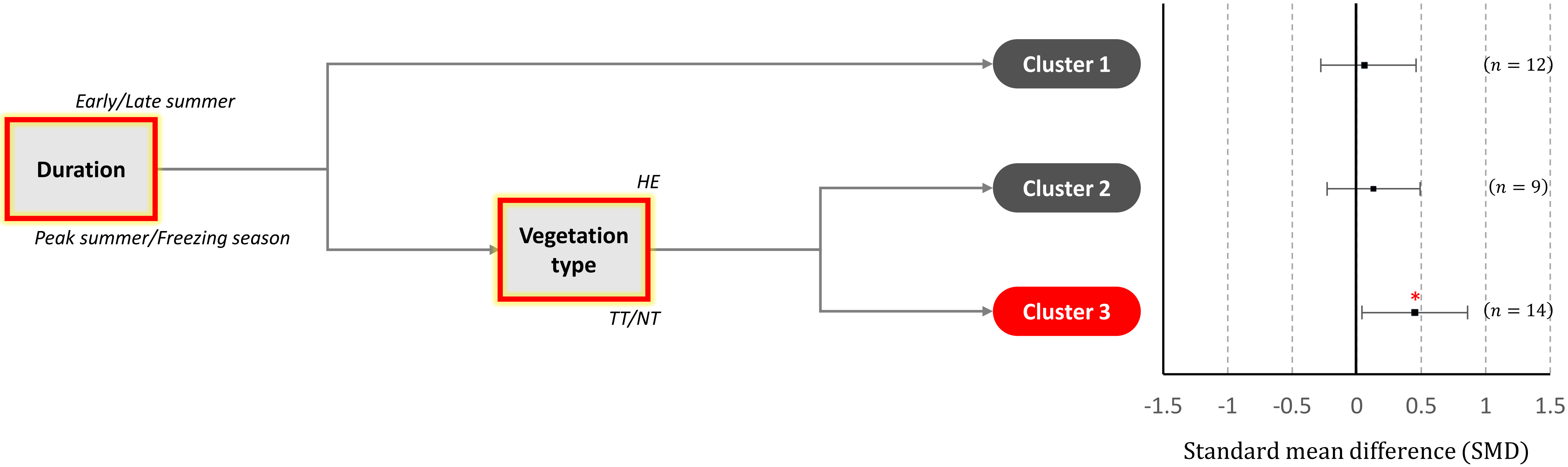
Climate manipulation	Soil N pool	I^2	P-value
	DON	4%	0.04
Warming	NH_4^+	30%	<0.01
	NO_3^-	9%	<0.01

- The I^2 statistic <40% is typically interpreted as low heterogeneity among the meta-data.
- The P-value represents the significance of the overall SMD at a 0.05 level.

