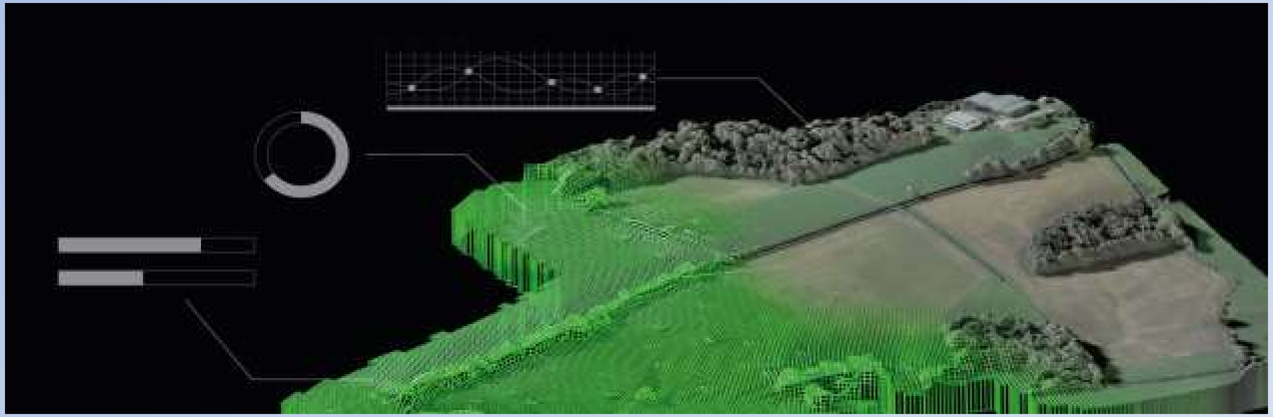
Envisioning Digital Twins for Instrumented Farms of the Future

Paul Harris

27/08/24



ROTHAMSTED RESEARCH North Wyke Farm Platform

Engineering and Physical Sciences Research Council

Natural Environment Research Council

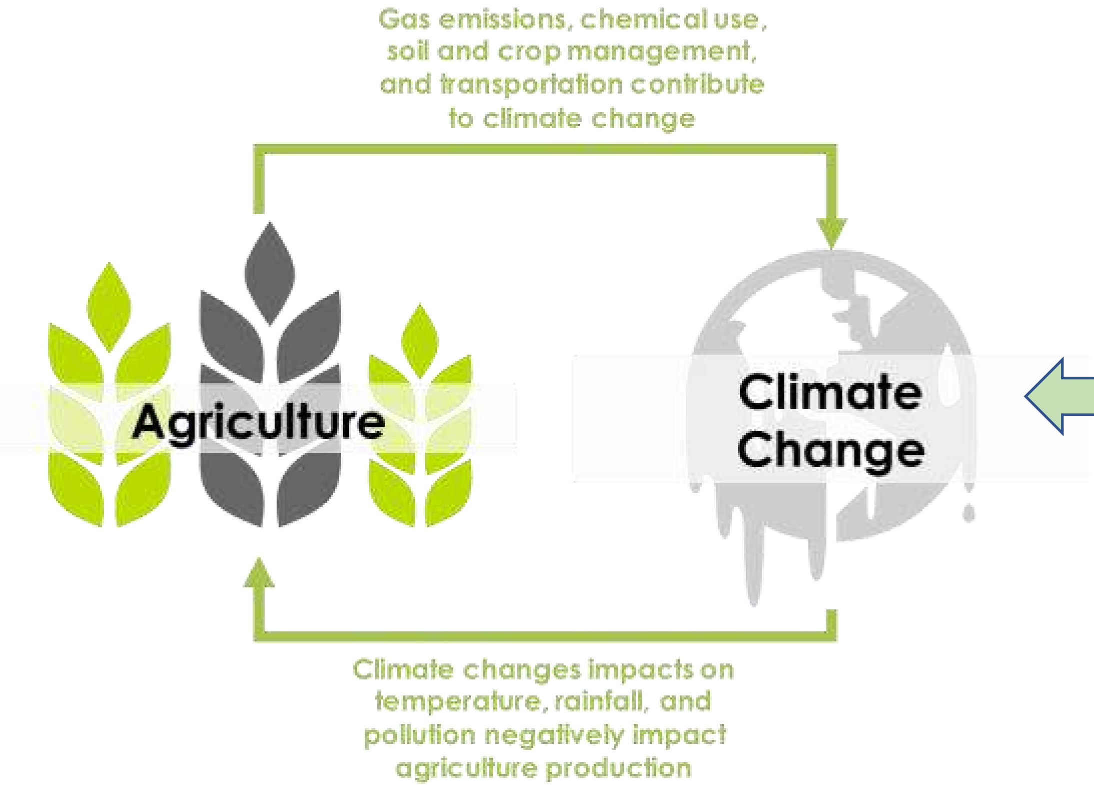
Biotechnology and Biological Sciences Research Council

ROTHAMSTED RESEARCH

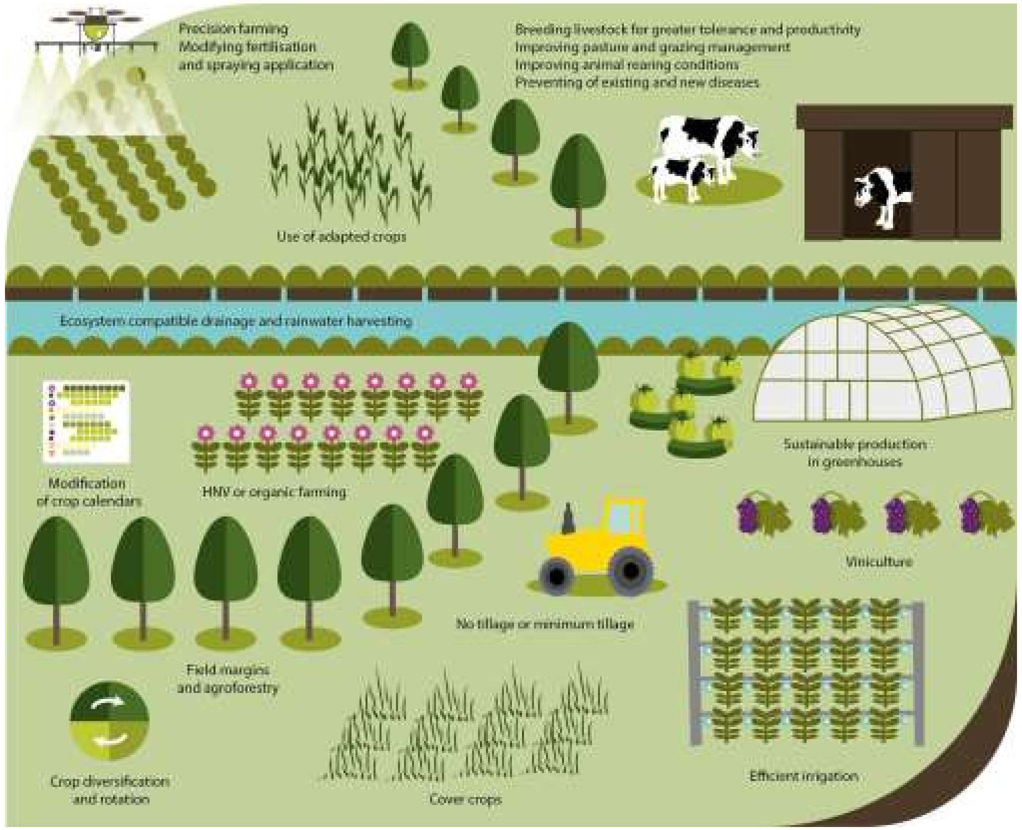
The Challenge

Agricultural challenges in the context of climate change

Agriculture both Contributes to and is Impacted by Climate Change



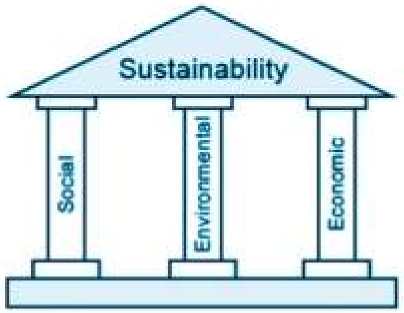
Solutions via On-farm Mitigations and Interventions



https://digital.hbs.edu/platform-rctom/submission/can-vertical-farming-reduce-agricultures-impact-on-climate-change/

