Modelling the impacts of climate change on European sheep and goat production systems

Martha Dellar

Contents

- Climate change
- Meta-analysis
- Statistical modelling
- Process-based modelling
- How to choose a modelling approach
- Adaptation options

Learning objectives

- How sheep and goat systems are affected by climate change

- How to perform a meta-analysis
- How to develop a statistical model
- How to use a process-based model

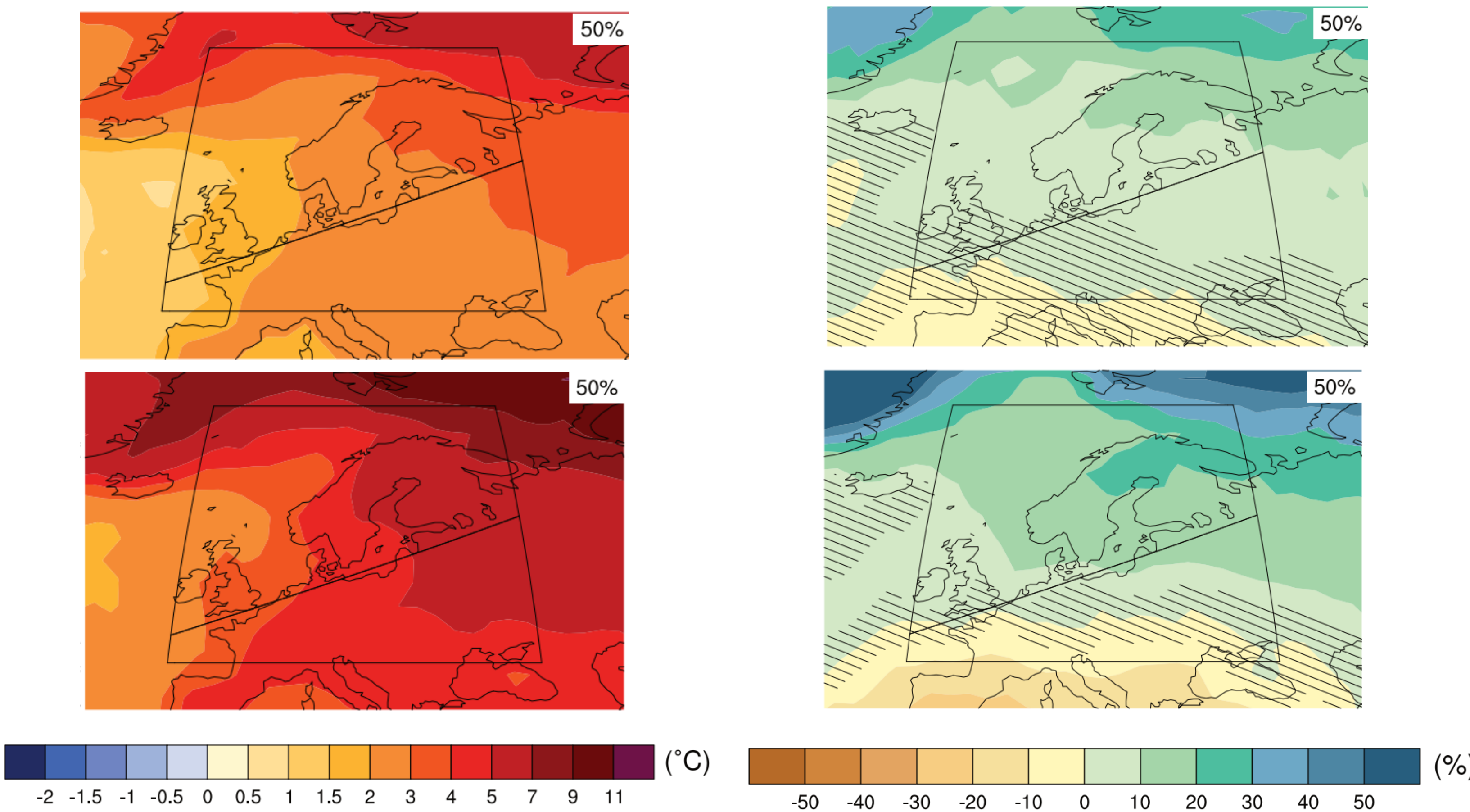
Climate change

Average annual predictions for 2081 - 2100, relative to 1986 - 2005

Temperature | Precipitation

Midrange scenario (RCP4.5)

Extreme scenario (RCP8.5)



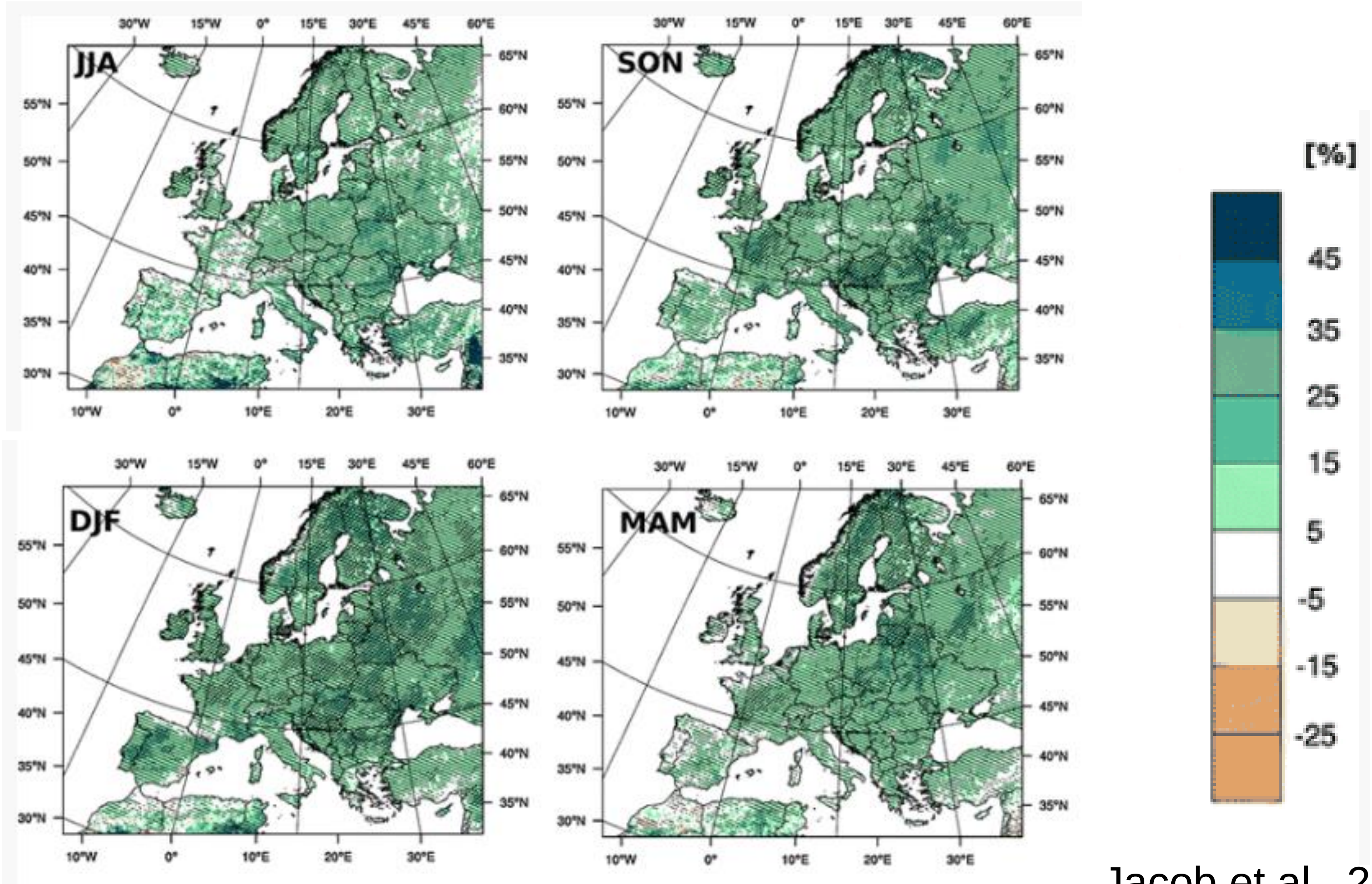
IPCC, 2013

Heavy precipitation events

Intensity of 95th percentile of daily precipitation (only considering days >1mm)