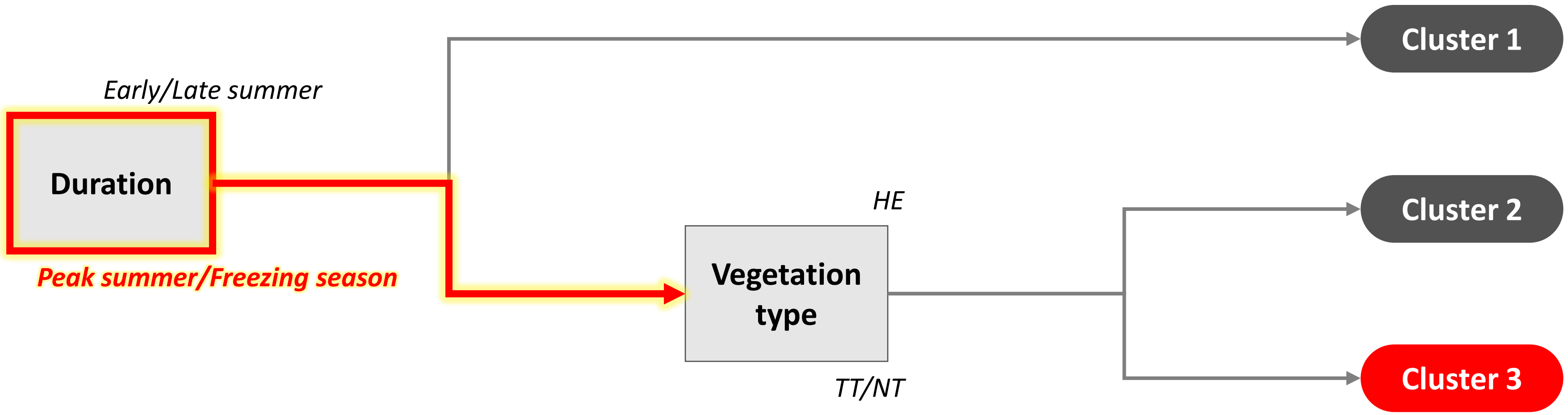


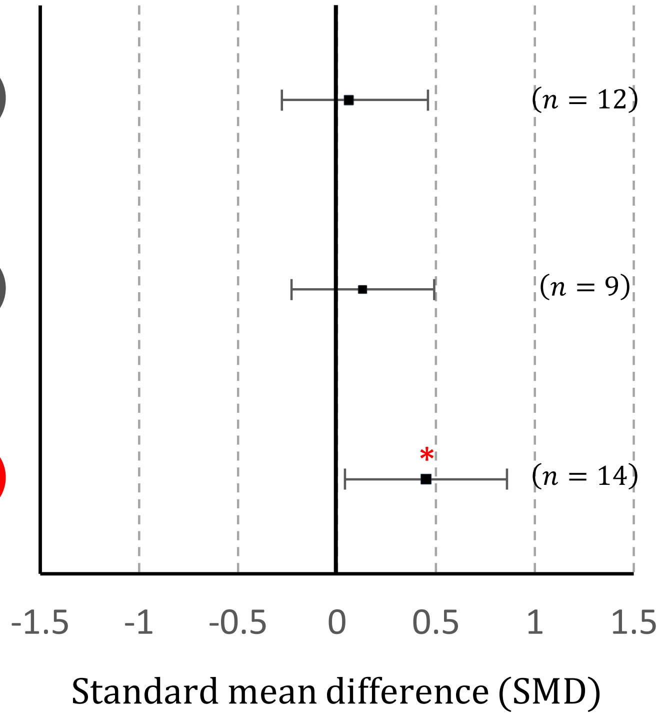
- Vertical-dashed lines = overall SMD; funnel shapes = 95% confidence level
- The presence of most observations within the funnel areas = a likely absence of literature bias