https://www.eea.europa.eu/highlights/climate-change-threatens-future-of

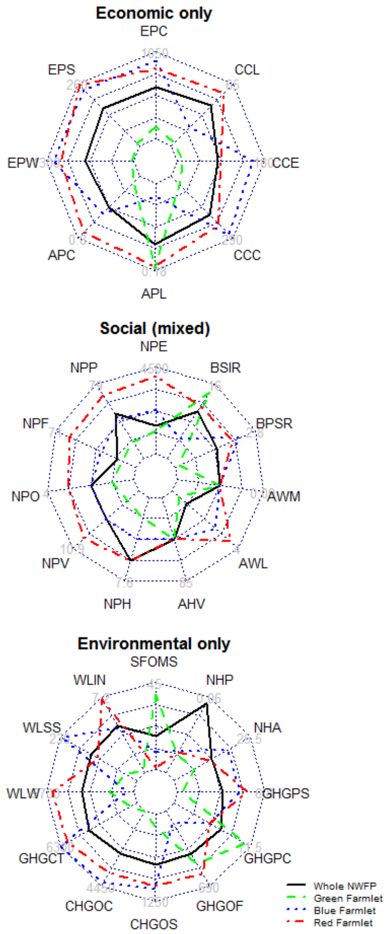
Sustainable versus Resilient Farming

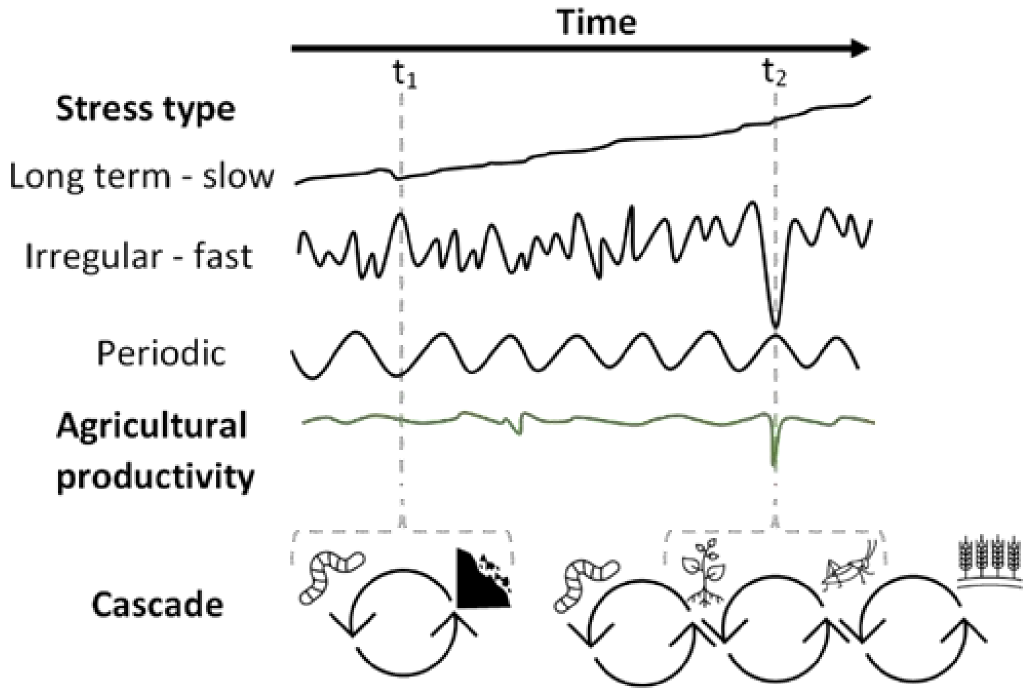


Balancing & Trade-offs

Requires data / metrics

Multi-dimensional with weights





Farming needs to be resilient to single & compound stresses

Need to detect signs of collapse / critical slowing down

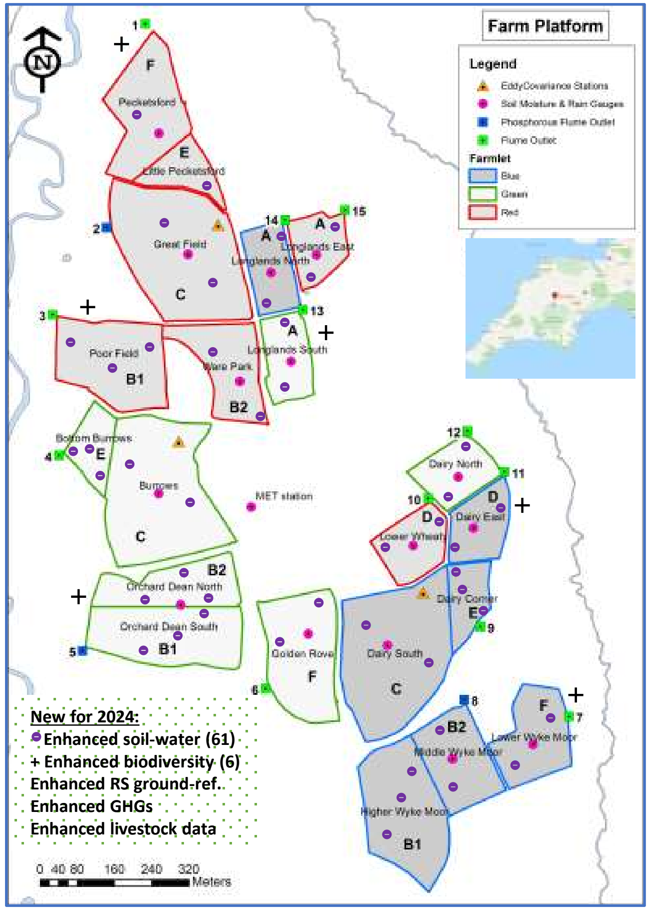
in time (& space-time) datasets

Analysis of data from farm-scale monitoring platforms can inform on either concept…

The Farm-scale Data Platform

Our Experimental Data Site: The North Wyke Farm Platform (est. 2010)

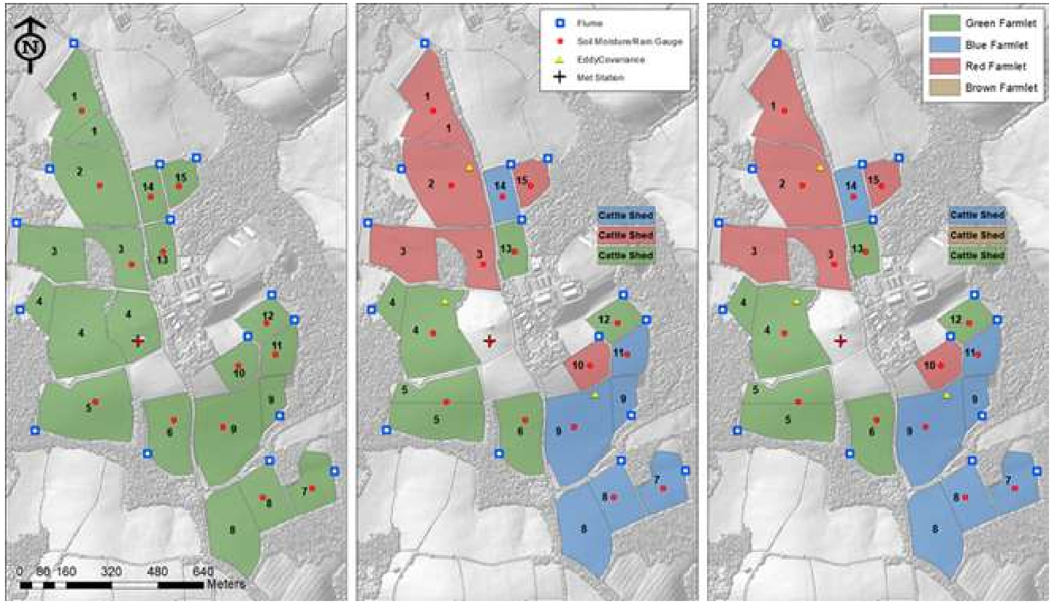
Mid-Devon, SW England









- Delivering 4-farm **systems-scale data** that is **representative** of all component processes. **Systems / treatments change periodically**
- Currently, **Grassland** (cattle & sheep; **green** & **blue** farms); **arable** (wheat/oats; **red** farm) & **housed** (cattle; **brown** farm)
- Objective: to facilitate **scalable research** for **alternative** (sustainable & resilient) land management strategies
- **Open data collections. Open facility**
- **Demonstrable impact from 14 years of data provision**

NWFP Hypotheses for each System Change period:

Many sub-hypotheses also…

Hypotheses associated with the baseline period include (2010 to 2013/5):

- Emissions to water under best practice lowland grazing farming will still exceed intrinsic losses as driven by soil type and slope.
- Emissions to water under best practice lowland grazing farming will still exceed some environmental thresholds for aquatic biology.
- Animal performance will be benchmarked within typical UK production levels (sheep and beef)

Hypotheses associated with the first system change period include (2013/5 to 2019):

- The re-seeding of permanent grassland with varieties that increase C sequestration and improve animal nutrition provide more sustainable grassland systems.
- The use of clover in pasture-based livestock production offers a high-risk high-return option for both commercial producers and the natural environment.
- Re-seeding of permanent pasture will provide greater returns in terms of animal performance than permanent pasture and in concert, reduce emission intensity.

Hypotheses associated with the second system change period include (2019 to present):

- In agro-ecological zones where the geographical environment does not suit human-edible crop production, farming systems without livestock are unsustainable - economically, environmentally and socially.
- Intensive housed finishing of cattle provides more sustainable outputs than extended grazing systems – economically, environmentally and socially.
- ~~Multi-functional swards with no in-organic fertilisation can deliver comparable sustainable returns – economically, environmentally and socially.~~

Some key questions for the NWFP to help answer…


Huge reduction in meat-eating 'essential' to avoid climate breakdown

Major study also finds huge changes to farming are needed to avoid destroying Earth's ability to feed its population

We label fridges to show their environmental impact - why not food?

Steak and a healthy vegetarian meal with pulses. Composite: Getty Images

A future with reduced meat consumption?

What are the positives / negatives of removing livestock from the landscape?
+ Reduce methane, reduce nitrous oxide, use land for rewilding instead?
- Loose source of dense nutrition

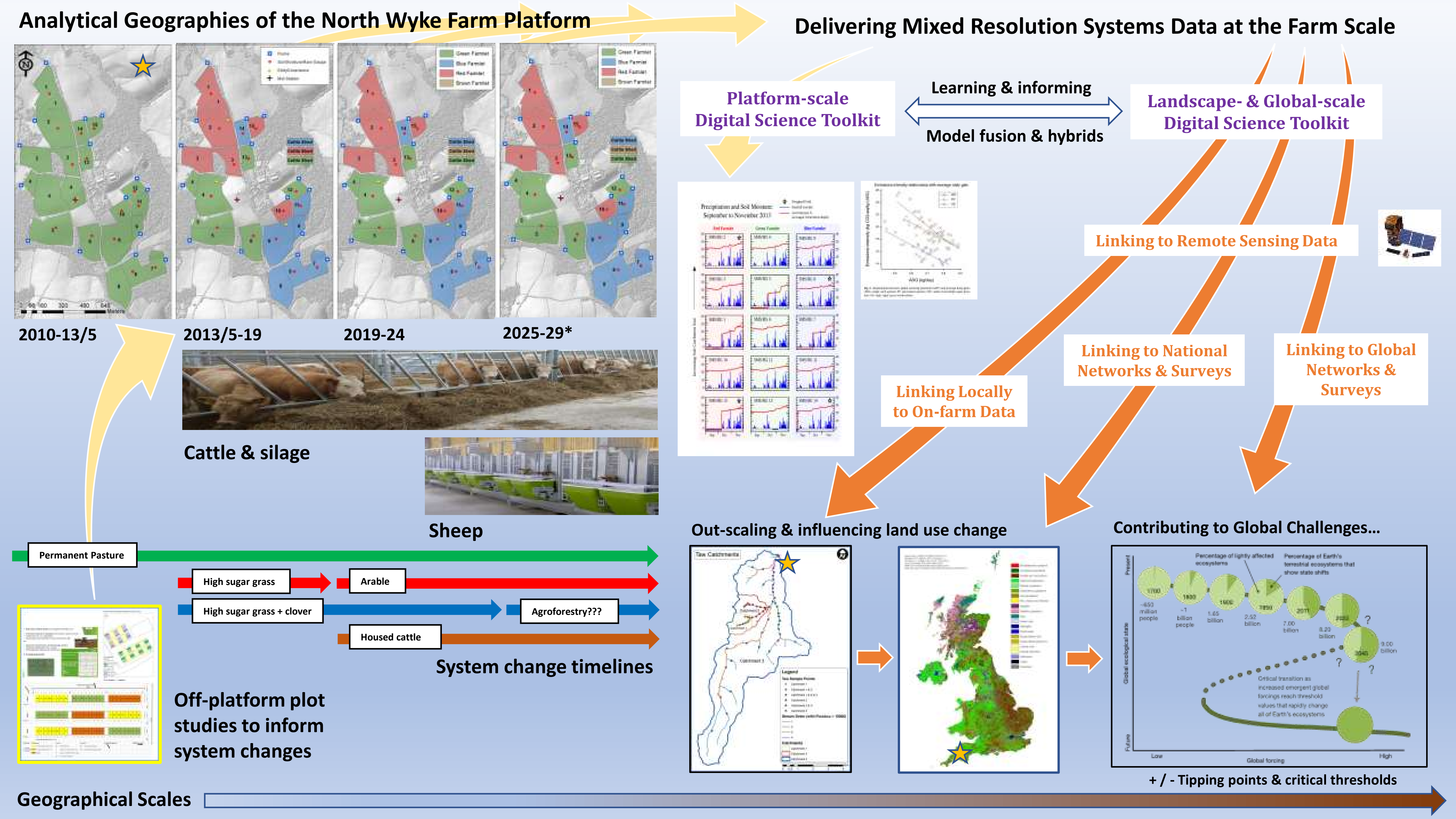
What are the positives / negatives of growing human edible crops on marginal land?