RCP4.5

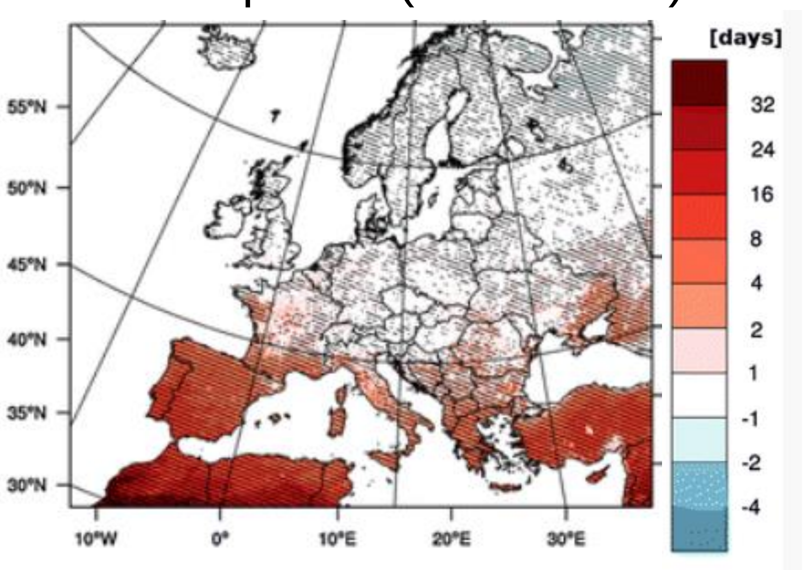
2071-2100 compared with 1971-2000

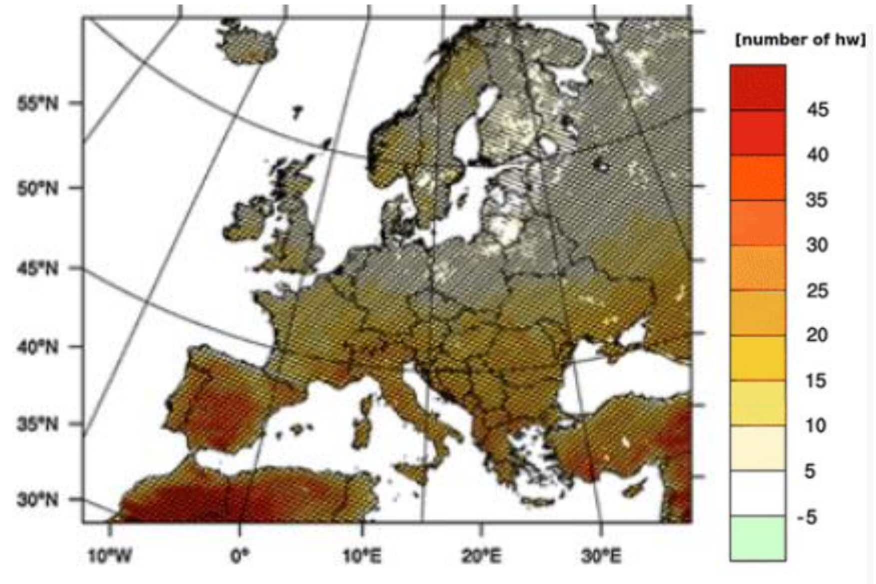


Jacob et al., 2014

Dry spells and heat waves

- Dry spell: period of at least 5 consecutive days with daily precipitation <1 mm
- Heat wave: period of >3 consecutive days exceeding the 99th percentile of the daily maximum temperature of the May to September season of the control period (1971–2000)





RCP4.5
2071-2100 compared with 1971-2000

Jacob et al., 2014

CO_2 concentrations

Global atmospheric CO_2 concentration:

421 – 936 ppm by 2100

How will this affect sheep and goat systems?

Pastures

- Changes in plant species
- Reduced plant protein and increased carbohydrates
- Need for more bought-in feed
- Changing grazing seasons
- Changes in plant yields

Livestock

- Increased disease risk / More parasites
- Changes in mortality
- Harder to raise lambs
- Heat stress:
  - Reduced fertility
  - Reduced productivity
  - Reduced meat/milk quality

General

- Difficult to plan for the future due to increasing variability (in terms of both farm management and profits)
- Higher costs
- Lack of knowledge on how to deal with extreme events
- Farmer health (e.g. increased stress)

How to respond

The impacts of climate change are influenced by:

- Location
- Farming system
- Management practices
- Livestock breed
- And many other factors

Farmers need to know what will happen on their farm and what adaptation measures to take

We can’t run experiments on all farms individually

Modelling approaches

- Meta-analysis
- Statistical modelling
- Process-based modelling

"All models are wrong, but some are useful."

George Box, statistician

Pasture modelling

What influences how pastures grow?

- Location
- Intensive/extensive
- Plant species
- Legumes
- Climate
- Exposure
- Fertiliser (timing, type, quantity)
- Cutting frequency
- Livestock
- Soil
- Nutrient leaching

Experimental research

Photos from:
Oak Ridge National Laboratory
Indiamart Free Air Temperature Elevation Engineering Solution
Western Sydney University DryGrass experiment

Meta-analysis

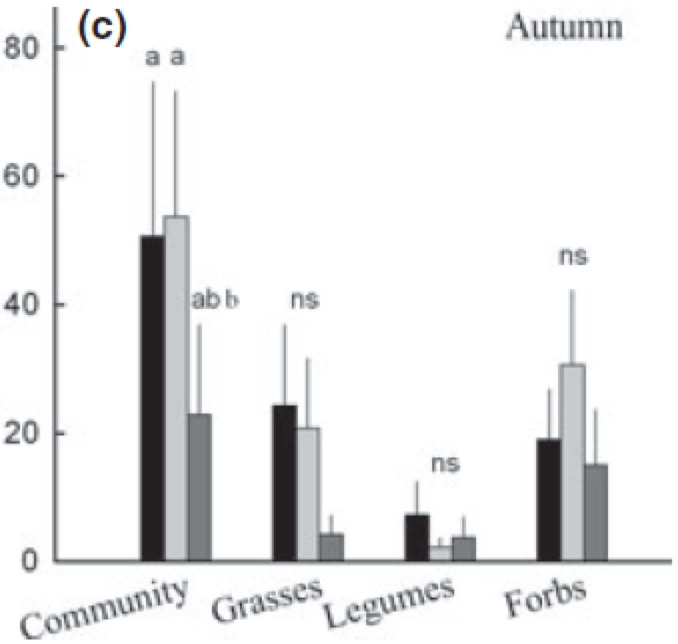
- A huge number of experiments have been conducted on the effects of climate change on grasslands
- These give us detailed information about specific locations
- A meta-analysis lets us use these results to get a more general picture

Meta-analysis

- Define your question
  - E.g. “What are the effects of elevated CO_2, elevated temperature and changes in water availability on grassland yield in Europe?
- Identify keywords
- Literature search
  - Web of Science, Scopus, other meta-analyses, Google Scholar, Google, experts

Data extraction

- Identify relevant studies
- Criteria for inclusion
  - Ideally use studies which provide variance/standard error
- Make database with all relevant information
- Useful tools for extracting data from graphs:
  - GraphClick
  - WebPlotDigitizer
  - Graph Grabber



Analysis

Aim:

$$\text{Yield} = a_0 + a_1\text{*Region} + a_2\text{*Fertiliser} + a_3\text{*Environmental change} + a_4\text{*Experiment duration} + a_5\text{*Plant type} + b_0\text{*study ID}$$

a's and b_0 are numbers to be determined

$a_{1\text{-}5}$ are *fixed effect* terms

b_0 is *random effect* term

Analysis - methods

- Moment and least squares inference
  - Estimates parameters by matching moments or minimizing the squared residuals
  - Most common methodology
  - For simple models (not hierarchical or mixed)
  - For estimating expected value, variance, regression coefficients, …
  - Very similar to linear regression
  - Normally distributed data
  - R packages: MetaWin, Meta, Metafor, …

Analysis - methods

- Maximum likelihood inference
  - For more complex models
  - Suitable for non-normal data
  - Chooses parameters which maximise the probability of the data
  - Estimates all parameters simultaneously – can give better estimates than previous methodology
  - R packages: Meta, MetaLik, Metafor, Metaplus