Responses of Soil DON to Snow Addition



Responses of Soil DON to Snow Addition

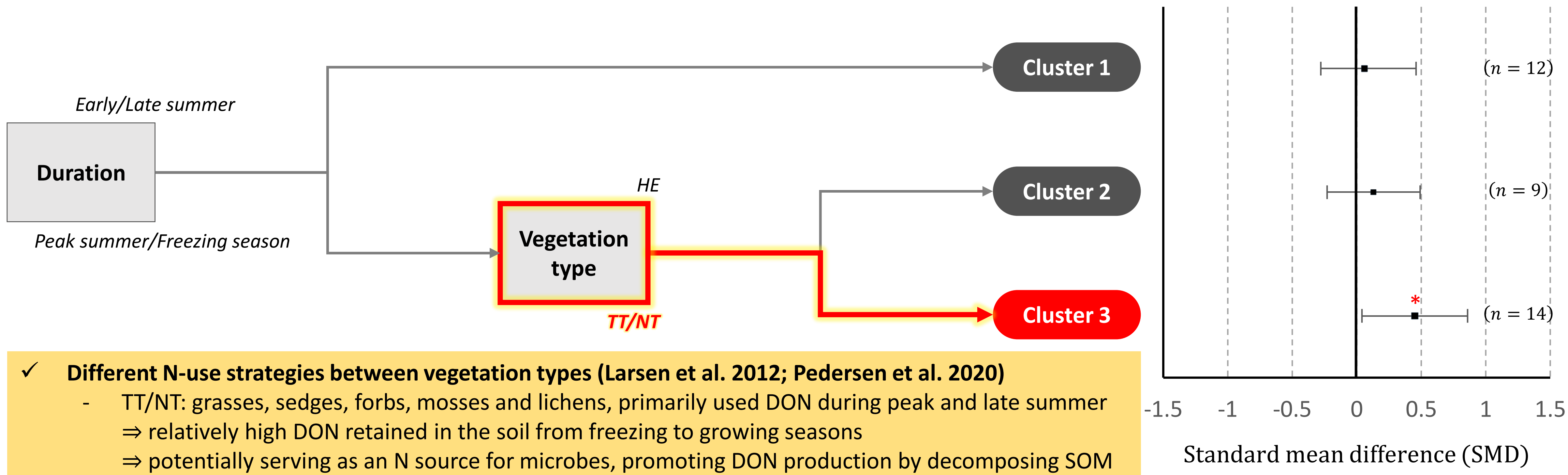




✓ **The different effects of snow addition on the Arctic soil environment**

- In winter, insulation effect on soil surface
  ⇒ a slow but steady decomposition of soil organic matter (SOM)
- In summer, natural reservoir
  ⇒ enhancing plant and microbial activity/growth, root exudation, and SOM decomposition
- In spring, flush of nutrients from snowpack & In fall, exhausted nutrients by biological uptake
  ⇒ overshadowing the effects of snow addition on soil DON

