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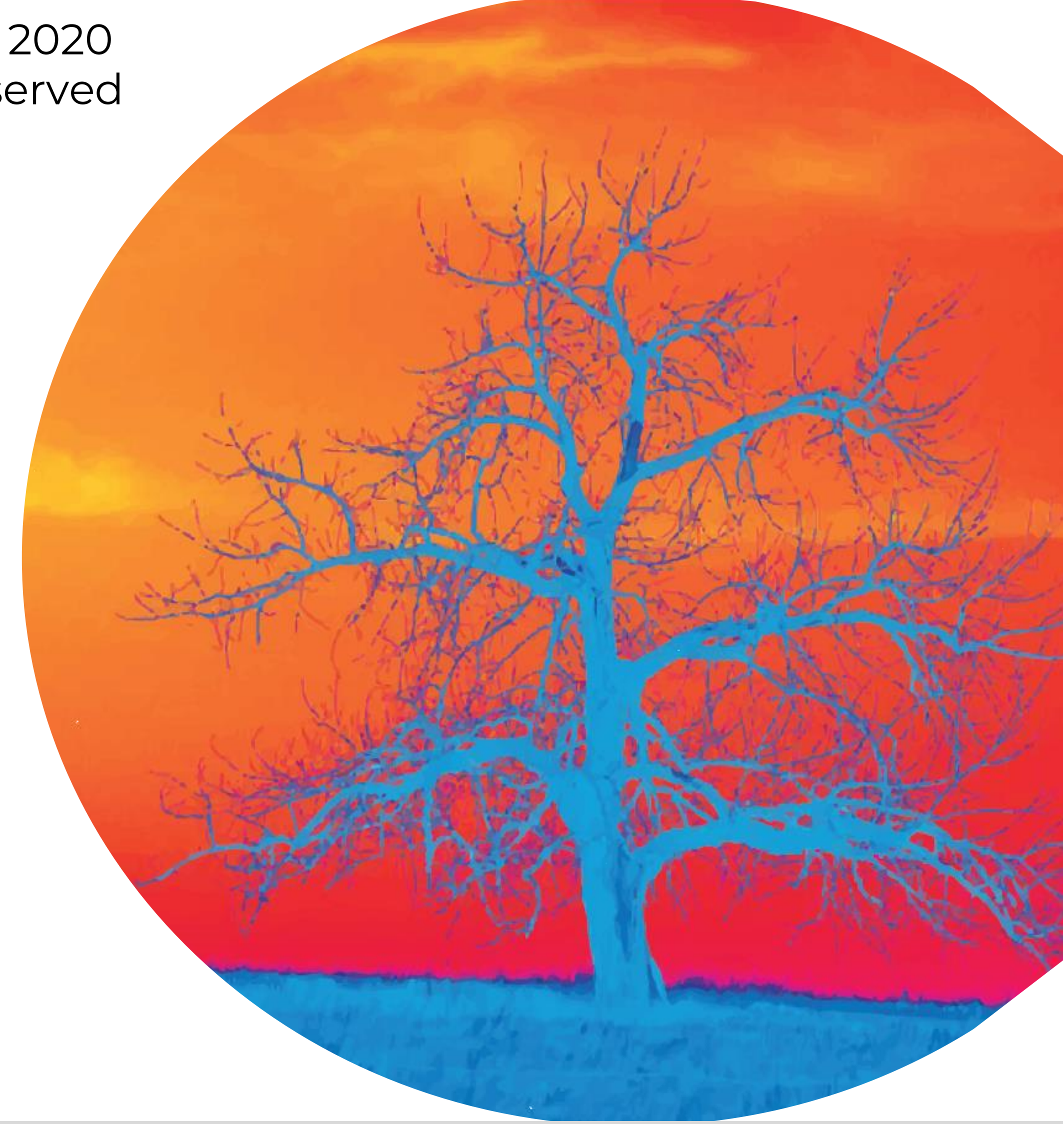
Plant Thermal Tolerance:
An overview of current methodological approaches & the difficulties in moving from metrics to models



Review submitted to *New Phytologist*

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Plant thermal tolerance

Temperature is a key determinant of species adaptation & distribution

Past research focuses on:

- Crop development for food
- Fundamental ecological insights
- Predict individual species responses

BUT knowledge is scattered across research fields and interests

Defining plant thermal tolerance?