Analysis - methods

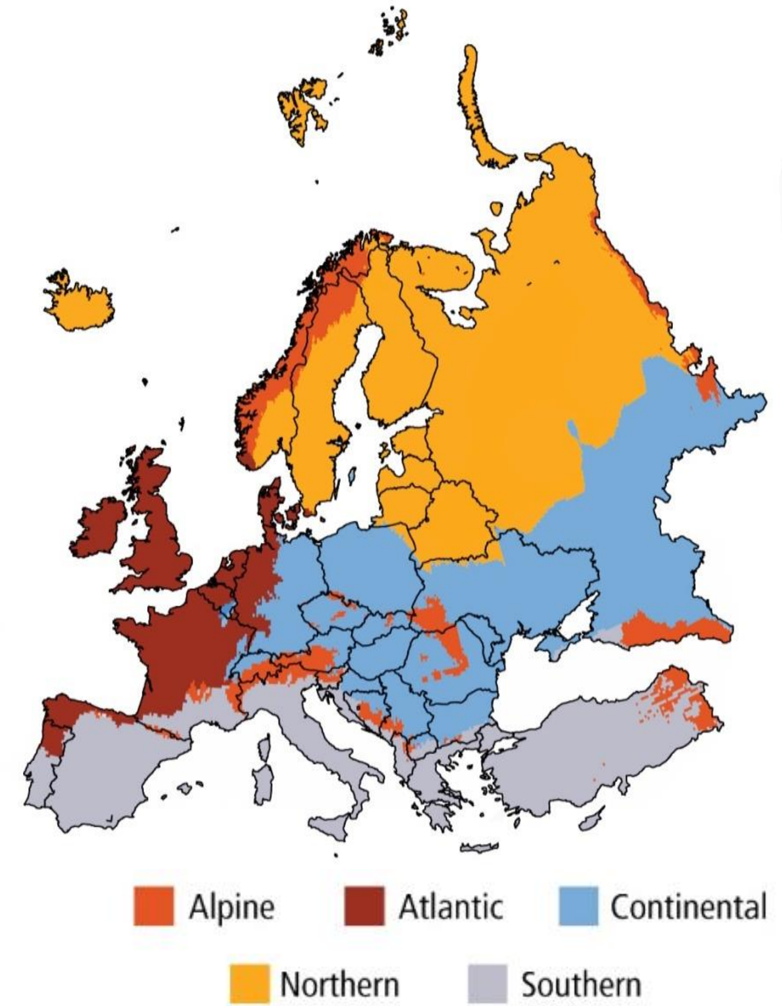
- Bayesian inference
  - For more complex models
  - Suitable for non-normal data
  - Uses both the data and extra information on the individual parameters (*priors*)
  - Uses Markov Chain Monte Carlo simulations to try huge number of possible solutions and determine the best one
  - Computationally intensive
  - R packages: Bayesmeta, Bmeta
  - Other software: BUGS, WinBUGS, JAGS

Analysis - weighting

- You can weight the studies in your meta-analysis according to their reliability
- Ideally you use the variance reported by the individual studies for this
- If this is not available, you can use sample size instead
- Maximum likelihood and Bayesian inference methods weight studies implicitly

Example

Analyse the expected changes in European pasture yield under elevated CO_2, elevated temperature and changes in water availability



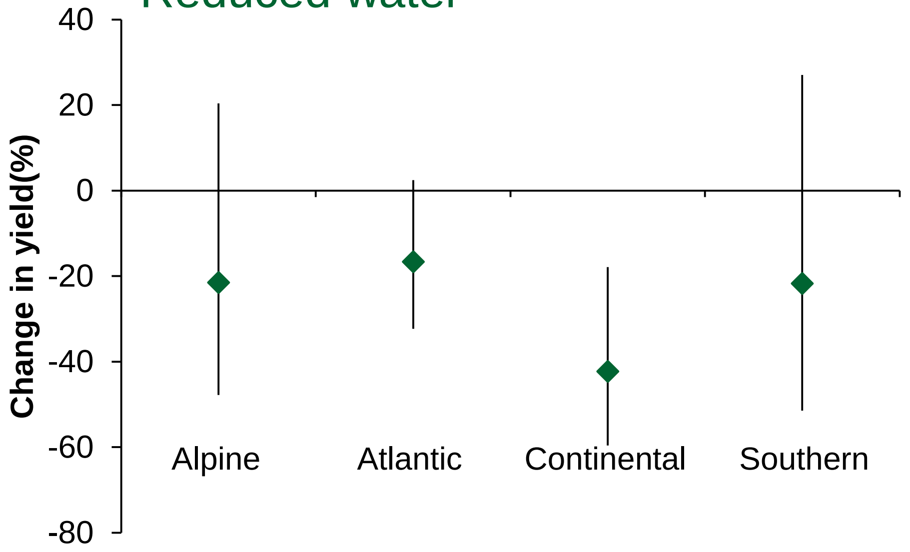
Summary of studies used

Treatment	No. studies	No. observations	Average difference from control	Average duration (days)
Elevated CO_2	58	248	+289ppm	475
Elevated Temp.	34	178	+3.3°C	418
Elevated Water	7	29	76% more water than control	189
Reduced Water	43	207	81% less water than control	70