What are the unintended consequences?

It's a complicated story: Ruminants are very good at turning something we can't digest (grass) into something we can: high quality protein.

How does a change in land use play out regionally, nationally, globally?
E.g. UK livestock relatively good nutritionally than elsewhere

The NWFP has the infrastructure to help answer some of these challenging questions.


Analytical Geographies of the North Wyke Farm Platform
Delivering Mixed Resolution Systems Data at the Farm Scale
2010-13/5
2013/5-19
2019-24
2025-29*
Cattle & silage
Sheep
Platform-scale
Digital Science Toolkit
Learning & informing
Model fusion & hybrids
Landscape- & Global-scale
Digital Science Toolkit
Linking to Remote Sensing Data
Linking Locally
to On-farm Data
Linking to National
Networks & Surveys
Linking to Global
Networks &
Surveys
Permanent Pasture
High sugar grass
Arable
High sugar grass + clover
Agroforestry???
Housed cattle
System change timelines
Off-platform plot
studies to inform
system changes
Out-scaling & influencing land use change
Contributing to Global Challenges…
+ / - Tipping points & critical thresholds
Geographical Scales

Open data collections: 80+ million measurements & counting…

400+ Environmental Sensors

Category & Resolution	Core open collections	Other collections (mixture of open/closed)
Farm management Events - farm level	Grazing & arable management; field events (e.g. fertilizer apps.; silage cuts); housed management	*Farm economics (tractor hours, fuel use etc.)*
Crop performance - Periodic (weekly & coarser) - field level	Grass forage, silage & wheat/oats quality (nutrients & mass), silage cuts (mass)	*Take-all & fungi presence^; plate-meter* (Grasscheck GB)*
Livestock performance - 4-weekly - individual level	Liveweight gain & condition scores	*Livestock health & welfare^ (incl. animal-based sensors); carcass quality (abattoir); carcass imagery. Within-field livestock movement^ & behaviour^; cattle genomics* & phenotypes*, meat quality**
Water emissions - 15-minute - catchment (15)	Water physics & chemistry (flumes) (17 parameters)	*Storm sampling sediment / nutrients^ & microbiology^*
Soil/water - 15-minute - field level (20)	Soil moisture at 4 depths / temp (3 per field) & rainfall	*COSMOS Soil Moisture (one field only & open via CEH)*
MET - 15-minute - platform level	MET data (single site co-located with MO site) (6 parameters)	
GHG emissions - 30-minute (plume footprint) 3 fields only and housed GHGs (cattle / sheep)	Eddy Covariance GHG emissions (CO_2 & CH_4) *(49 parameters)* Greenfeed housed (CO_2 & CH_4)	*Other GHGs; field chambers (N_2O, CO_2, CH_4)^; direct livestock emissions (SF_6 tracers for CH_4)^; N_2O aerodyne (on EC site)**
Field surveys - Seasonal (quarterly), within-field & field level surveys	Soil / plant micro- & macro-nutrients; soil physics; soil fauna; grass flora biodiversity	*Some co-location with ECN collections*
Remote Sensing	Collections for ground-reference of RS data	*Forage Harvester, Drone (multispectral, hyperspectral, thermal)* & Satellite & further ground reference**
Biodiversity		*Bioacoustics (x6)*, Transects* and traps**

14 years of data across 3 outdoor farms Consisting of 15 hydrologically-isolated catchments and 20 fields

14 years of data from housed facilities for cattle & sheep

Data portal & website:

https://nwfp.rothamsted.ac.uk/

https://www.rothamsted.ac.uk/north-wyke-farm-platform

http://resources.rothamsted.ac.uk/farm-platform-national-capability/data-collections

^ Campaign data from a FP experiment (170+ to date)

*** Monitoring data & core funded**

❑ IoT data to the cloud

ROTHAMSTED RESEARCH

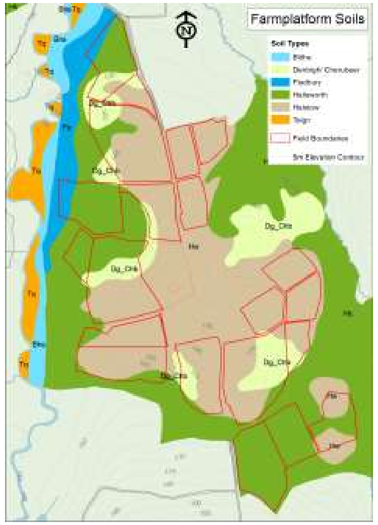
NWFP Data categorised by spatial unit, temporal frequency & level of automation…

Type-1 Collection	Spatial or Operational unit	Temporal Frequency	Start	End	Type-2 Collection	Spatial or Operational unit	Temporal Frequency	Start	End
Grazing & arable farm management activities (e.g., fertilizer apps, ploughing)	Farm-scale	Variable	2011	Ongoing	Livestock (cattle) welfare (behaviour & health)	Individual animal	Weekly	2019	Ongoing
Housed livestock management activities	Farm-scale	Variable	2011	Ongoing	Eddy Covariance GHG (CH4 & CO2 from soil, plant & livestock).	Sited in 3 of 20 platform fields (CH4 measured in 2 fields only)	30-minute	2017	Ongoing
Livestock performance (liveweight gain, condition scores)	Individual animal	2- to 4-weekly	2010	Ongoing	Eddy Covariance GHG (CH4 & N2O from soil, plant & livestock)	Addition of third CH4 & single N2O sensors	30-minute	2025	To start
Livestock performance (sales & carcase data)	Individual animal	End of life	2010	Ongoing	Citizen science app for wildlife sightings	Farm-scale	Intermittent	2022	2023
Livestock (cattle) performance (fat scanning)	Individual animal	2-scans per lifetime	2023	Ongoing	Bio-acoustic monitoring for biodiversity (birds, insects, bats) (x6 sensors)	Platform-scale	Continuous (1 week per month)	2023	Ongoing
Livestock (cattle) genomics & phenotypes	Individual animal	1-sample per lifetime	2018	Ongoing	Housed Greenfeed GHG (CH4 & CO2 from cattle)	Farm-scale (individual animal)	Variable	2017	Ongoing
Grazing crop quantity (silage cuts); RS ground reference	Field-scale	2-cuts per grazing season	2011	2020	Housed Greenfeed GHG (CH4 & CO2 from sheep)	Farm-scale (individual animal)	Variable	2022	Ongoing
‘GrassCheckGB’ extension; Un-grazed grass growth; RS ground reference	Off-platform (‘Top Burrows’ Met site)	Weekly	2018	2021	Forage Harvester (FH)	Within-field scale	Variable	2020	Ongoing
RS ground reference for ecosystem provisioning & plant communities	Field-scale	2-weekly	2024	Ongoing	Coordinated RS from Drone & Satellite with links to Forage Harvester	Within-field scale	Variable	2024	Ongoing
Grazing crop quality (forage)	Field-scale	2-weekly	2015	Ongoing	Water flow, physics and chemistry	Catchment-scale	15-minute	2012	Ongoing
Grazing crop quality (silage)	Farm-scale via Clamp / Bale	2-weekly	2015	Ongoing	Water flow, physics and chemistry ('bluemons' enhanced for Total C, N & P)	Catchment-scale	15-minute	2024	Ongoing
Arable crop quantity & quality (wheat, oats, beans)	Field-scale	Annual Harvest	2020	Ongoing	Soil Moisture (10cm) and Temperature (existing)	Field-scale (1 in 15 of 20 fields) (point sensors)	15-minute	2011	Ongoing
Fine-scale field surveys (soils & herbage nutrients, soil insects, vegetation)	Within-field level	Annual but intermittent	2012	Ongoing	Soil Moisture (10, 20, 30, 40 cm) and Temperature (enhanced)	Field-scale (3 in 20 of 20 fields + one extra) (point sensors)	15-minute	2024	Ongoing
Coarse-scale field surveys (soil & herbage nutrients)	Field-level (bulked samples)	Quarterly	2018	Ongoing	Rainfall (existing)	Field-scale (1 in 15 of 20 fields) (point sensors)	15-minute	2011	Ongoing
Above-ground biodiversity surveys (vegetation); RS ground reference	Transects across all 3 farms & into field margins / adjacent habitats	Bi-annual	2023	Ongoing	Rainfall (enhanced)	Field-scale (1 in 20 fields) (point sensors)	15-minute	2024	Ongoing
Above- & below-ground biodiversity surveys (soil insects); genetics (bioscan)	Sub-terranean traps	Campaign-style	2023	Ongoing	MET data	Platform-scale (Top Burrows) (point sensors)	15-minute	2011	Ongoing
Automated Chambers GHG (N2O, CH4 & CO2 from soil & plant).	Campaign deployment for 3 fields at any given time	Sub 10-minute	2013	Ongoing					
Sampling for PBMs (Ksat, soil texture, soil-water retention curves)	Within-field level (not all fields)	One-off campaigns	2019	Ongoing					

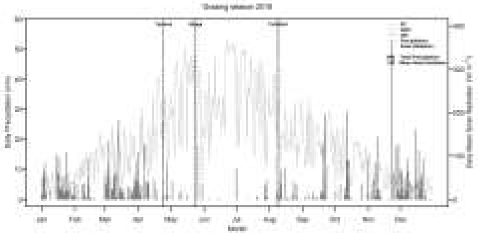
Type-1 data (orange) have an inherent human element. Type-2 data are either IoT-based (yellow) or have the potential to be so (gray).