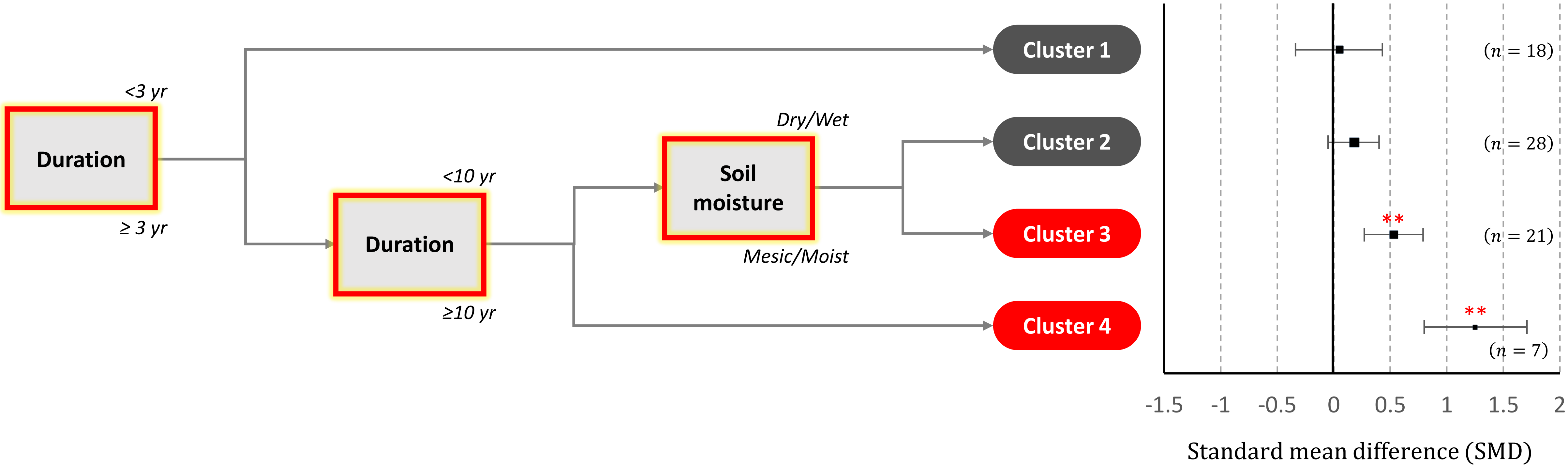
Responses of Soil DON to Snow Addition



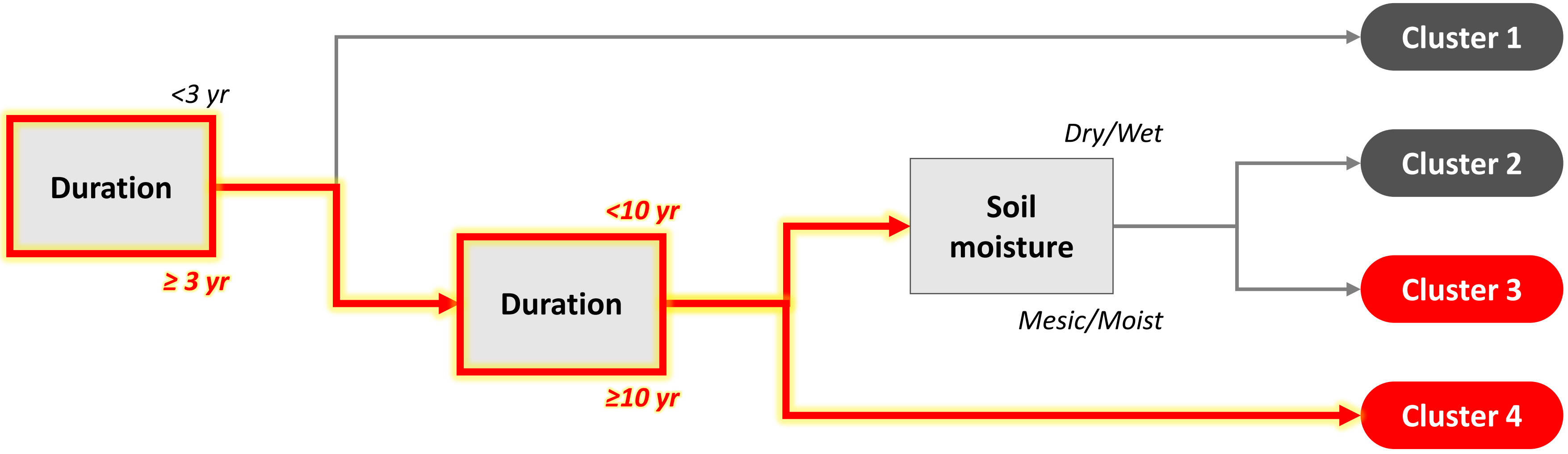
✓ **Different N-use strategies between vegetation types (Larsen et al. 2012; Pedersen et al. 2020)**

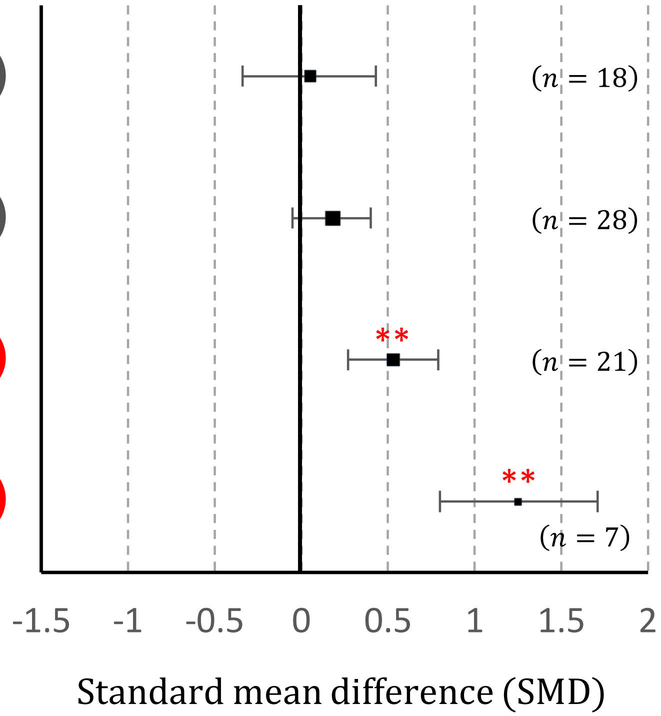
- TT/NT: grasses, sedges, forbs, mosses and lichens, primarily used DON during peak and late summer
  ⇒ relatively high DON retained in the soil from freezing to growing seasons
  ⇒ potentially serving as an N source for microbes, promoting DON production by decomposing SOM
- HE: evergreen/deciduous shrubs, used DON in spring or early summer
  ⇒ intensifying N competition with microbes
  ⇒ potentially obscuring soil DON increases from snow addition