Variable approaches to exploring thermal tolerance may lead to

Studies may investigate…

heat tolerance ⟷ cold tolerance ⟷ both

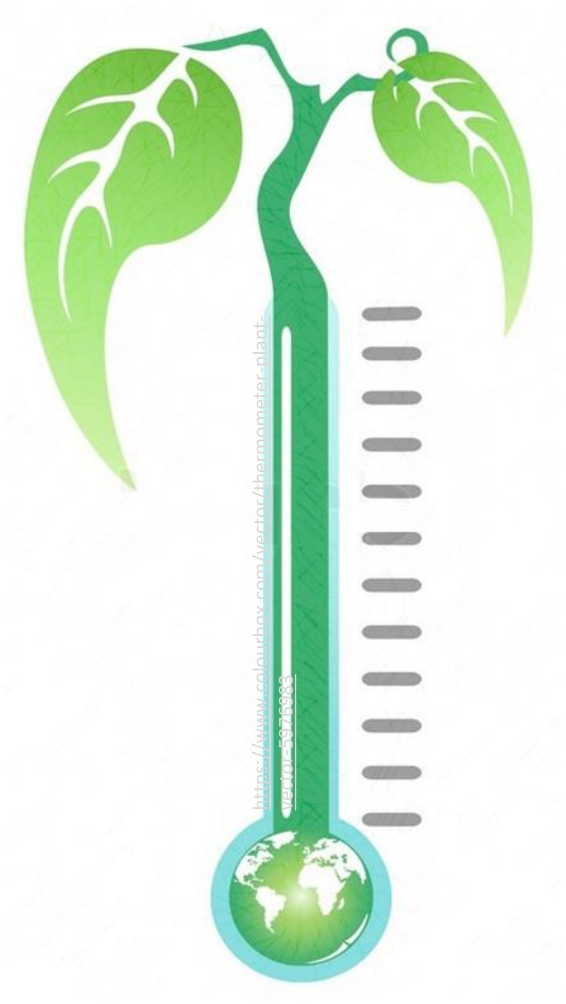
subjective estimates ⟷ in-depth physiological studies