Multiple processes measured across different spatial & temporal scales each of varying form / type…

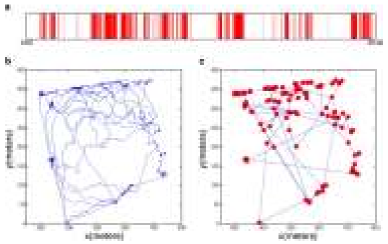
Topography, Soil Class & Boundaries

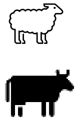


Farm management & Weather

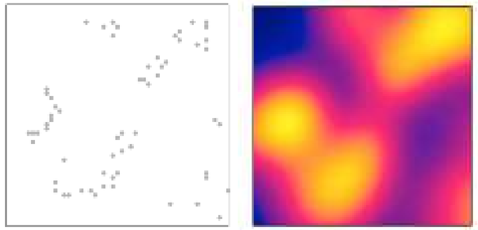


Livestock movement

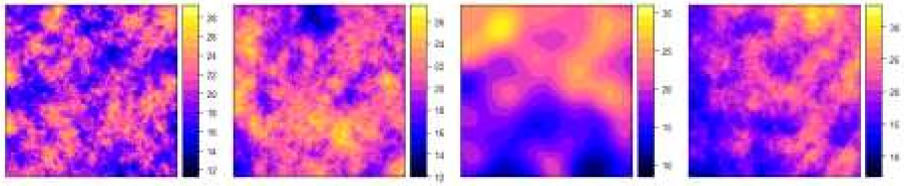




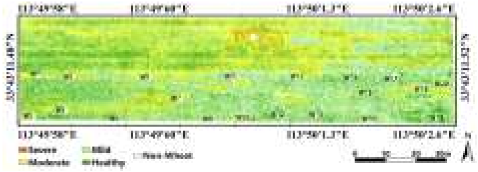
Dung & urine patches

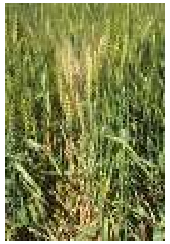


Soil physics & chemistry

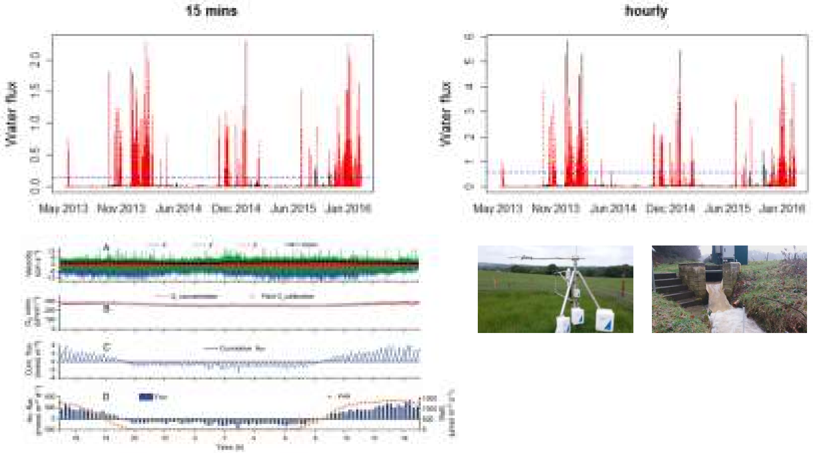


Disease & pests

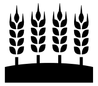


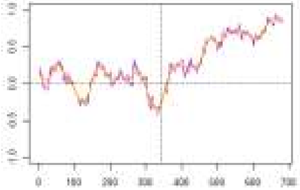


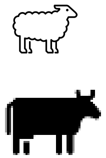
Emissions (Fluxes for water & gaseous emissions)

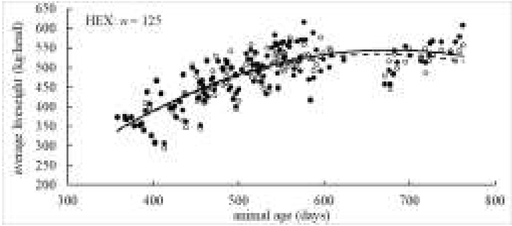


Livestock & crop performance

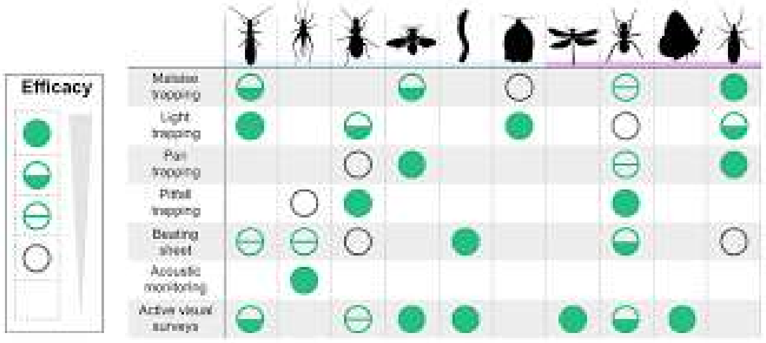








Biodiversity Status



Process-based Models on the NWFP

Can enrich FP measurements with simulations from process-based models (PBMs)

FP provides an enhanced data resource for PBM inputs, parameterisation & validation

Hind-cast, now-cast, forecast (simulate) for:

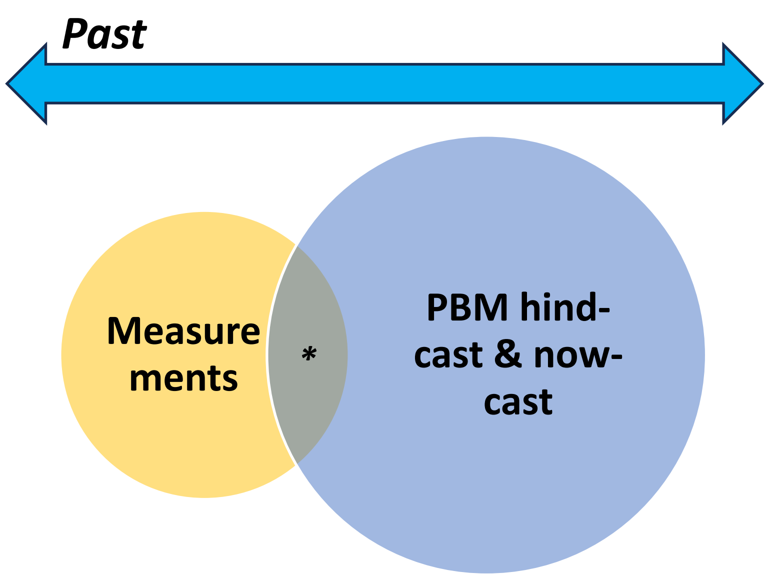
- ❑ Crop / livestock performance
- ❑ Soil-water status
- ❑ Nutrient (C, N & P) budgets / use efficiency
- ❑ Emissions to air & to water
- ❑ And more….

PBMs are ideal for:

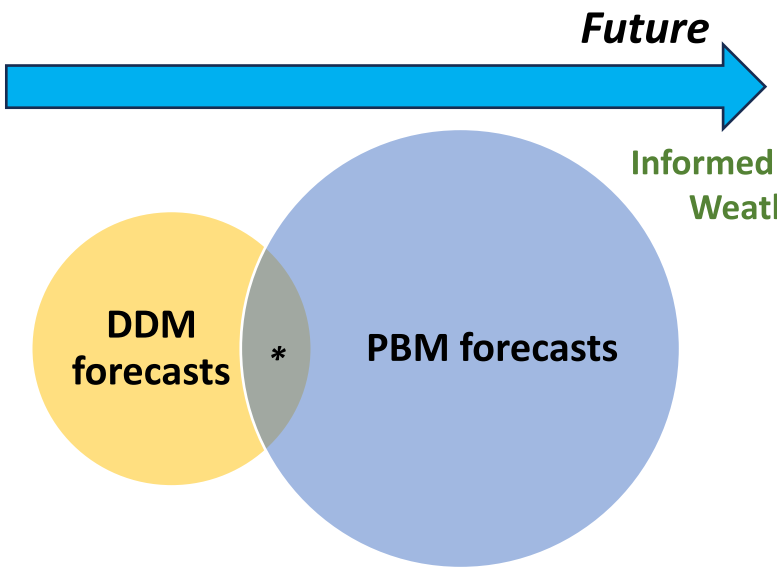
1. When data are scarce (as on real farms)
2. Processes that are difficult to measure
3. Forecasting & decision-making
4. Complementing Data-Driven Models (DDMs)

Minimal data inputs

Multiple outputs



** PBM validation space on FP*



Informed by Simulated Weather & Climate Scenarios

** Coincidental forecasts*


Agriculture, Ecosystems and Environment

Impact of transition from permanent pasture to new swards on the nitrogen use efficiency, nitrogen and carbon budgets of beef and sheep production

Agricultural Systems

Simulating grazing beef and sheep systems

FP has rich history of PBM development

PBM inputs and parameterisation:

Typical scale of operation:

- ❖ Daily Time step at field level

Inputs/parameterisation:

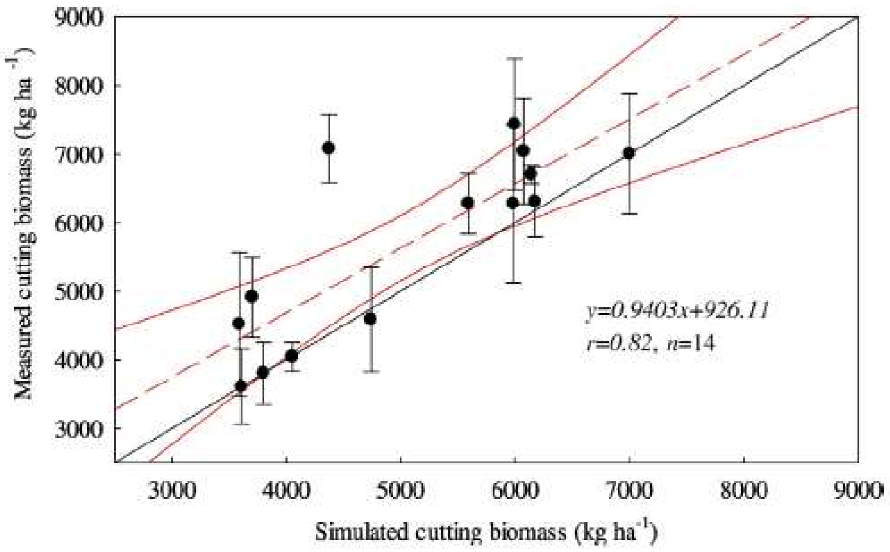
- ○ Weather data (time series) (simulated if in forecast mode)
- ○ Management data (projected if in forecast mode)
- ○ Book values (single)
- ○ Values from literature (single)
- ○ Soil survey data (if available – otherwise use above)

Outputs:

- ❑ Crop / livestock performance (productivity)
- ❑ Soil-water status
- ❑ Nutrient (C, N & P) budgets / cycling / efficiency
- ❑ Emissions to air & to water
- ❑ Trade-offs - Production / Environment