Responses of Soil NH_4^+ to Snow Addition



Responses of Soil NH_4^+ to Snow Addition

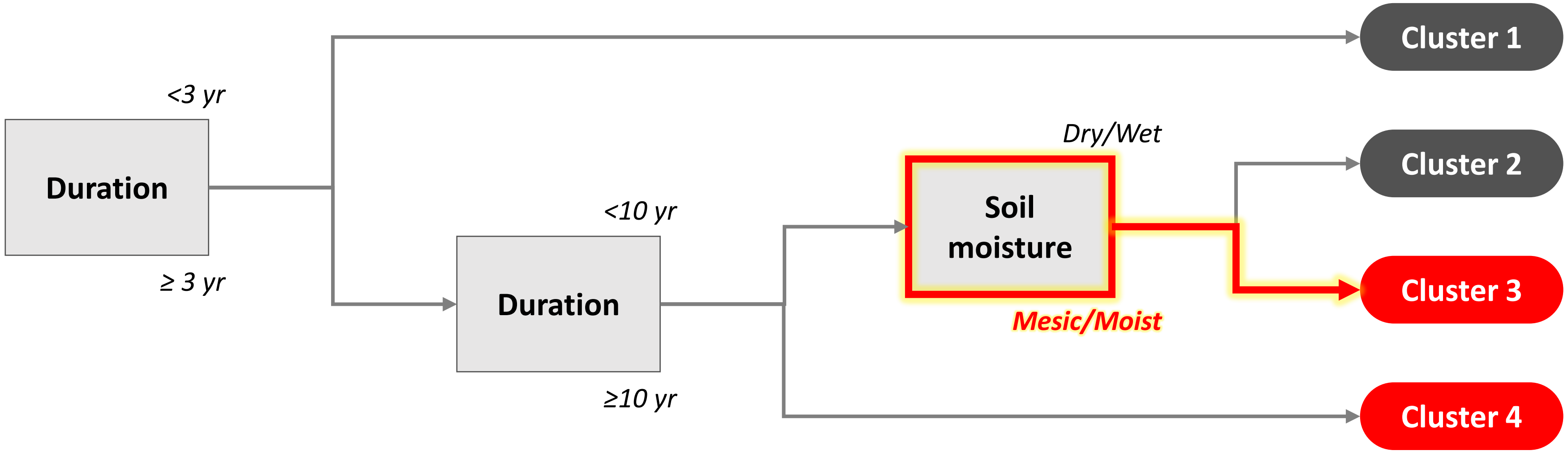


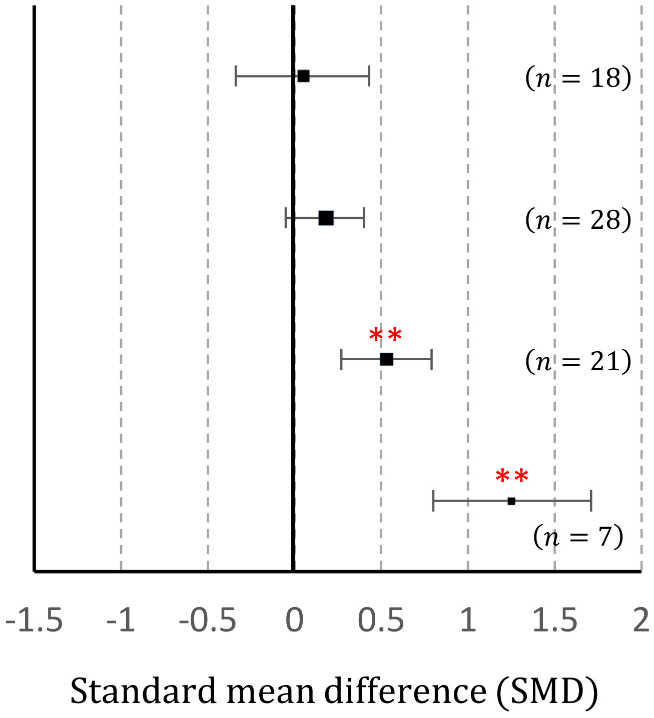


✓ **Experimental duration**

- Significant increases in its subgroups involving snow-added experiments lasting 3-10 years
- A more pronounced increase in its subgroups prolonged experiments exceeding 10 years, but limited number of observations and wide range of confidence intervals

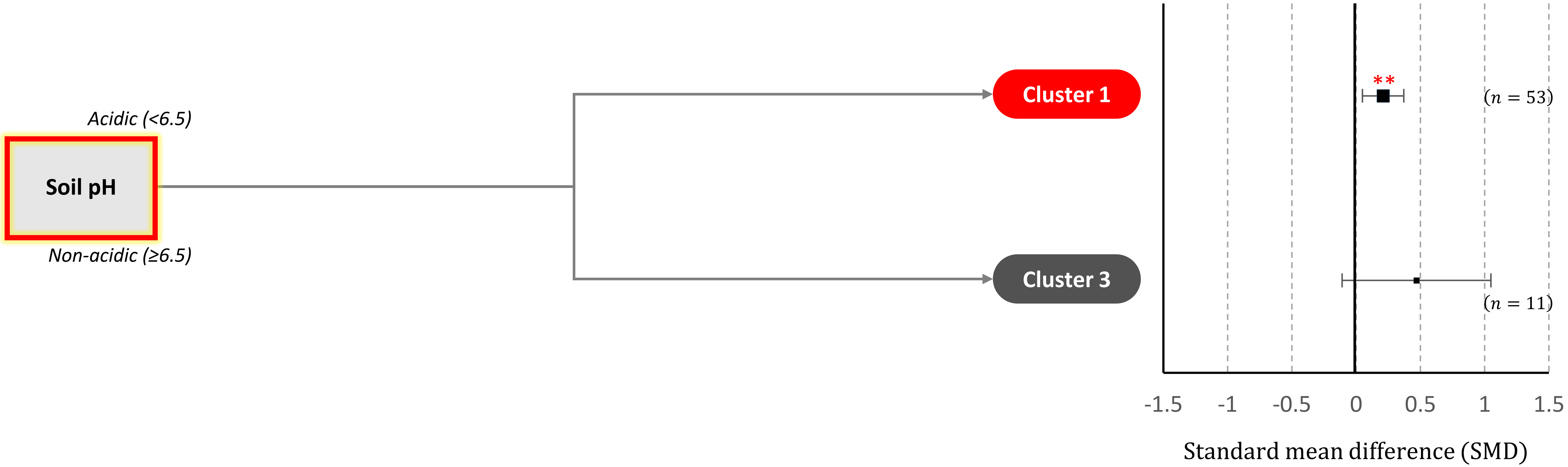
Responses of Soil NH_4^+ to Snow Addition