entirely natural conditions ⟷ growth chambers

gradually applied thermal stress ⟷ one-off shock treatments

highly specific assays ⟷ thermal metrics/thresholds

Our Objectives

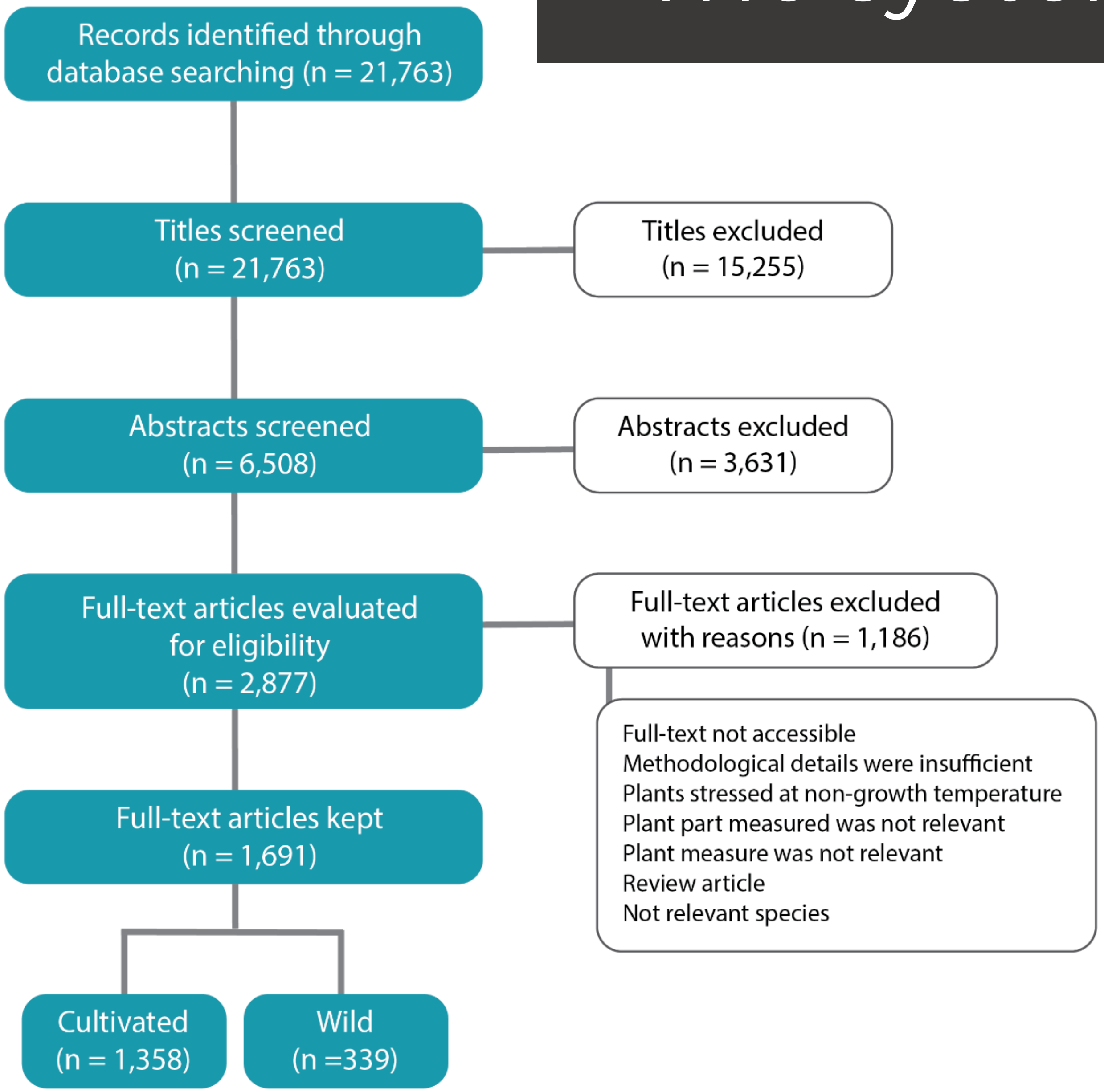


To determine the distribution of thermal tolerance studies **that measured the tolerance of photosynthetic tissues of land plants to extreme temperatures** for both cultivated and wild species across life forms, biomes and the globe.

To reveal knowledge gaps, ambiguities and commonalities in plant thermal tolerance research.

To identify emerging techniques and opportunities for addressing plant species persistence under increasing temperature extremes.

The systematic review process



Evidence synthesis is rapidly becoming a valuable research tool

Nakagawa et al. 2020

Systematic reviews use explicit search strategies, and criterion based selection procedures to provide an unbiased overview of a research field

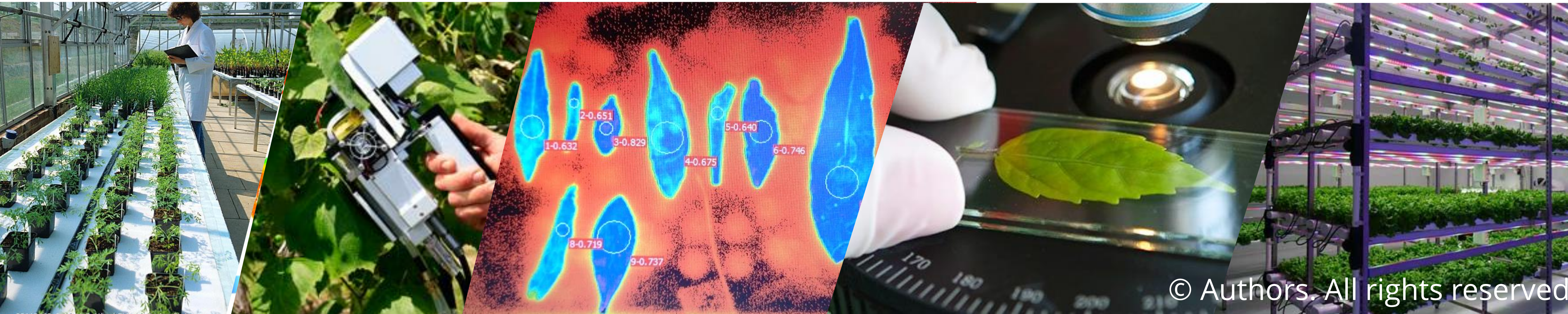
Haddaway et al. 2015

Our review process ultimately led to **1,691 unique studies** being included in the final analysis, comprising **3,743 records of thermal tolerance technique** use

Assessment Criteria

1) Whether the article dealt with **cultivated or wild species**;
2) Whether the assay investigated **heat, cold, or both**;
3) The **diversity of the species** measured in the study;
4) For papers on cultivated species – the **type of cultivation**;
5) For wild species – the **biome** of origin;
6) The **life forms** of species;
7) The **thermal tolerance technique(s)** used;
8) The **nature of the thermal stress** applied in the experiment (manipulated or natural);
9) Whether **other experimental factors** (water, light, etc.) were considered;
10) Whether a **thermal metric was reported** for the technique(s);
11) Whether **stress temperature was gradually ramped, applied as a shock during thermal assay(s)**;
12) The **maximum duration** of the thermal assay;
13) Whether the thermal assay was **repeated**