Almost exclusively C3 perennial species

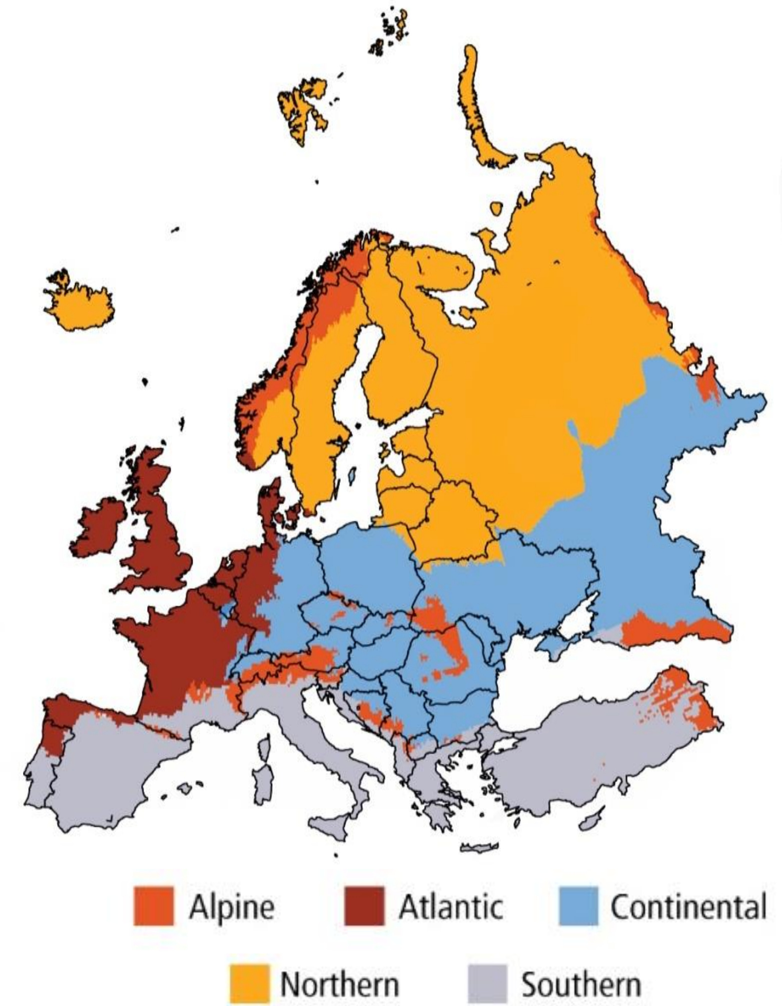
Yield change by region

Reduced water

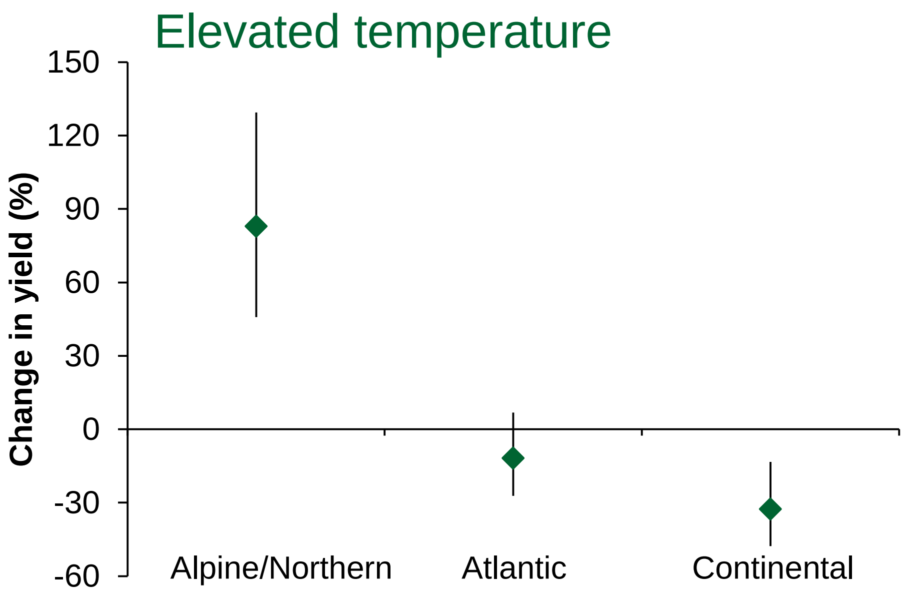


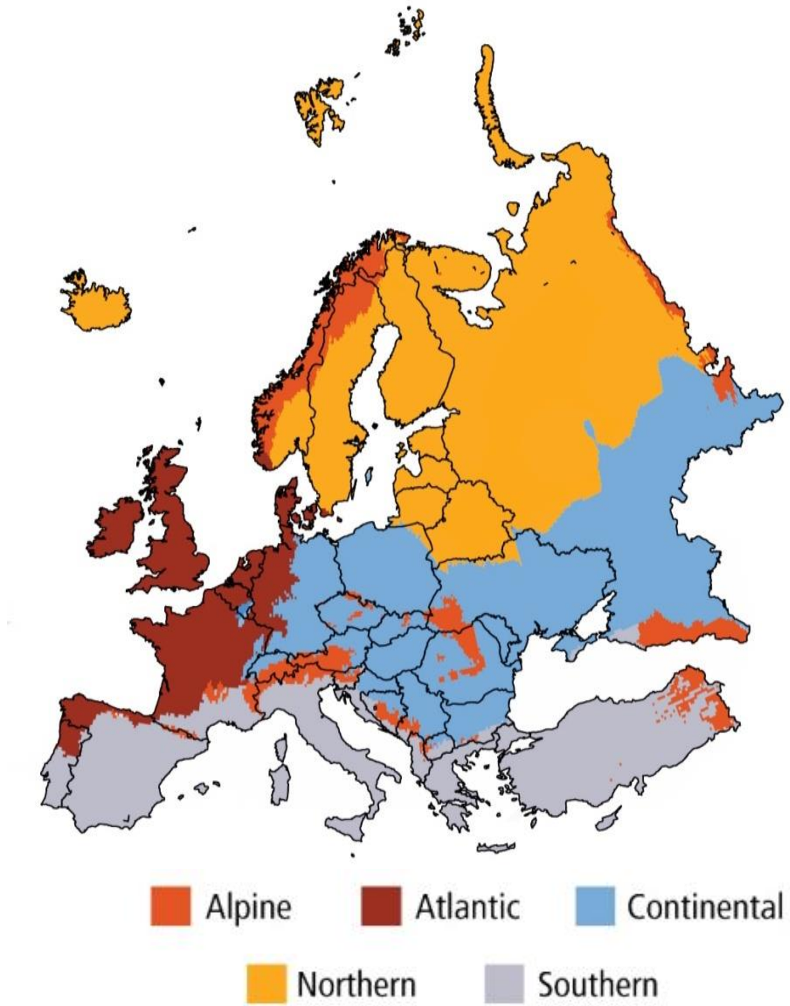
Elevated water

Alpine, Continental and Atlantic:
+57.1 ±19.9%



Yield change by region





Benefits and limitations

+ Uses actual experimental data – reliable
+ Wide spatial scale
- Only considers one climatic change at a time (very few experiments look at multiple simultaneous climatic changes)
- Dependent on data availability

Further reading

Book:

- Handbook of Meta-Analysis in Ecology and Evolution, Koricheva, J., Gurevitch, J. and Mengersen, K.

Examples:

- Dellar, M., Topp, C.F.E., Banos, G., Wall, E., 2018. A meta-analysis on the effects of climate change on the yield and quality of European pastures. Agric. Ecosyst. Environ. doi:10.1016/j.agee.2018.06.029
- Dumont, B., Andueza, D., Niderkorn, V., Lüscher, A., Porqueddu, C., Picon-Cochard, C., 2015. A meta-analysis of climate change effects on forage quality in grasslands: specificities of mountain and Mediterranean areas. Grass Forage Sci. 70, 239–254. doi:10.1111/gfs.12169
- Wang, D., Heckathorn, S.A., Wang, X., Philpott, S.M., 2012. A meta-analysis of plant physiological and growth responses to temperature and elevated CO2. Oecologia 169, 1–13. doi:10.1007/s00442-011-2172-0

Statistical modelling

Example: What is the impact of weather on grass yield?

Basic idea:

- Collect data on grass yield, along with corresponding weather data
- Use linear regression to create an equation for yield as a function of weather variables
- Put future climate data into the equation to predict what yields will be like in the future

Data collection

- Data from experiments with no climate manipulation
- Ideally long-term experiments (≥3 years)
- Need information on location, grazing, fertiliser, harvests, …
- Literature search, contact experts, …

Weather

- Weather stations or gridded data
- Useful databases: MIDAS (mostly UK), CRU, EUSTACE

Example

29 experiments

89 sites

All experiments lasted at least three years

Northern

Atlantic

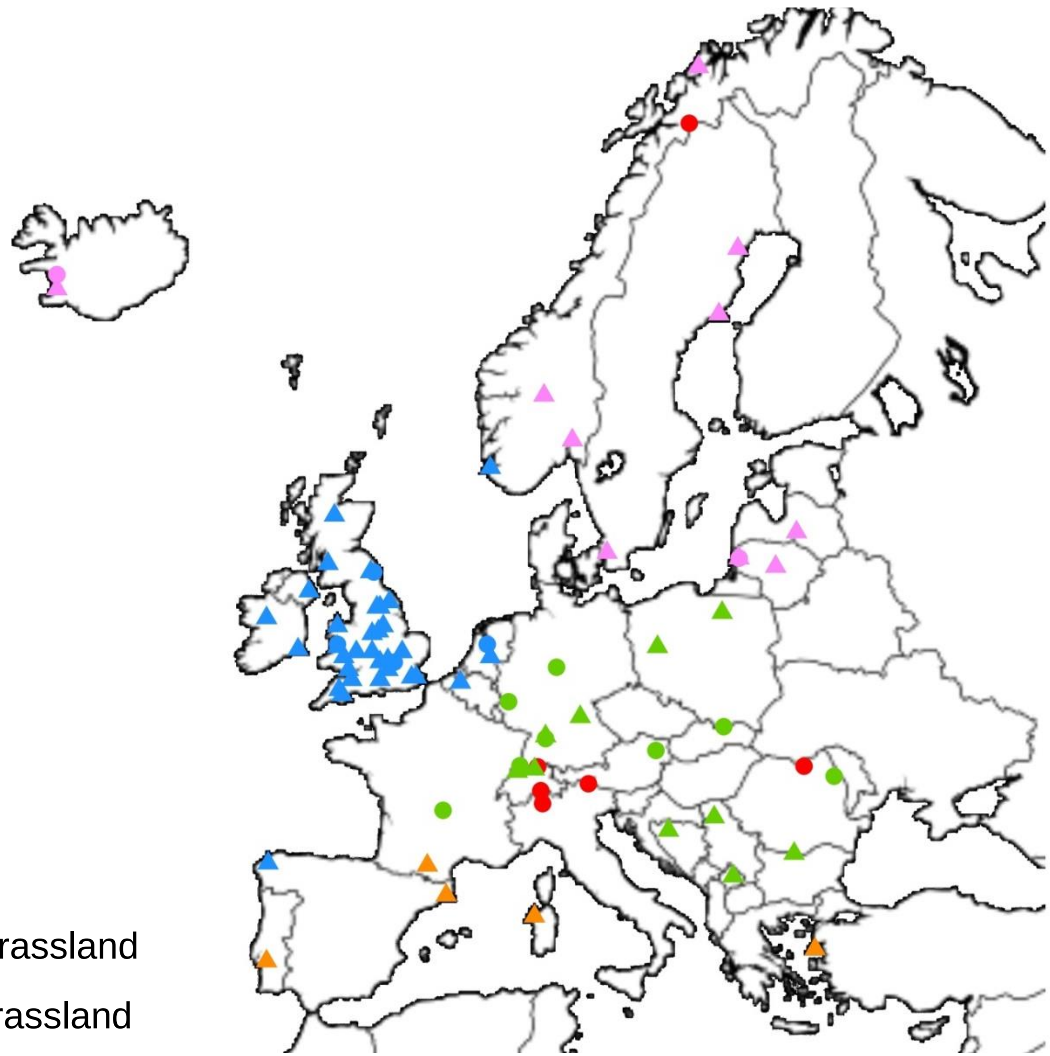
Continental

Alpine

Southern

Permanent grassland

Temporary grassland



Inputs

- Mean monthly temperatures (grouped?)
- Total monthly rainfall (grouped?)
- Altitude
- Fertiliser
- Number of harvests per year
- Grazing information
- Information on pasture composition (e.g. legume %)

Analysis

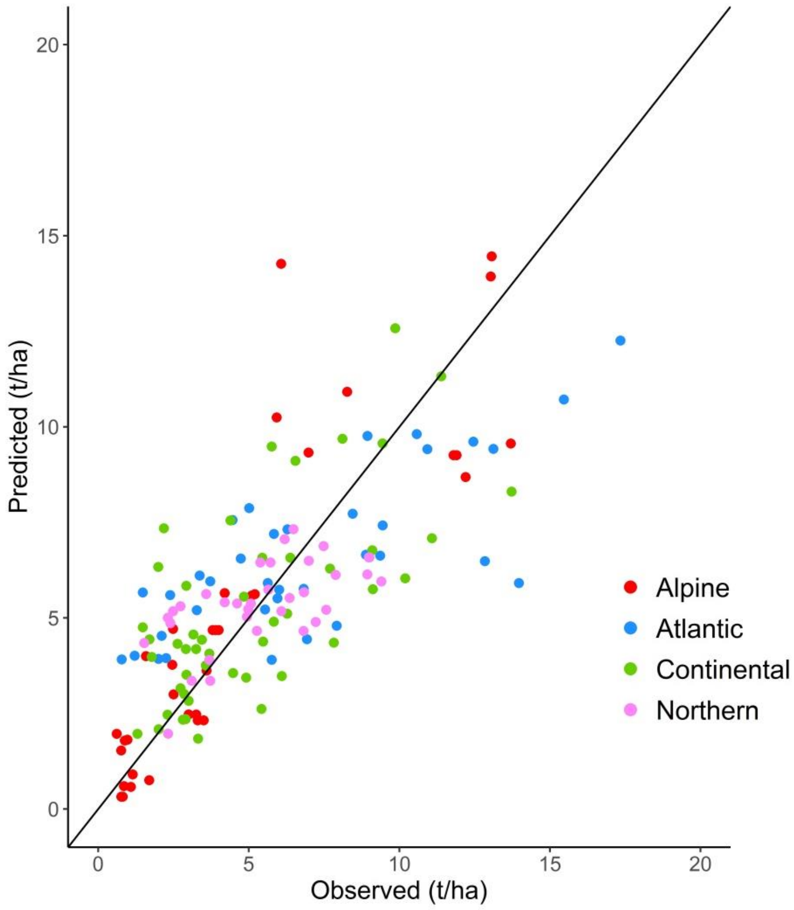
- Use standard statistical tools to run linear regression (R, SPSS, GenStat, …)
- Can include squared and interaction terms to see if this improves the fit