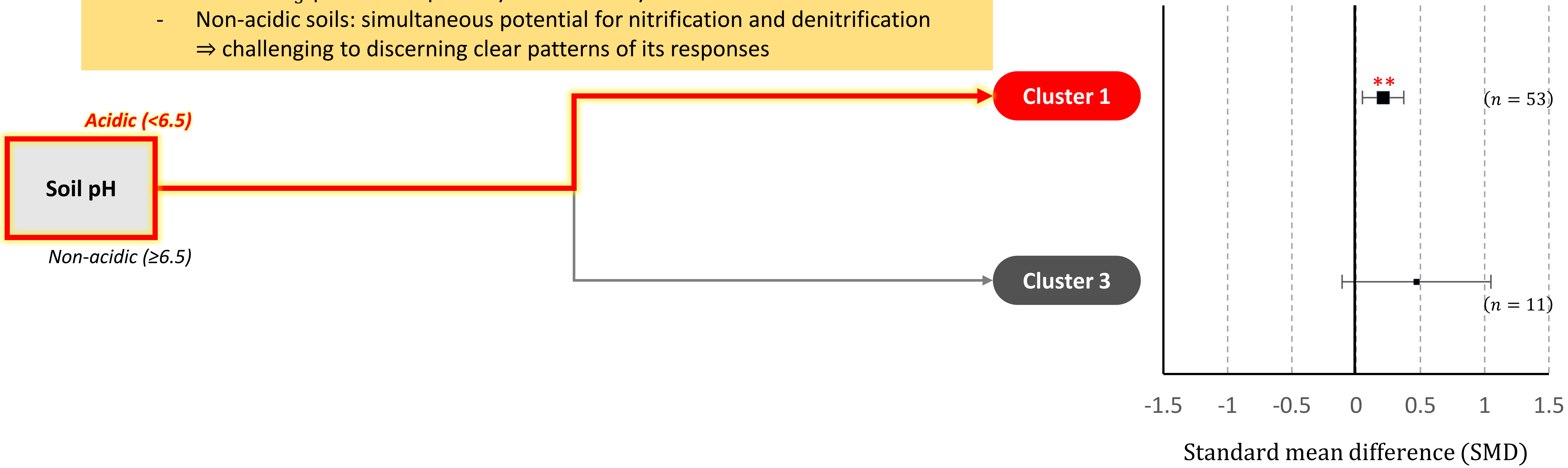
- ✓ **Under 3-10 yr warming, the mesic and moist soil conditions: increase in soil NH_4^+ pool**
  - Under dry conditions, water limitation ⇒ lower N mineralization
  - Under wet conditions, less variability in soil temperature in response to climate manipulation

Responses of Soil NO_3^- to Snow Addition



Responses of Soil NO_3^- to Snow Addition

✓ **Nitrification vs denitrification under acidic soil conditions**
- Acidic soils: favored archaeal nitrification, but not optimal pH for denitrification
  ⇒ soil NO_3^- production possibly stimulated by snow addition
- Non-acidic soils: simultaneous potential for nitrification and denitrification
  ⇒ challenging to discerning clear patterns of its responses



Implications and recommendations for future research

- **Emphasizing that soil labile N responses to climate change are contingent on the inherent complexity of Arctic tundra ecosystems**
  - **Climatic (MAT_{Summer} and MAP)** and **soil (moisture, pH, and layer)** conditions are key factors that determine the overall/specific processes related to soil labile N dynamics, providing environments sensitive to climate manipulations.
  - **Vegetation types** may lead to different N-use strategies, resulting in diverse responses of soil labile N to climate manipulation.

- **The settings of experimental methodologies drive significant changes in soil labile N pools.**
  - **Experimental duration**: initial vs prolonged response of soil DON and NH_4^+ pools to experimental warming and snow addition
    ⇒ Despite its importance, there is a scarcity of empirical observations extending beyond 10 years
  - **Warming treatment period**: year-round vs summer warming to soil NH_4^+ pool
    ⇒ The need for additional warming experiments that encompass both growing and non-growing seasons
  - **Sampling timing**: seasonal fluctuations in soil labile N pools in Arctic tundra ecosystems
    ⇒ Essential for periodic and dense high-frequency sampling

- Finally, while our results focused on the net changes in labile N forms remaining in the soil, **their fluxes** should be investigated to reveal how N pools are influenced by climate change.

Thank you