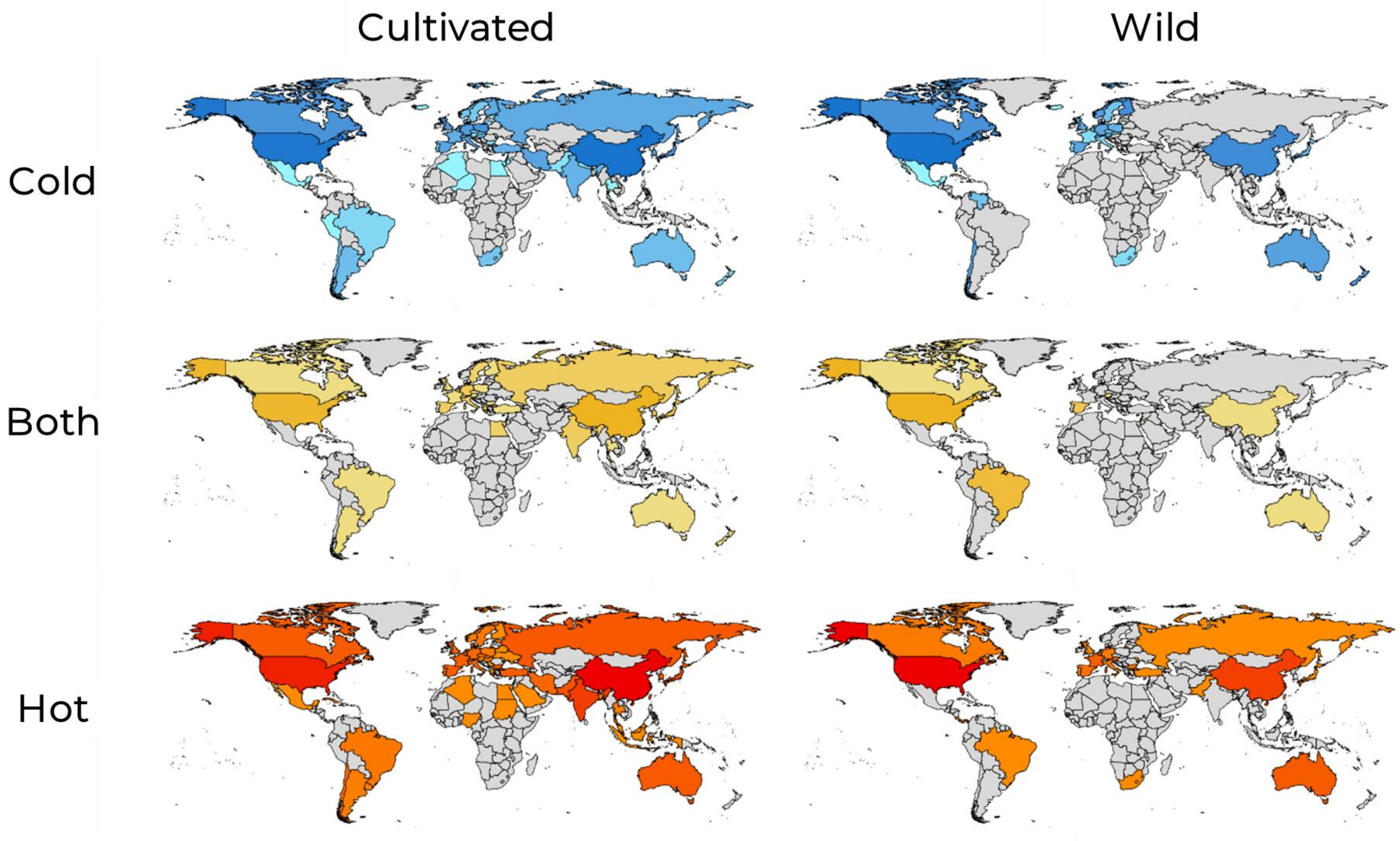
Highlighted outcomes



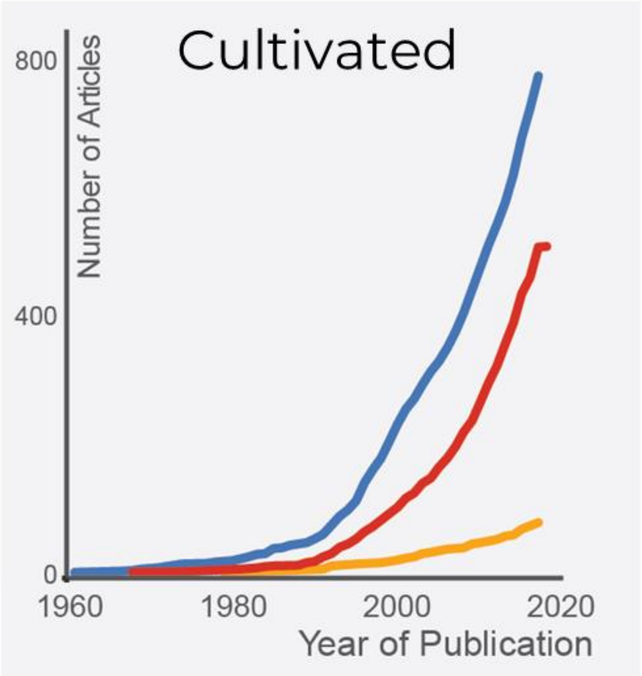
Global distribution of the research field