$$\text{Yield of permanent grasslands} = \alpha_0 + \alpha_{REGION} + \alpha_1 Rain_{JFM} + \alpha_2 Rain_{AMJ} + \alpha_3 Rain_{JA} + \alpha_4 Temp_{FM} + \alpha_5 Temp_{AMJ} + \alpha_6 Temp_{JA} + \alpha_7 Rain_{JFM}^2 + \alpha_8 Rain_{AMJ}^2 + \alpha_9 Rain_{JA}^2 + \alpha_{10} Temp_{JA}^2 + \alpha_{11} Altitude + \alpha_{12} Cuts + \alpha_{13} Fertiliser + \alpha_{14} Cuts^2 + \alpha_{15} Fertiliser^2 + \alpha_{16} Fertiliser*Rain_{JFM} + \alpha_{17} Fertiliser*Temp_{JA}$$

Model fit

- Before we can use the model to make predictions about climate change, we need to make sure it's sufficiently accurate
- Do this by splitting the original dataset into two parts, one for developing the model (~3/4), the other for testing (~1/4)
- Compare the test dataset with model predictions (correlation, RMSE, …)

Model fit



Yield of permanent grasslands

Correlation: 0.77 ± 0.014

RMSE: 2.23 ± 0.03

Model is good enough to use for climate change predictions

Climate change data

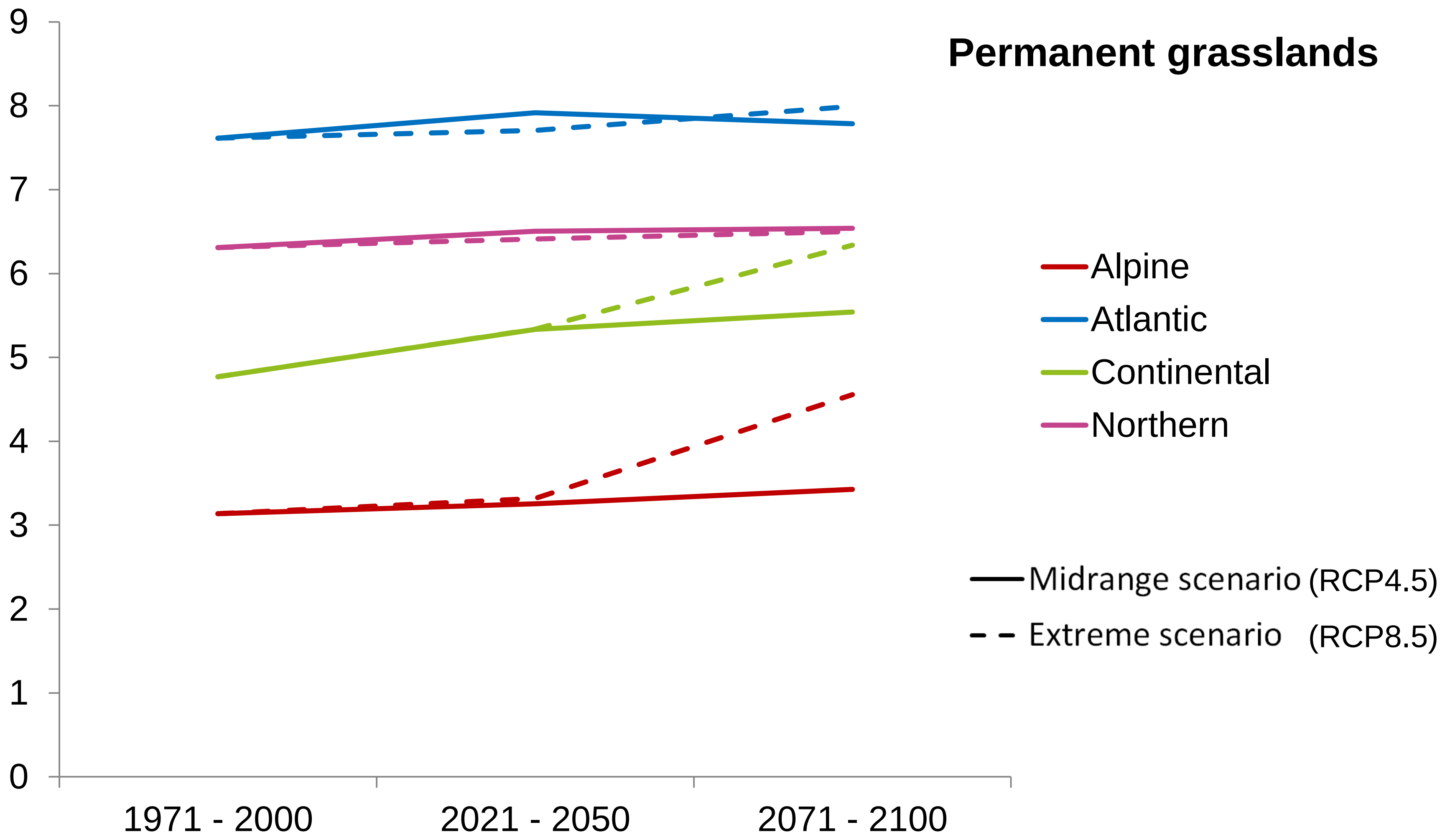
Weather data:

- EUROCORDEX: daily/monthly gridded weather data up to 2100 for Europe

Extrapolation issue:

- Model developed on current climate – this is only climate for which it is valid
- We want to input a different climate
- Options:
  - Accept that you are extrapolating and results are less certain
  - Bound climate change data so it doesn’t exceed extremes of current climate data

Predicting future yields



Benefits and limitations

- \+ Wide spatial scale
- \+ Simple to develop and use
- \- Dependent on data availability
- \- Only consider one output variable
- \- Extrapolation when looking at future climate
- \- Doesn't account for increasing CO_2 concentrations (in this example)
- \- Can be too simple and not be sufficiently accurate