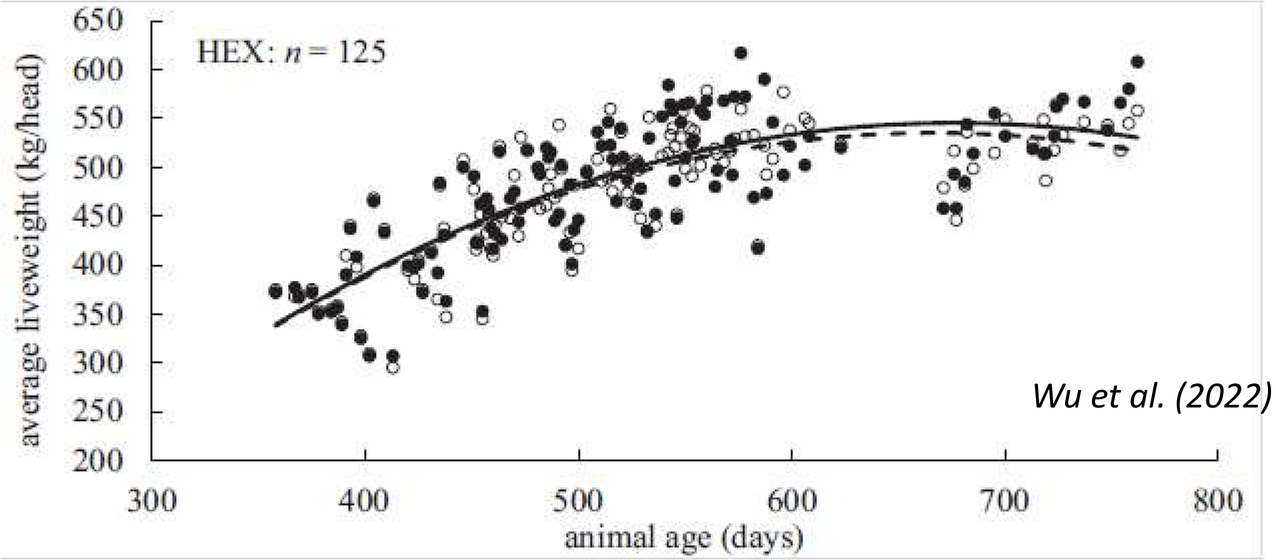
Direct validation (verification) possibilities for productivity

Crop Yield



Li et al. (2017)

Livestock weight gain



Wu et al. (2022)

Solid circles are measured average liveweight and open circles are simulated average liveweight.

What about capture of error and uncertainty with PBMs?

1. Diagnostics for in-sample prediction error / prediction accuracy (PBM validation)

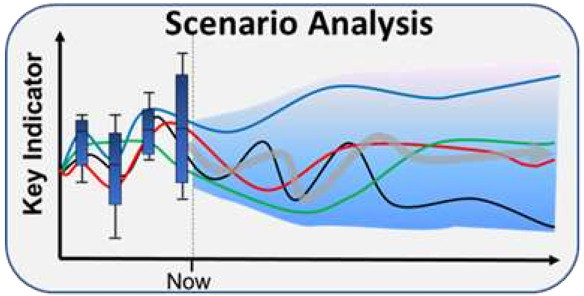
Table 3
Statistical analysis of simulated and measured water flow for the five sub-catchments (Total number of samples for each sub-catchment is 999).

Sub-catchment	No. 1	No. 2	No. 3	No. 10	No. 15
r	0.90[a]	0.90[a]	0.90[a]	0.86[a]	0.92[a]
$RMSE_{95\%}$	98.26%	119.82%	113.25%	154.56%	88.04%
EF	0.8	0.8	0.8	0.7	0.82
CD	1.58	1.14	1.23	0.84	1.65
$RE_{95\%}$	−353.39	−339.17	−331.4	−533.74	−187.06
MD	0.19	−0.49	−0.31	−0.59	0.43
ME	19.72	9.46	13.8	10.8	15.9

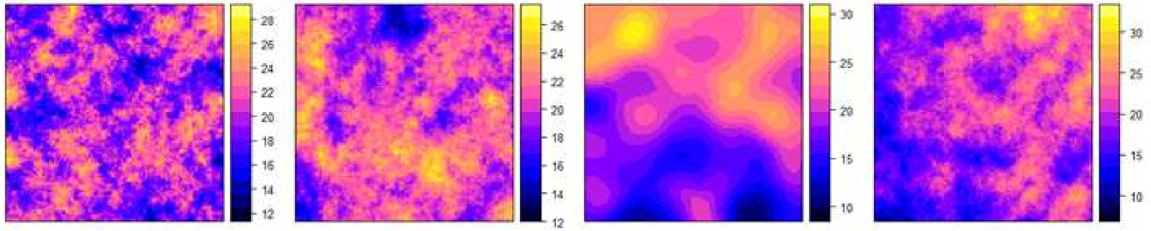
[a] Denotes significant association at the 5% level.

Li et al. (2017)

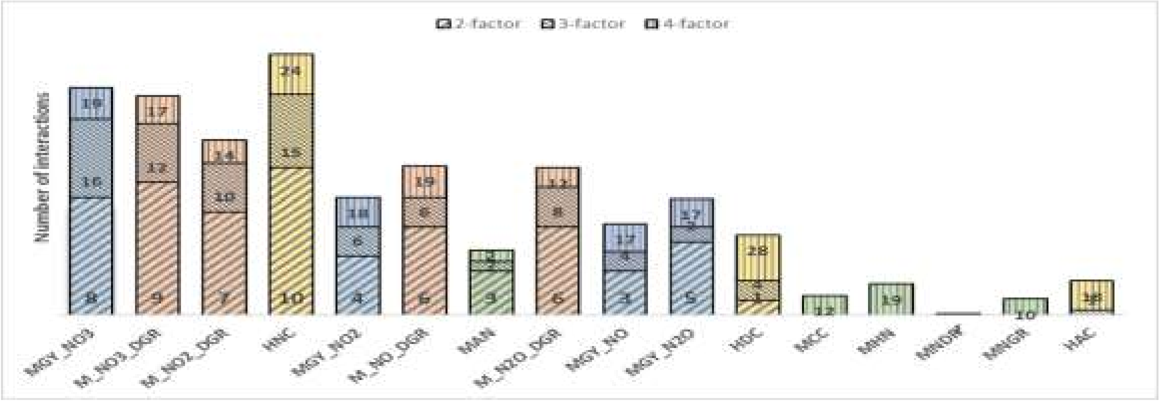
2. Scenario analyses for different future climates, different cropping times and durations etc. Provides 'Envelopes of Future Possibilities'



3. Parameterise with multiple realisations of a given process – sometimes conditioned to measured data. For example, within-field soil nutrients



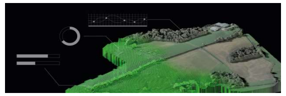
4. Local and global parameter sensitivity analyses

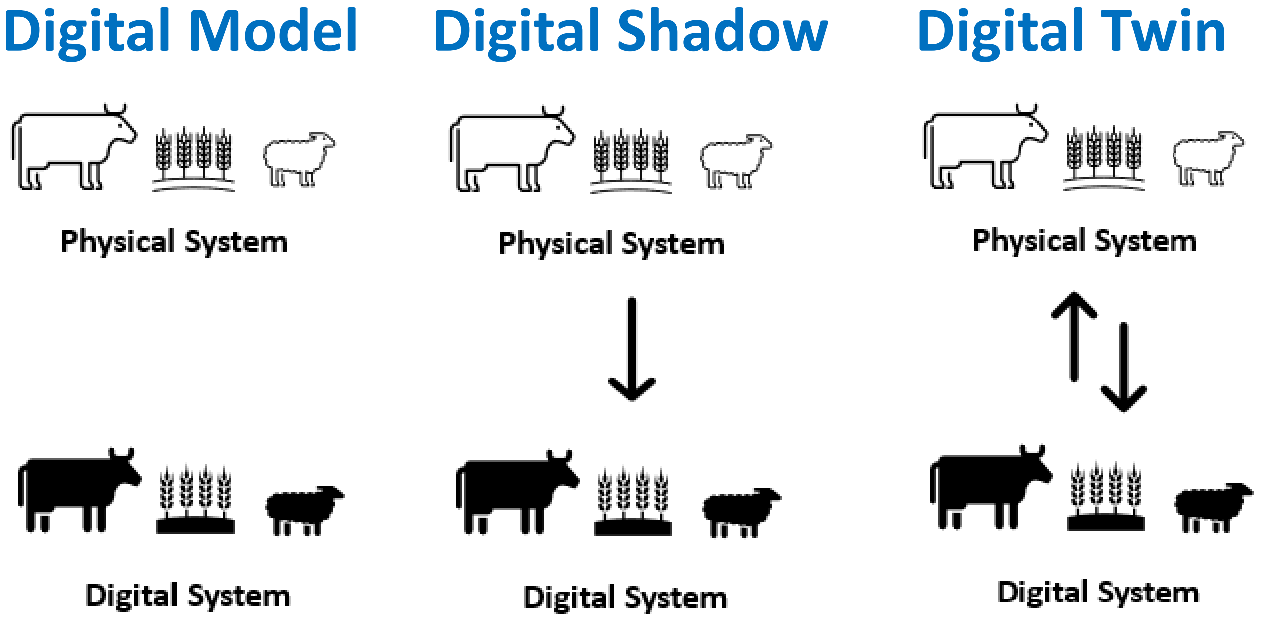


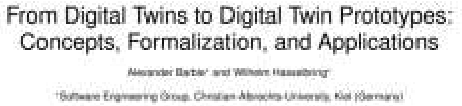
BUT - no true capture of prediction uncertainty – e.g.no 95% prediction confidence intervals or risk of exceedance, etc.