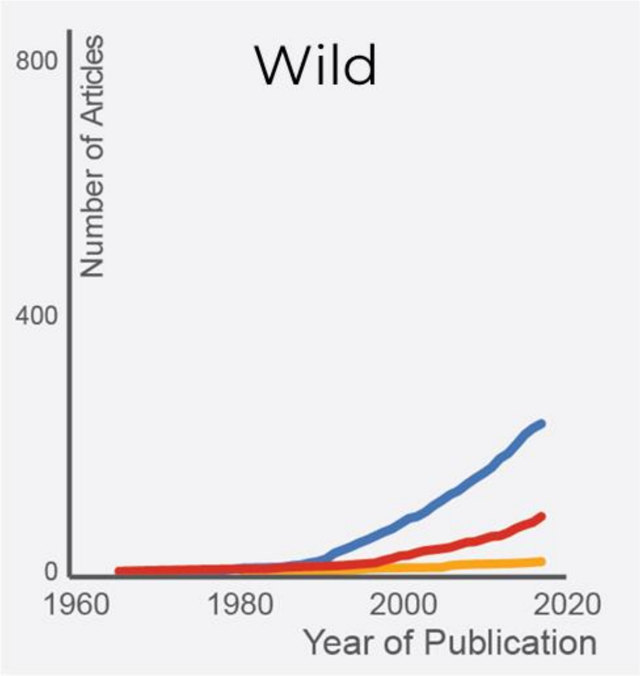
Knowledge is derived from a concentrated but highly uneven distribution of countries, and even regions within countries

Broader distribution of cultivated studies than wild ones



Hot or cold tolerance?





Research into plant thermal tolerance is dominated by investigations in to cultivated species

It turns out that there are many more studies that consider cold tolerance than heat tolerance

But also notable is the paucity of studies that consider both heat and cold tolerance

These patterns are generally consistent across crop types or biomes

Plant growth forms and species diversity

Plant growth forms

Cultivated: mostly graminoids, herbs and vines

Wild: emphasis on trees, forbs and shrubs

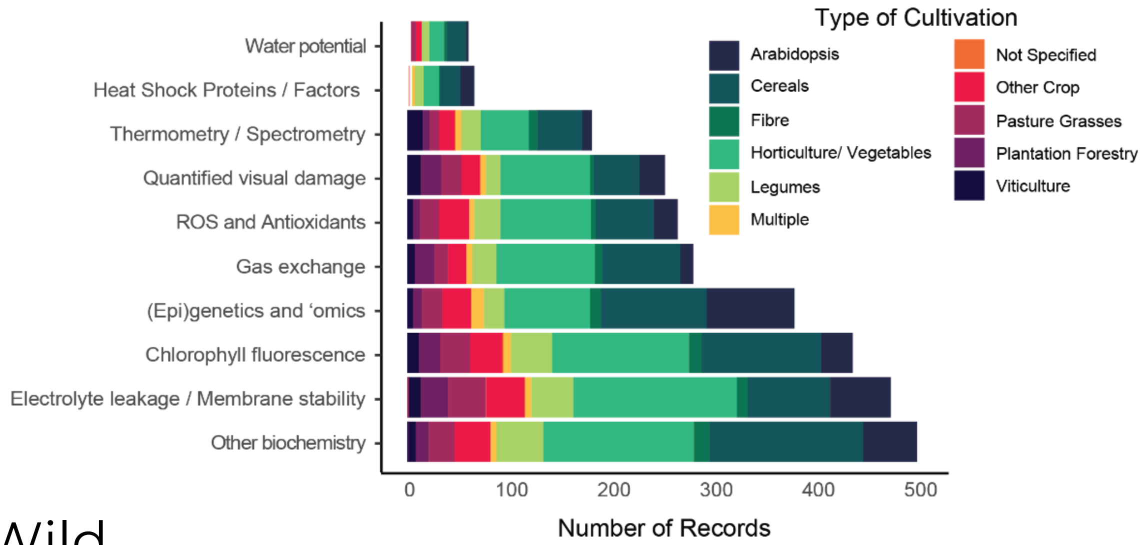
Species diversity i.e. intraspecific, single- & multi-species