Further reading

- Dellar, M., Topp, C., Pardo, G., del Prado, A., Fitton, N., Holmes, D., Banos, G., Wall, E., 2019. Empirical and dynamic approaches for modelling the yield and N content of European grasslands. Environ. Model. Softw. 122, 104562. doi:10.1016/j.envsoft.2019.104562
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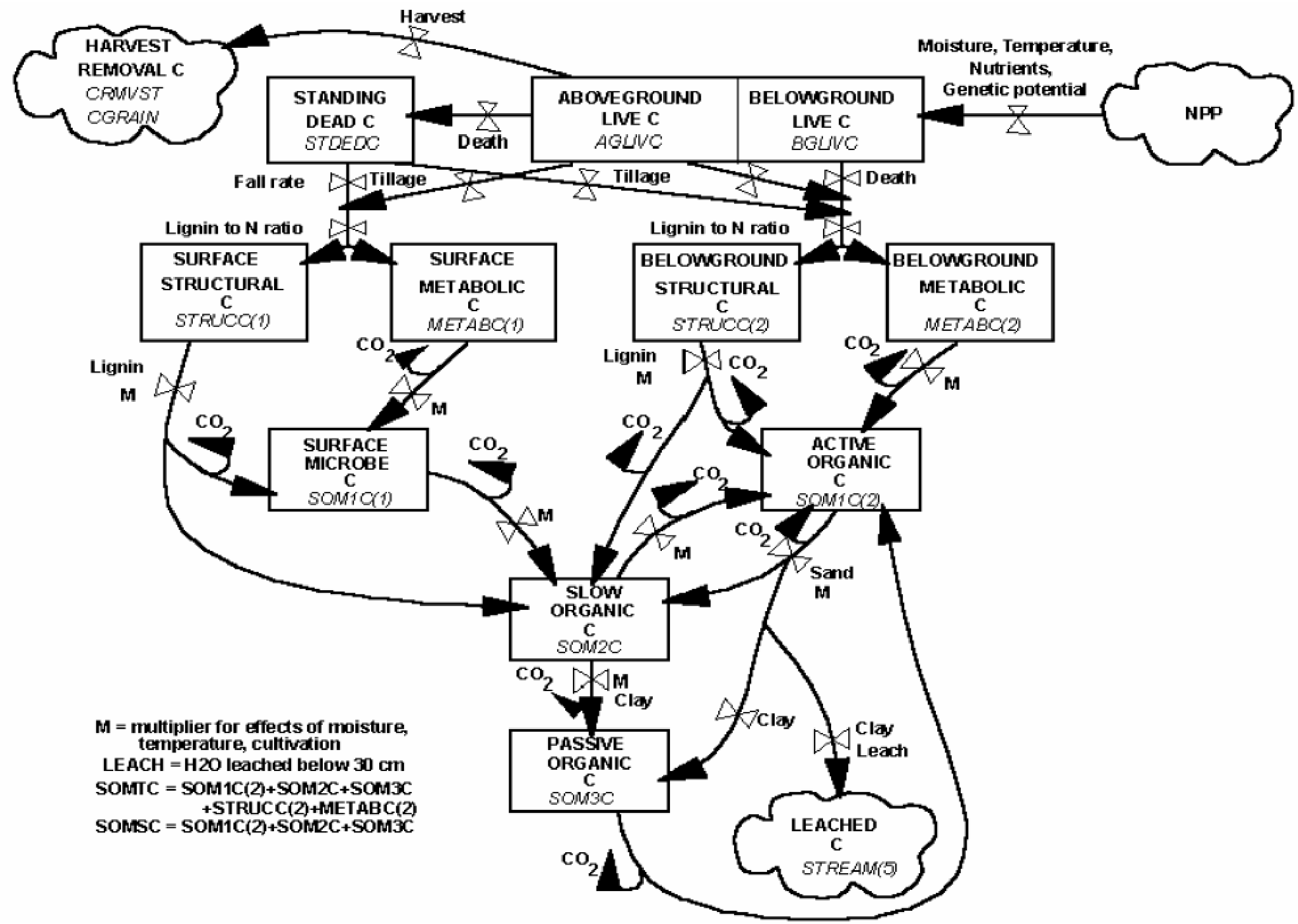
Process-based modelling

- A process-based model (also called dynamic or mechanistic model) simulates the biological processes in a system
- Usually quite complex
- Tells you about all aspects of the ecosystem, rather than just e.g. yield
- Examples of models that can be used for pastures: Century, DailyDayCent, NGAUGE, PaSIM

C flows in the Century model



Inputs

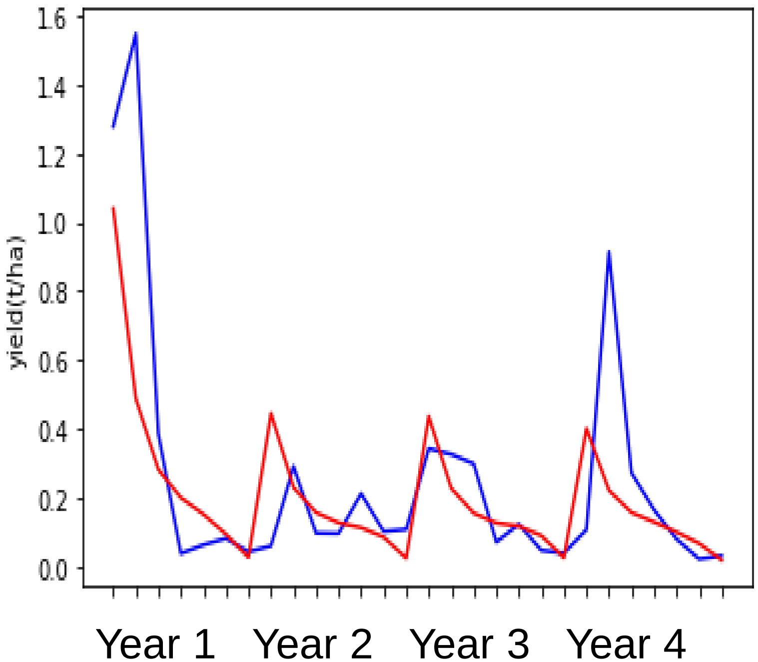
- Process-based models often have several thousand inputs
- For grassland, main inputs: Weather, soil properties, plant properties, site management, site history
- Some you know precisely, some are estimated, most are default values
- Some are site-specific, but difficult to measure or estimate (e.g. maximum potential productivity)
- Determining the correct inputs for a site is known as *parameterisation*

Parameterisation

- Try to determine key model inputs by trying different values. Compare the model outputs with measured observations and see what inputs give the best fit
- This can be done manually, one input at a time
- Can also be done using automated algorithms, which look at multiple inputs simultaneously and try thousands of combinations (requires programming in R, Python, or similar)

Model fit

Compare predictions with observations
Can calculate correlation, RMSE, …



Observed

Predicted

Is it good enough?

Climate change

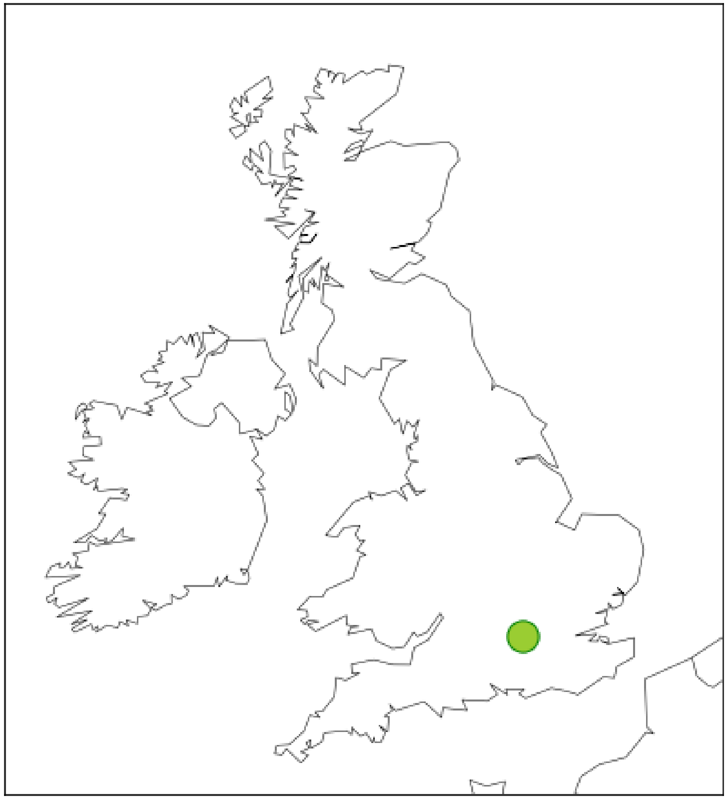
- If the model gives sufficiently good predictions, it can be used to look at the effects of climate change
- Use the same input values as previously and change the temperature, rainfall and CO_2 data

Weather data:

- EUROCORDEX: daily/monthly gridded weather data up to 2100 for Europe

Example - pastures

Grassland Research Institute, Hurley, UK

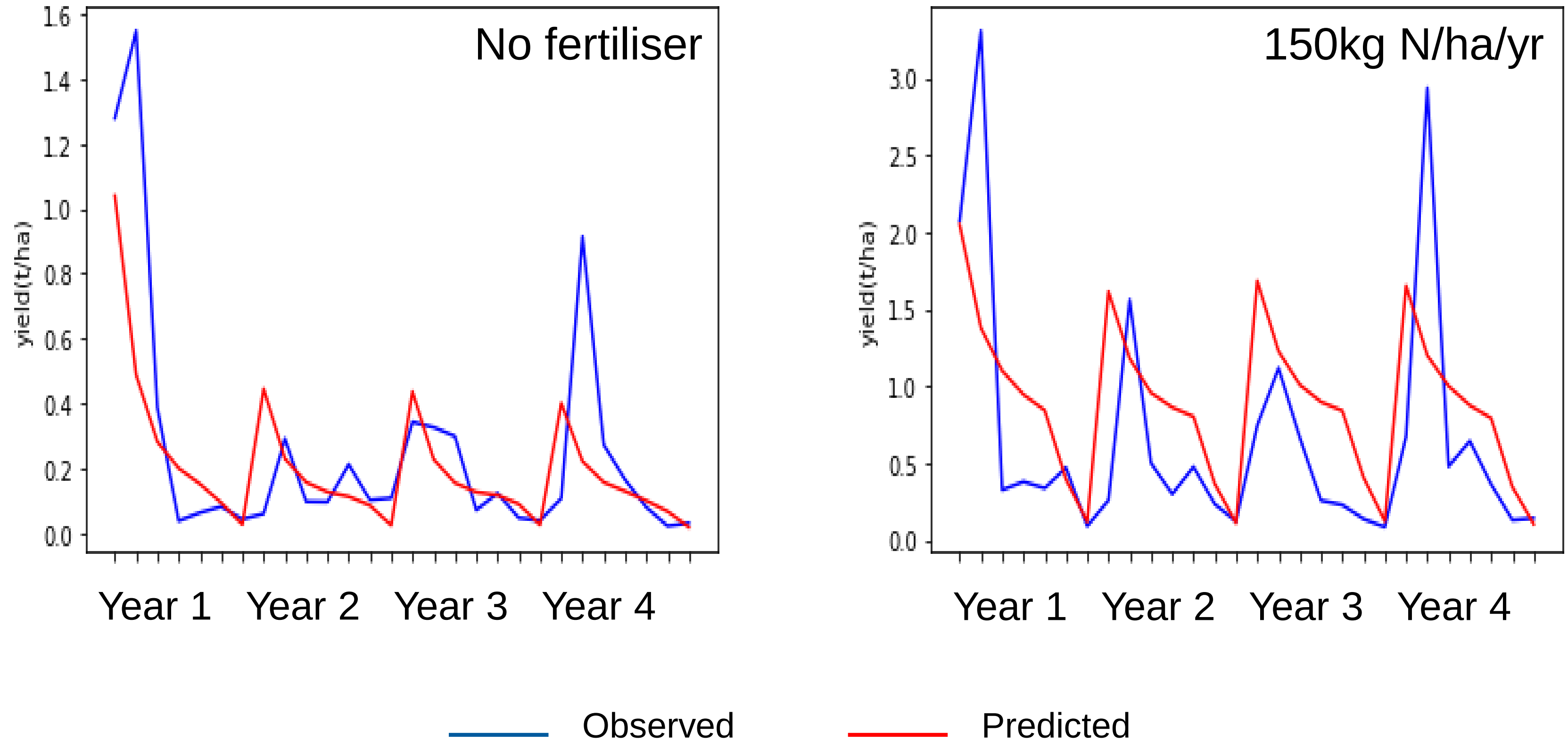


4 year perennial ryegrass trials with different fertiliser levels

(Photo: The Hurley and North Wyke Story, 2009)

Model fit: yield

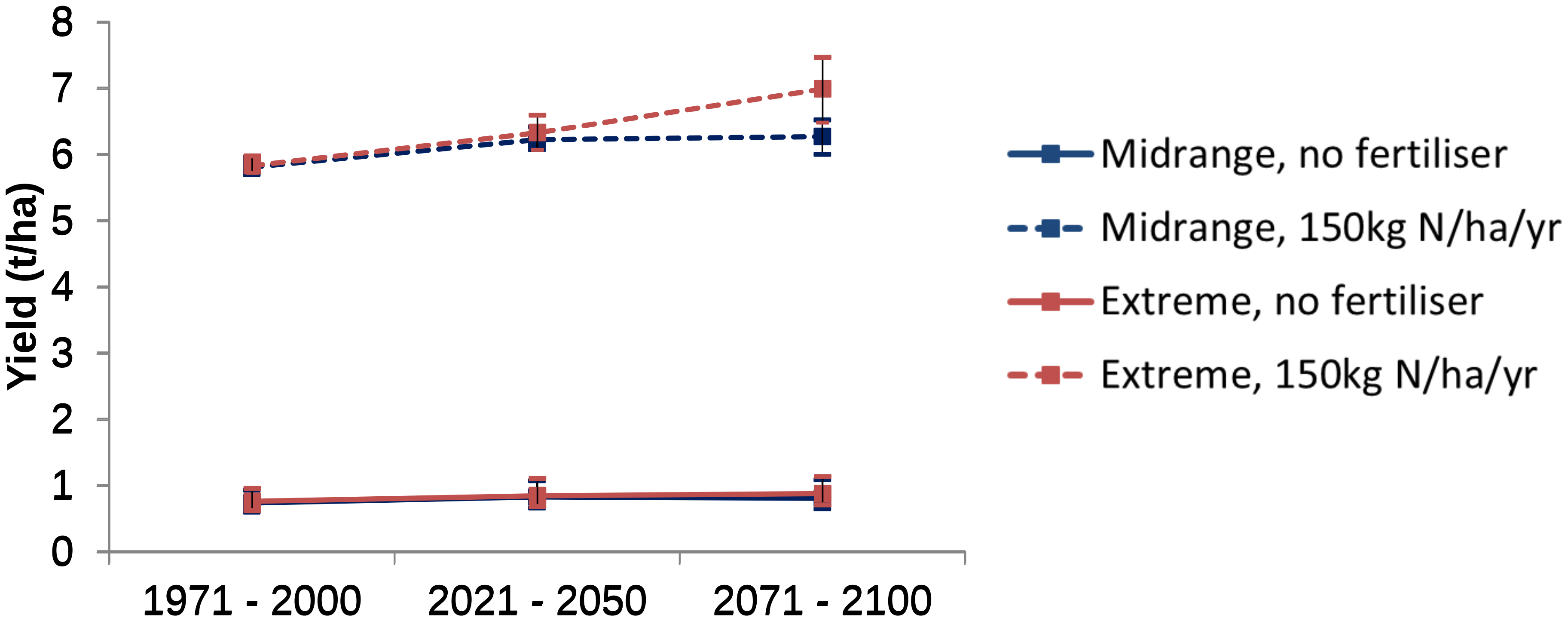
UK, temporary grassland



Correlation: 0.74
RMSE: 13.8% of annual mean

Correlation: 0.57
RMSE: 14.8% of annual mean

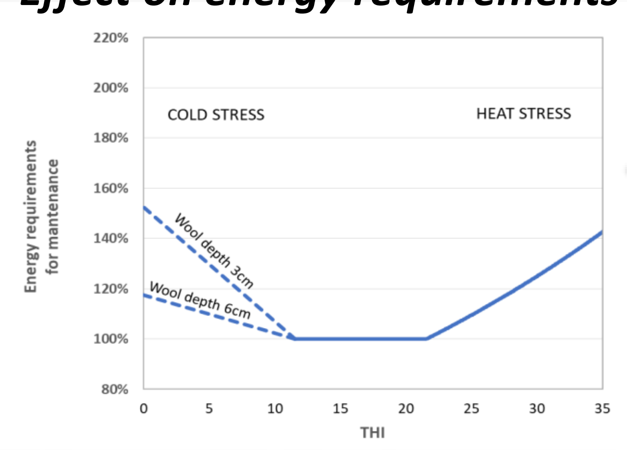
Climate change



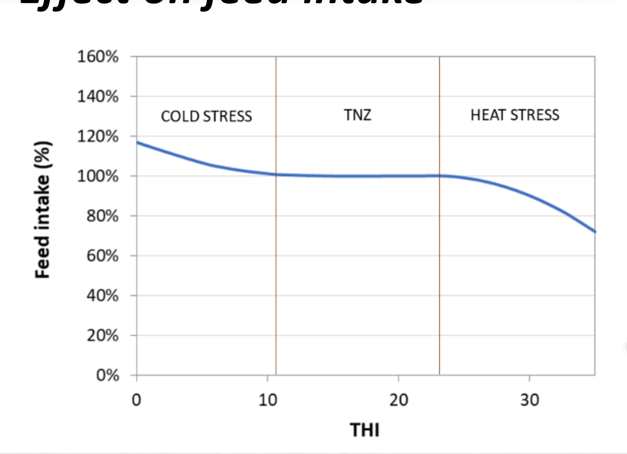
Development of models on animal performance:

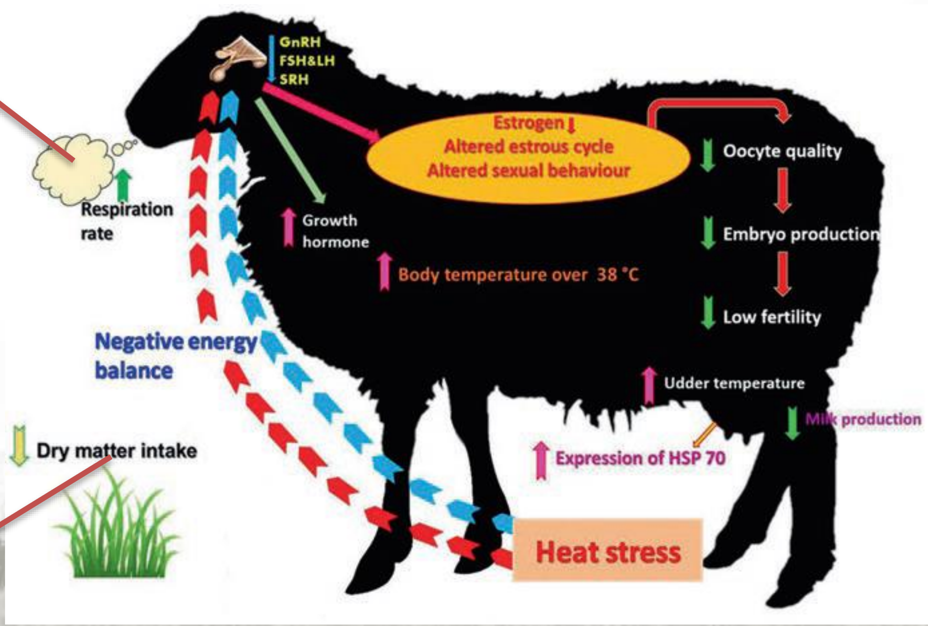
Semi-mechanistic model:

Effect on energy requirements



Effect on feed intake





Sejian et al., 2017

Development of models on animal performance:

Semi-mechanistic model:

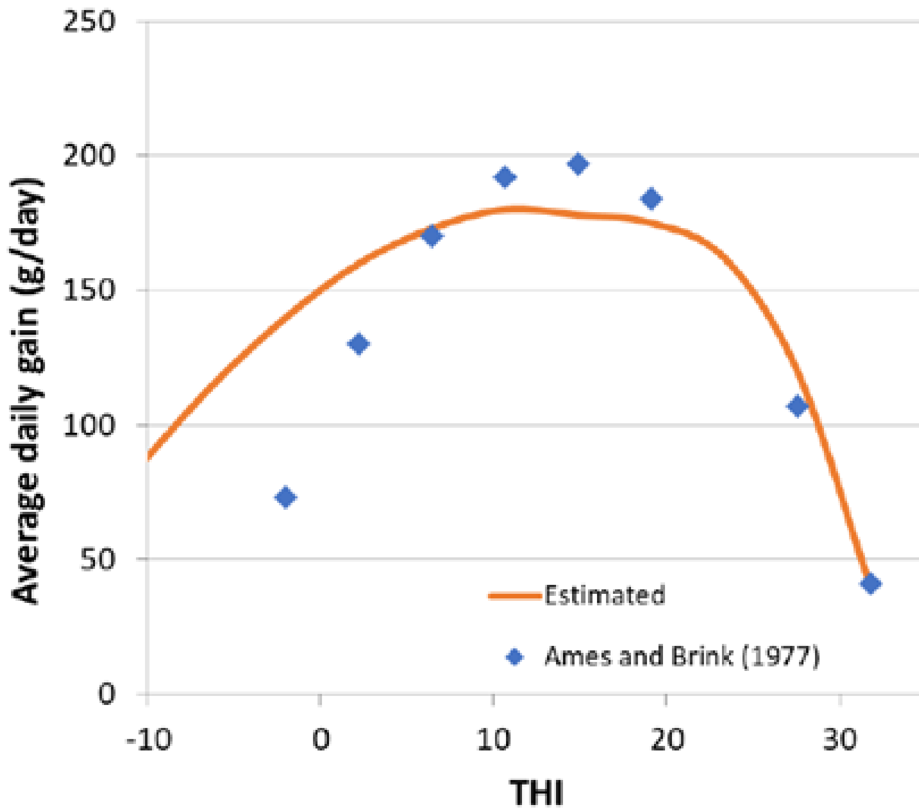


Figure 15 – Estimated (line) vs measured average daily gain of growing lambs under heat stress (Datasets from Ames and Brink, 1977)

Effect of heat stress on growth of May-born lambs

- Breed: rasa Aragonesa
- Location: Zaragoza (Spain)
- Period of study: from weaning (13.9 kg LW) to slaughter (22 kg LW)
- Number of ewes: 550, 650 lambs sold/yr (40% born in May)

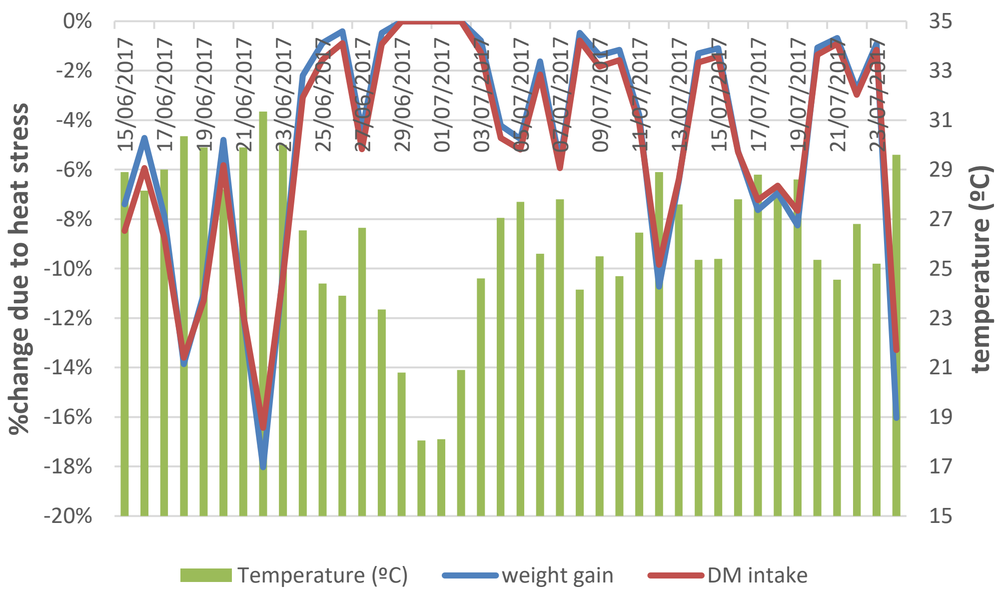
Diet composition (wean to slaughter)

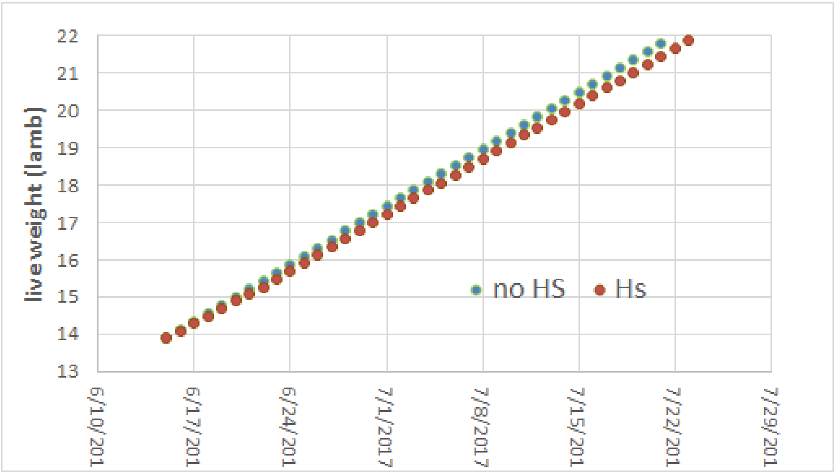
FEED	%	GE MJ/kg DM	DE MJ/kg DM	ME MJ/kg DM
Barley	33.6%	18.4	14.8	12.4
Maize	27.3%	18.7	16.1	13.6
Soybean Meal	23.6%	19.7	18.2	13.6
Wheat	6.4%	18.2	15.6	13.1
straw	9.0%	18.2	8	6.5

iSAGE Innovation for Sustainable Sheep and Goat Production in Europe

Effect of heat on Lamb growth & DM Intake

Lamb growth reduction and DM intake (%)





2 extra days with heat stress

450 g DM extra/lamb

228 kg extra concentrates

iSAGE

Innovation for Sustainable Sheep and Goat Production in Europe

Benefits and limitations

+ High accuracy
+ Models whole system, not restricted to one output
+ Can be used to make predictions about future climate
• Site/Flock/Animal specific
- Requires large number of inputs
- Can be computationally intensive
- Requires a large amount of data for model parameterisation

Further reading

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How to choose a modelling approach?

- What scale are you looking at?
  - Local, regional, national, international?
- What data do you have available?
- How much time do you have?
- Do you want to make predictions about the future?

Climate change impacts on sheep/goat production

Pastures

- Changes in plant species
- Reduced plant protein and increased carbohydrates
- Need for more bought-in feed
- Changing grazing seasons
- Changes in plant yields

Livestock

- Increased disease risk / More parasites
- Changes in mortality
- Harder to raise lambs
- Heat stress:
  - Reduced fertility
  - Reduced productivity
  - Reduced meat/milk quality

General

- Difficult to plan for the future due to increasing variability (in terms of both farm management and profits)
- Higher costs
- Lack of knowledge on how to deal with extreme events
- Farmer health (e.g. increased stress)

Adaptation options

Pastures

- Alternative plant species:
  - Deeper-rooting (more drought resistant)
  - More legumes (to increase protein content)
  - Multi-species swards (more resilient to a variety of changes)
- Plant trees around pastures (provides shade, conserves water, flood protection, attracts birds which eat pests, encourages pollinators, prevents eutrophication, …)

Adaptation options

Livestock

- Switch to more resilient breeds
- Breed for resilience to new climate
- Adjust stocking densities

Other

- Train farmers on the effects of climate change and how management practices need to change (e.g. water and soil management)
- More on-farm facilities, e.g. housing, ventilation systems

We neither fear complexity nor embrace it for its own sake, but rather face it with the faith that simplicity and understanding are within reach.

Fred Adler

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