Farm Digital Twins

Re-casting the FP, its data & associated PBMs for Digital Twin technologies





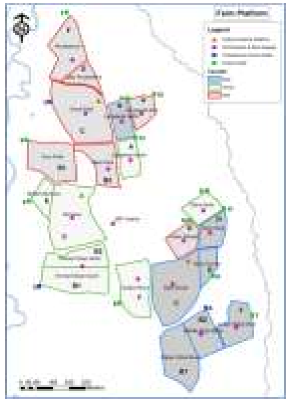

From Digital Twins to Digital Twin Prototypes: Concepts, Formalization, and Applications

- ❑ All 3 Digital Systems can provide a farm **Decision Support Tool** (DST)
- ❑ DM based DSTs are commonplace (reframing of PBMs); DS based DSTs are rare as require farm instrumentation; **DT based DSTs rarer still**
- ❑ Each can answer **'What if questions'** to inform decision-making for **sustainable and/or resilient and/or net zero** farming
- ❑ **Forecast accuracy and estimates of uncertainty** tend to improve moving from the DM to the DS to the DT
    - ❑ Or **risk of making (ill-informed) poor farming decisions reduce** moving from DM to DS to DT
- ❑ **CAVEAT:** FP can only provide **demonstrator farm DTs** as can only implement feedback that does not compromise its monitoring status

Proposed Analytical Framework:

- **PBMs provide the core simulations** of the 3 farm systems (& can be used in ensemble).
- So, a separate DT for each FP farm (**Blue-DT**, **Red-DT** & **Green-DT**)
- Right (in) time coupling of PBM forecasts via *in situ* & remote sensor data, via:

New for 2024:
60 Soil moisture sensors
20 Rain gauges
6 Bio-acoustic Sensors
Enhanced RS ground-ref.
Enhanced GHGs
Enhanced livestock data

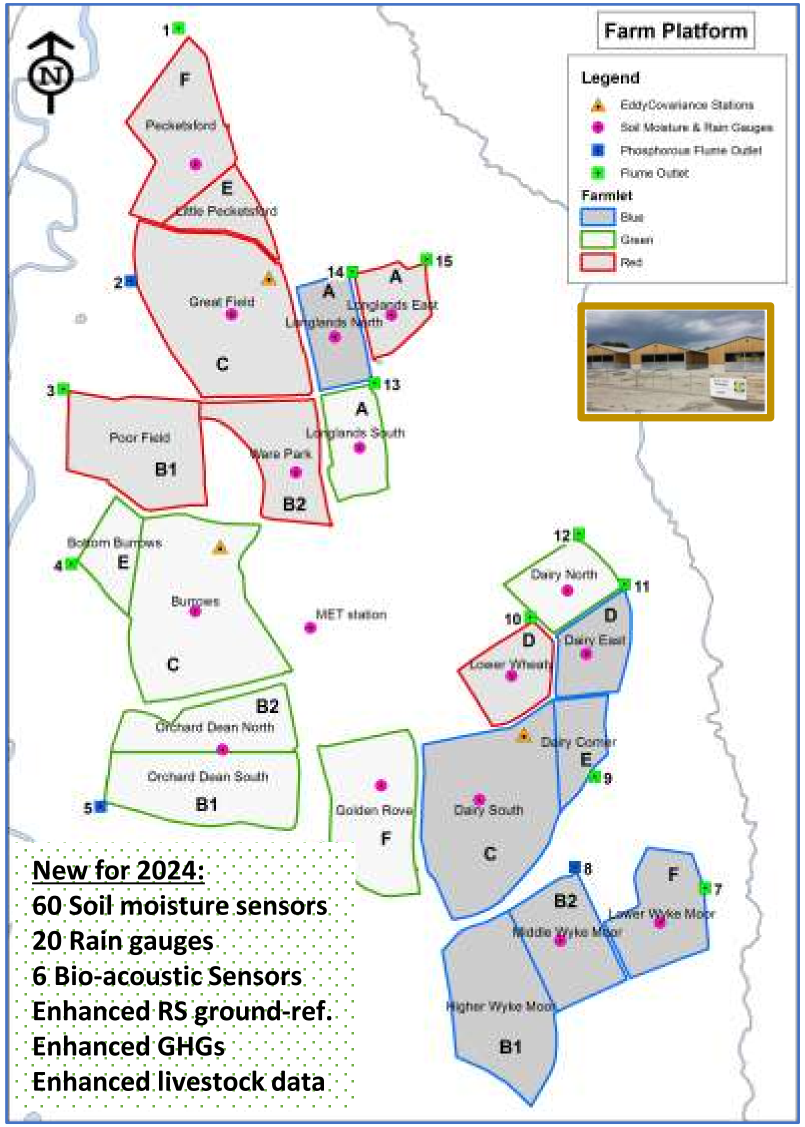


- ❖ **Option #1** PBMs but where any data-rich component process is replaced with a DDM that is continuously retrained
    - ❖ For example, apply a DDM to 15-minute soil moisture data to improve yield and gaseous emissions simulations
    - ❖ Suffices for forecasting broad trends and patterns
- ❖ **Option # 2** Use PBM-DDM hybrids to better capture detail and nuance (different to #1)
    - ❖ Ideal for changes in variance or the capture of extremes
- ❖ **Option # 3** Replace PBMs with their emulators (via DDMs)
    - ❖ Reduces computational overheads and ensures more timely decision making

❑ Each provide an improved quantification of uncertainty over a PBM (DM) alone, say via a Bayesian or quantile-based framework

Choice depends on the situation, the level of instrumentation, computational overheads, and the questions being asked of the twin

Data: North Wyke Farm Platform



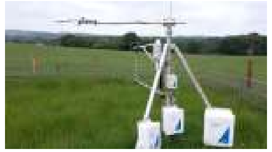
New for 2024:
60 Soil moisture sensors
20 Rain gauges
6 Bio-acoustic Sensors
Enhanced RS ground-ref.
Enhanced GHGs
Enhanced livestock data

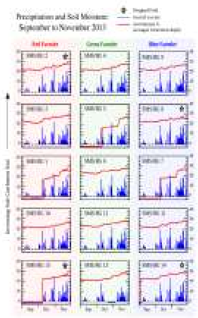
Type-1 Collection	Spatial or Operational unit	Temporal Frequency	Start	End	Type-2 Collection	Spatial or Operational unit	Temporal Frequency	Start	End
Grazing & arable farm management activities (e.g., fertilizer apps, ploughing)	Farm-scale	Variable	2011	Ongoing	Livestock (cattle) welfare (behaviour & health)	Individual animal	Weekly	2019	Ongoing
Housed livestock management activities	Farm-scale	Variable	2011	Ongoing	Eddy Covariance GHG (CH_4 & CO_2 from soil, plant & livestock).	Sited in 3 of 20 platform fields (CH_4 measured in 2 fields only)	30-minute	2017	Ongoing
Livestock performance (liveweight gain, condition scores)	Individual animal	2- to 4-weekly	2010	Ongoing	Eddy Covariance GHG (CH_4 & N_2O from soil, plant & livestock)	Addition of third CH_4 & single N_2O sensors	30-minute	2025	To start
Livestock performance (sales & carcase data)	Individual animal	End of life	2010	Ongoing	Citizen science app for wildlife sightings	Farm-scale	Intermittent	2022	2023
Livestock (cattle) performance (fat scanning)	Individual animal	2-scans per lifetime	2023	Ongoing	Bio-acoustic monitoring for biodiversity (birds, insects, bats) (x6 sensors)	Platform-scale	Continuous (1 week per month)	2023	Ongoing
Livestock (cattle) genomics & phenotypes	Individual animal	1-sample per lifetime	2018	Ongoing	Housed Greenfeed GHG (CH_4 & CO_2 from cattle)	Farm-scale (individual animal)	Variable	2017	Ongoing
Grazing crop quantity (silage cuts); RS ground reference	Field-scale	2-cuts per grazing season	2011	2020	Housed Greenfeed GHG (CH_4 & CO_2 from sheep)	Farm-scale (individual animal)	Variable	2022	Ongoing
'GrassCheckGB' extension; Un-grazed grass growth; RS ground reference	Off-platform ('Top Burrows' Met site)	Weekly	2018	2021	Forage Harvester (FH)	Within-field scale	Variable	2020	Ongoing
RS ground reference for ecosystem provisioning & plant communities	Field-scale	2-weekly	2024	Ongoing	Coordinated RS from Drone & Satellite with links to Forage Harvester	Within-field scale	Variable	2024	Ongoing
Grazing crop quality (forage)	Field-scale	2-weekly	2015	Ongoing	Water flow, physics and chemistry	Catchment-scale	15-minute	2012	Ongoing
Grazing crop quality (silage)	Farm-scale via Clamp / Bale	2-weekly	2015	Ongoing	Water flow, physics and chemistry ('bluemons' enhanced for Total C, N & P)	Catchment-scale	15-minute	2024	Ongoing
Arable crop quantity & quality (wheat, oats, beans)	Field-scale	Annual Harvest	2020	Ongoing	Soil Moisture (10cm) and Temperature (existing)	Field-scale (1 in 15 of 20 fields) (point sensors)	15-minute	2011	Ongoing
Fine-scale field surveys (soils & herbage nutrients, soil insects, vegetation)	Within-field level	Annual but intermittent	2012	Ongoing	Soil Moisture (10, 20, 30, 40 cm) and Temperature (enhanced)	Field-scale (3 in 20 of 20 fields + one extra) (point sensors)	15-minute	2024	Ongoing
Coarse-scale field surveys (soil & herbage nutrients)	Field-level (bulked samples)	Quarterly	2018	Ongoing	Rainfall (existing)	Field-scale (1 in 15 of 20 fields) (point sensors)	15-minute	2011	Ongoing
Above-ground biodiversity surveys (vegetation); RS ground reference	Transects across all 3 farms & into field margins / adjacent habitats	Bi-annual	2023	Ongoing	Rainfall (enhanced)	Field-scale (1 in 20 fields) (point sensors)	15-minute	2024	Ongoing
Above- & below-ground biodiversity surveys (soil insects); genetics (bioscan)	Sub-terranean traps	Campaign-style	2023	Ongoing	MET data	Platform-scale (Top Burrows) (point sensors)	15-minute	2011	Ongoing
Automated Chambers GHG (N_2O, CH_4 & CO_2 from soil & plant).	Campaign deployment for 3 fields at any given time	Sub 10-minute	2013	Ongoing					
Sampling for PBMs (Ksat, soil texture, soil-water retention curves)	Within-field level (not all fields)	One-off campaigns	2019	Ongoing					

Type-1 data (orange) have an inherent human element. Type-2 data are either IoT-based (yellow) or have the potential to be so (gray).