Cultivated: few cross-species comparisons

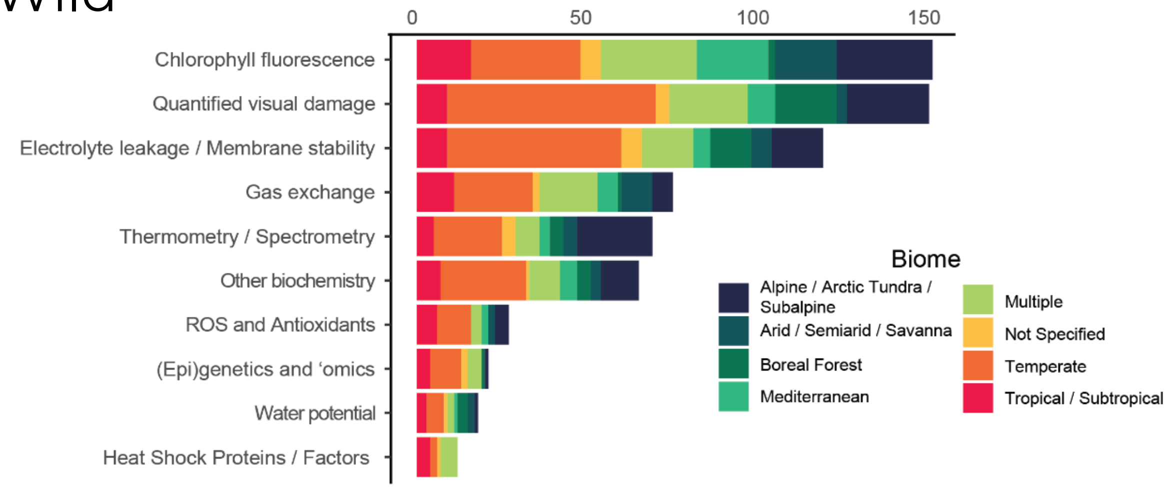
Wild: few focusing on intraspecific variation

The variety of thermal tolerance techniques

Cultivated



Wild



Researchers of cultivated species were consistently earlier adopters of emerging techniques

The most widely used techniques since 2000, have been chlorophyll fluorescence, electrolyte leakage and other biochemical assays.

Rapidly developing techniques are (epi)genetics and ‘omics, ROS and antioxidants, and other biochemistry

Little bias appeared based off cultivation types, biome or life form.

Metrics of thermal tolerance

10 main techniques reported

6 report a metric of damage

- Quantified visual damage
- Thermometry and spectrometry
- Gas exchange
- Electrolyte leakage / membrane stability
- Chlorophyll fluorescence
- Other biochemistry

(Epi)genetics and ‘omics

Heat Shock Proteins (HSPs)

Reactive Oxygen Species (ROS) / Antioxidants

Water potential

Thermal tolerance metric:

Quantifying a temperature at which some level of damage occurs to the tissue

Metrics only reported by 23% of studies

Wild studies reported more often

Even within techniques, many different approaches are taken

Critically, we have little knowledge on how these metrics of thermal tolerance compare - an important step for scaling, and developing generalized insights

Plant Thermal Tolerance Synthesis

Greater consideration of the **breadth of thermal tolerance**

Increased **understanding of how a diverse array of methodological approaches can be compared**, in order to create metrics for inclusion in modelling platforms

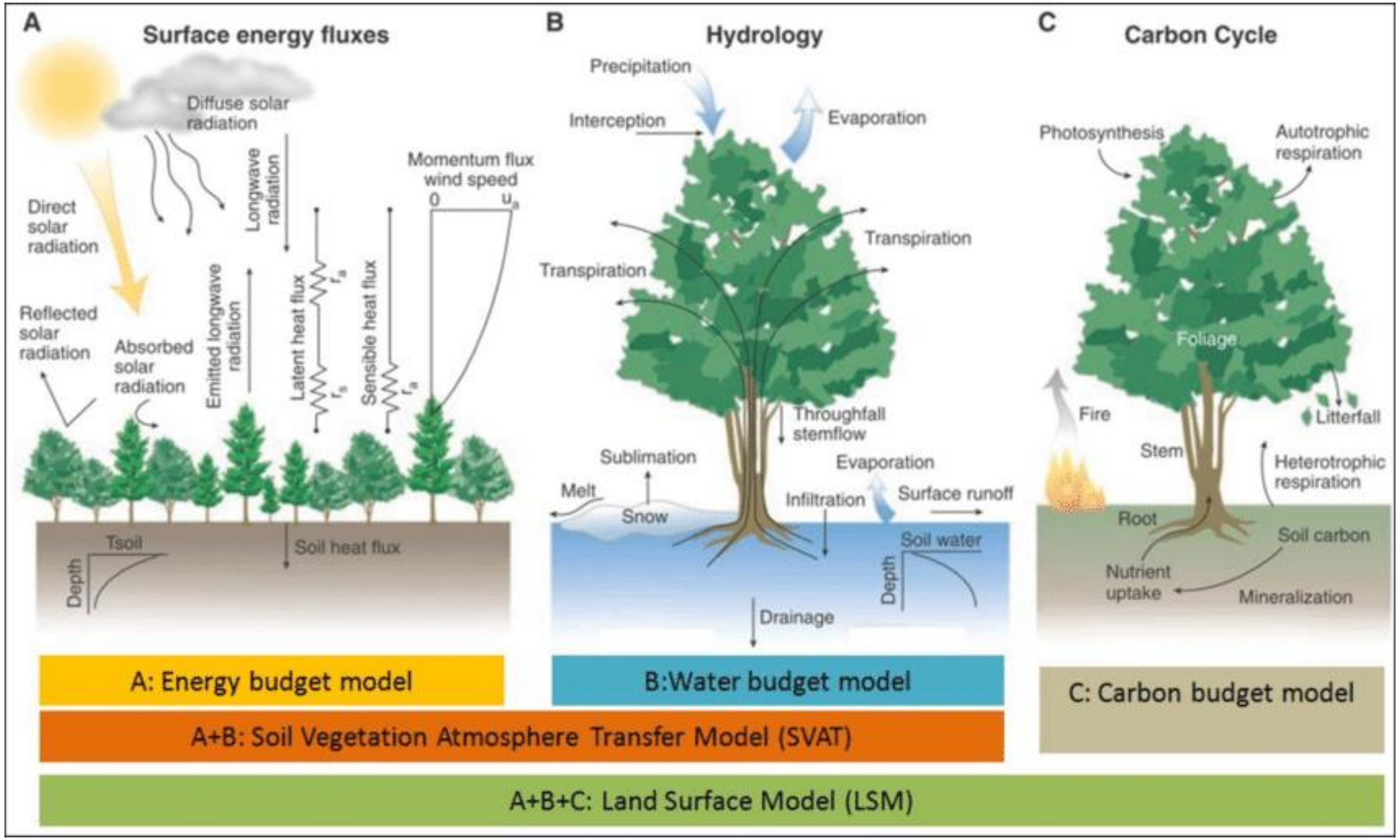
Integration into Land Surface Models

EMERALD Project: Improved representation of alpine and high latitude ecosystems and their climate interactions in the Norwegian Earth System Model

Saadi 2018

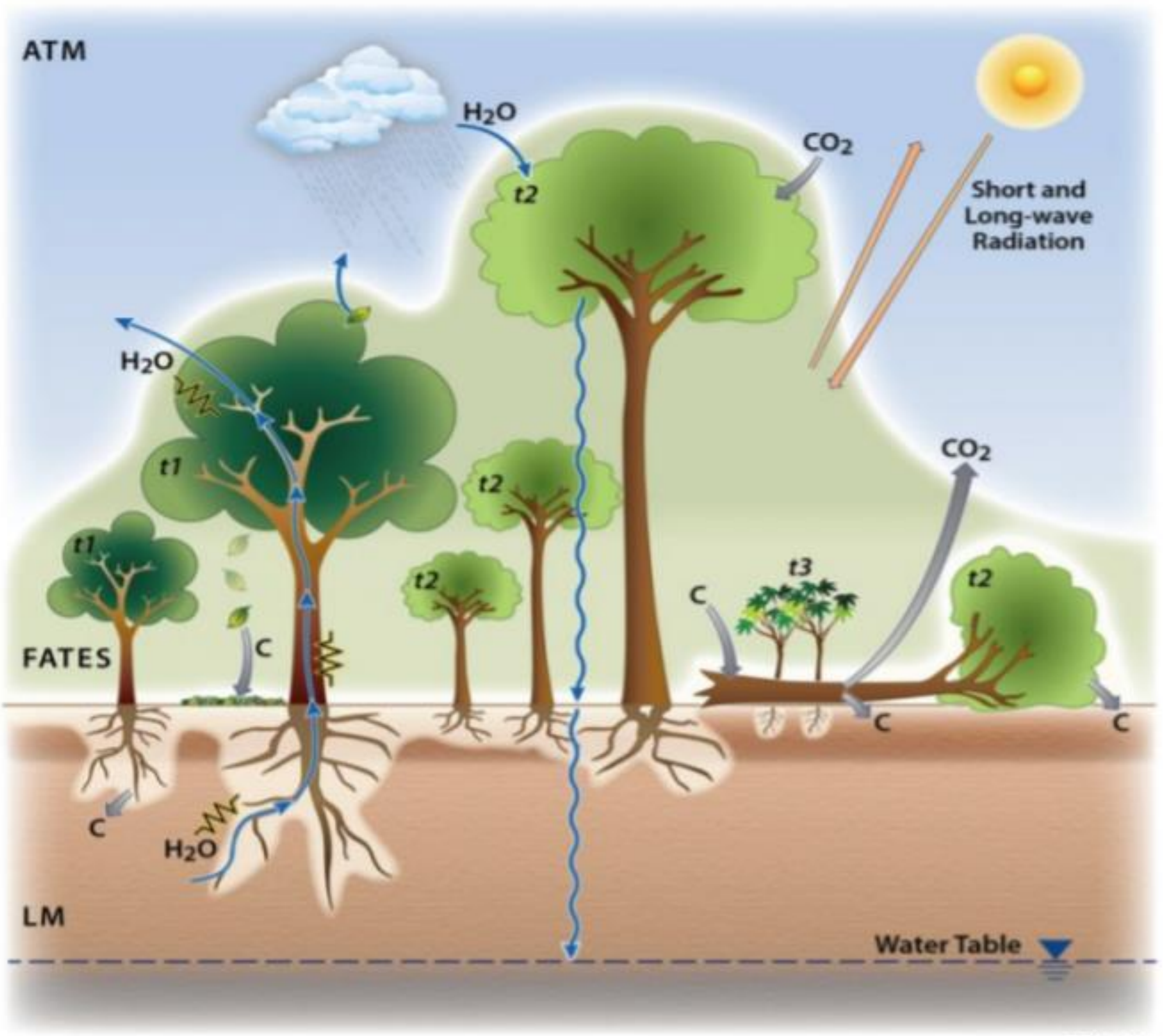
Land surface models (LSM's) use parameterized relationships to quantify and simulate the fluxes of surface energy, hydrology and carbon at the Earth surface – atmosphere interface