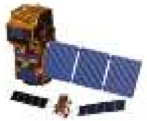


Environmental Sensors

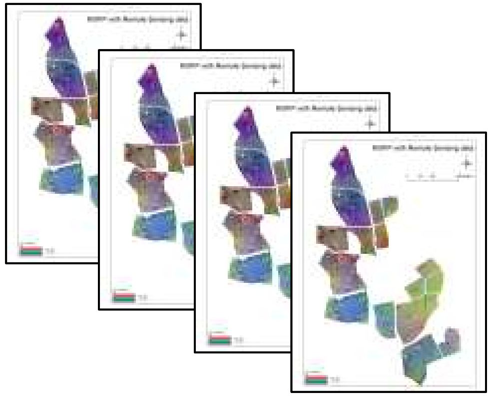




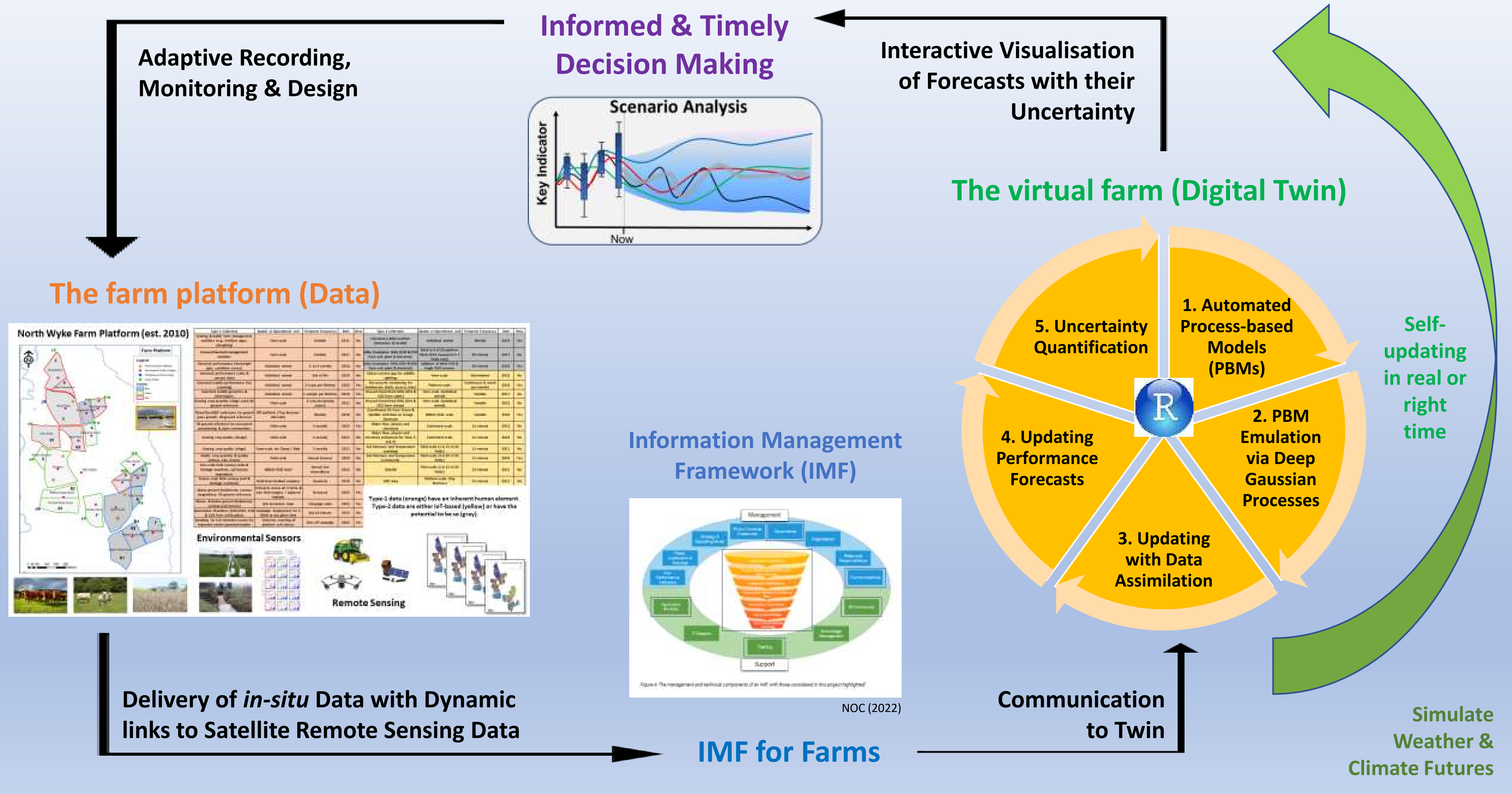




Remote Sensing

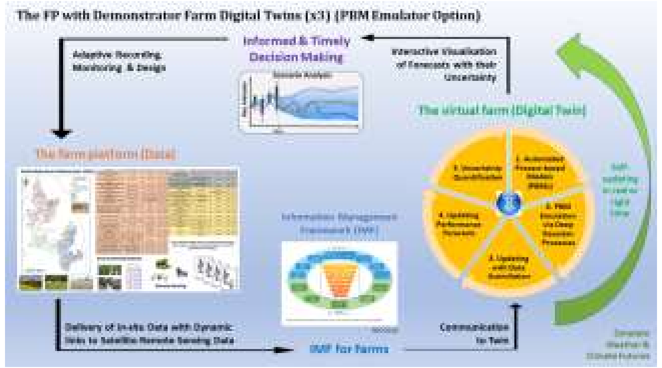


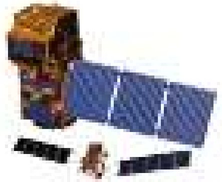
The FP with Demonstrator Farm Digital Twins (x3) (PBM Emulator Option)



Informing Bespoke Real Farm Digital Twins

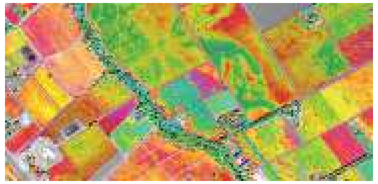
Transfer infrastructure developed on the Demonstrator Farm Digital Twins

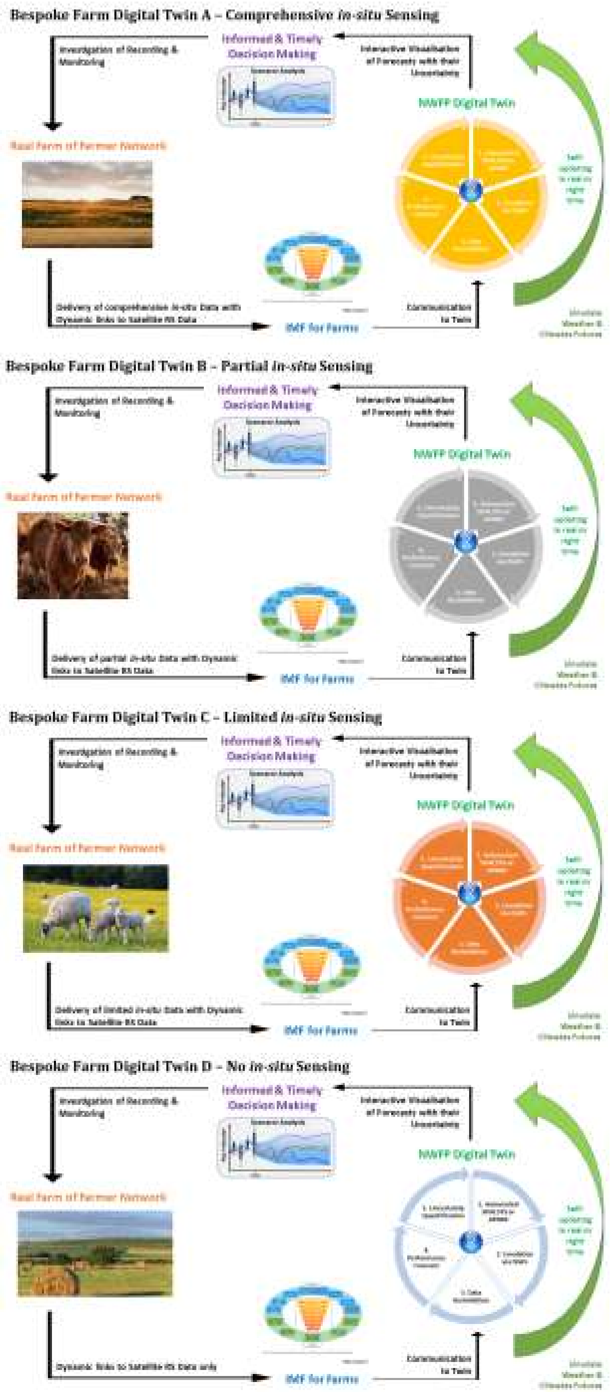




Satellite remote sensing for data assimilation

Basic level of forecasting and associated measures of risk



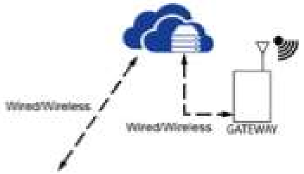


GOLD

SILVER

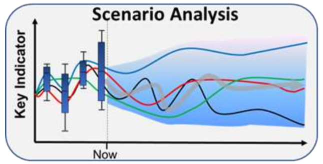
BRONZE

BASIC

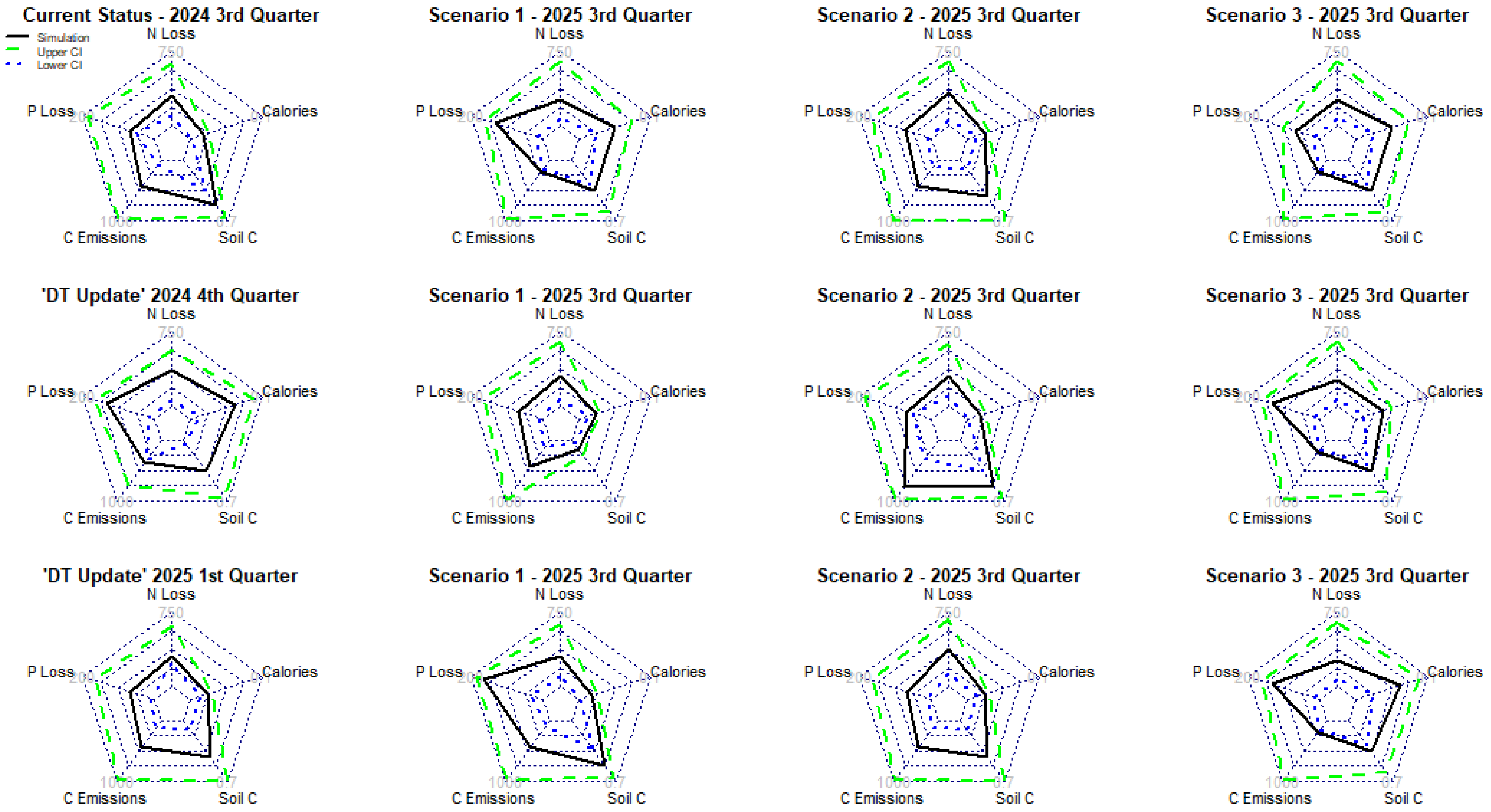


Increasing levels of on-farm sensing for improved data assimilation.