One platform is **FATES** - a demographic vegetation model



https://www.mn.uio.no/geo/english/research/projects/emerald/

FATES: Functionally Assembled Terrestrial Ecosystem Simulator



Simulates plant physiology, competition processes and ecosystem assembly along with distribution patterns for vegetation

Needs plant trait parameters to be integrated, robust and ecologically sound

BUT elements such as thermal tolerance are yet to be fully integrated – how should this concept be parameterized given the diversity in research approaches highlighted by this review?

Fisher et al. 2015.

How can we best integrate our thermal tolerance knowledge into these dynamic vegetation models?

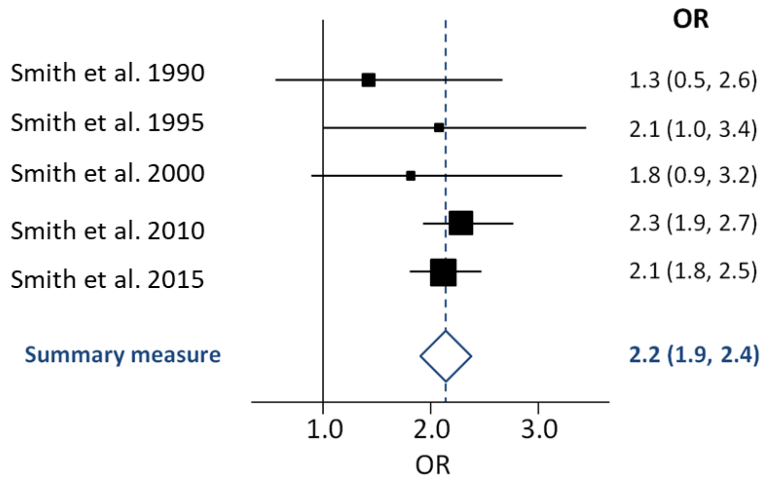
Meta-analysis approaches:

Using the methodologies that can provide thermal metrics, we can ask:

Do the different methodological approaches provide comparable parameters than can be incorporated into land surface models?

What role do experimental factors such as gradual vs rapid exposure to stress play?

What patterns could we find for thermal tolerance as a result of life form, biome, plant functional traits etc.



How can we best integrate our thermal tolerance knowledge into these dynamic vegetation models?

Increased communication between ecologists, data synthesizers, database managers, and the land surface modelling community

Improved integration of thermal tolerance metrics into existing and developing databases on plant functional traits, i.e. TRY, OpenTraits Network, or topic specific ones such as GlobTherm

+

Encourage the **development of an open evidence synthesis research community** where we bridge the gap between empirical researchers and data synthesizers resulting in faster research progress

Kattge et al. 2020, Gallagher et al. 2019, Bennett et al. 2018, Nakagawa et al. 2020

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Additionally, insights from the **EMERALD Project** members