Improves forecasting and associated measures of risk



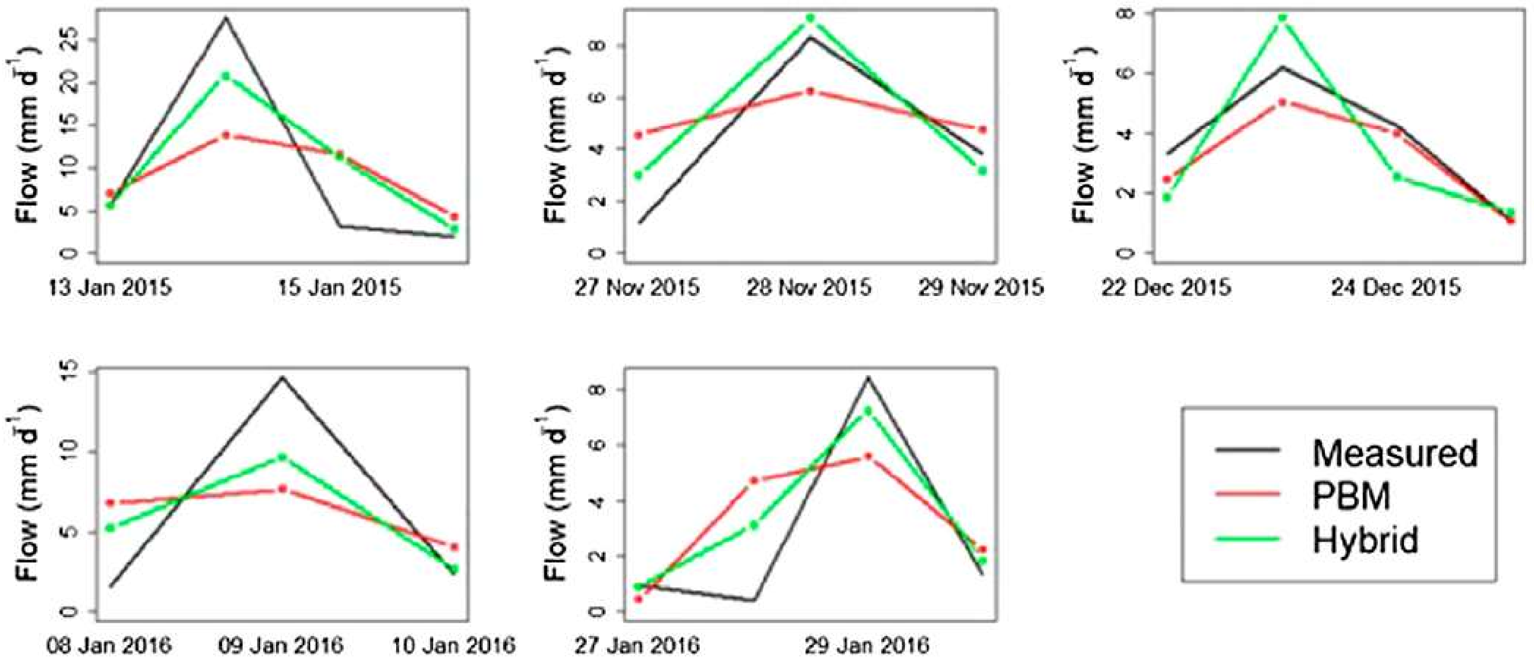
Example ‘What if’ Dashboard for Sustainable Farming: Blue-DT with three alternative management scenarios:

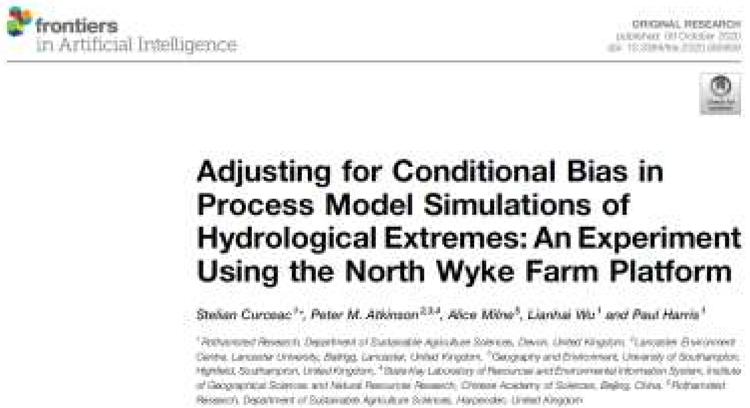


** Digital Twin provides 3-monthly updates ** ** In this instance, weather scenario is fixed ** ** Uncertainty captured via Credible Intervals **

Analytical Snippets:

Analytical snippet # 1: Addressing PBMs poor capture of detail and nuance via PBM-DDM Hybrids




frontiers in Artificial Intelligence

ORIGINAL RESEARCH

Adjusting for Conditional Bias in Process Model Simulations of Hydrological Extremes: An Experiment Using the North Wyke Farm Platform

Stelian Curceac[1], Peter M. Atkinson[2,3,4], Alice Milne[5], Lianhai Wu[1] and Paul Harris[1]*

Extreme water run-off events via a PBM coupled with two Data Driven Models (DDMs):

- ❖ **Statistical extreme-value model**
- ❖ **Machine Learning extreme-value model**

Analytical snippet # 2: Remote Sensing studies for Carbon dynamics

DDM (GAM) with harmonised Landsat time series

Journal of Environmental Management 365 (2024) 121573

Contents lists available at ScienceDirect

Journal of Environmental Management

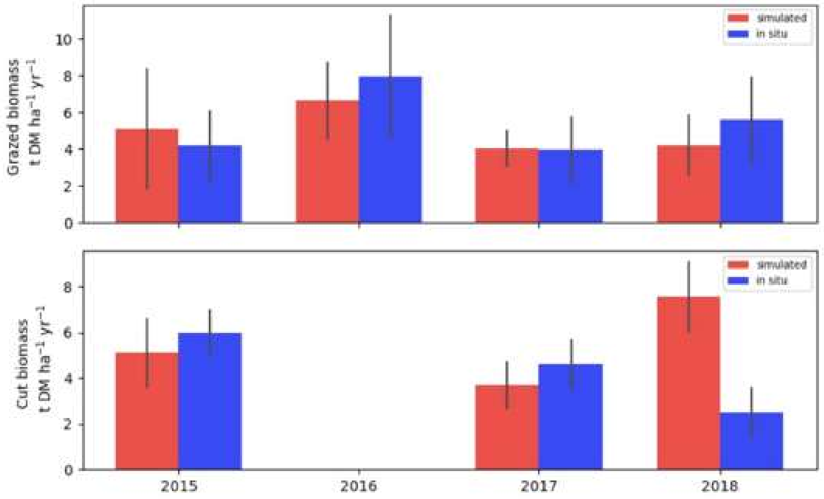
journal homepage: www.elsevier.com/locate/jenvman

ELSEVIER

Research article

Comparison of direct and indirect soil organic carbon prediction at farm field scale

C. Segura[a,*], A.L. Neal[a], L. Castro-Sardiña[b], P. Harris[a], M.J. Rivero[a], L.M. Cardenas[a], J.G. N. Irisarri[a]



PBM-DDM with Sentinal-2 / Proba-V Leaf Area Index data

Agricultural and Forest Meteorology 307 (2021) 108466

Contents lists available at ScienceDirect

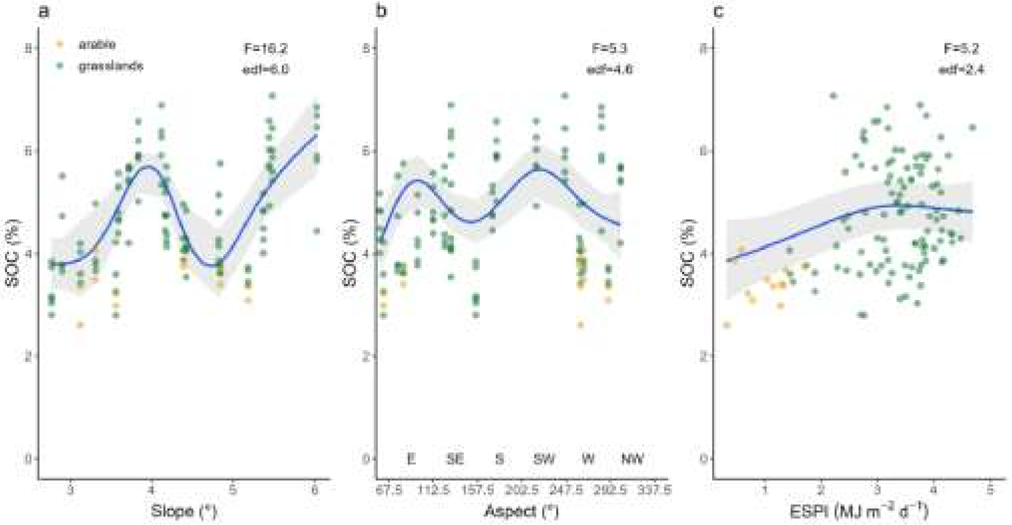
Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

ELSEVIER

Inferring management and predicting sub-field scale C dynamics in UK grasslands using biogeochemical modelling and satellite-derived leaf area data

Vasileios Myrgiotis[*,a], Paul Harris[b], Andrew Revill[a], Hadewij Sint[b], Mathew Williams[a]



Analytical snippet # 3: farm sensor design topics

Home > Web and Wireless Geographical Information Systems > Conference paper

Geosensor Network Optimisation to Support Decisions at Multiple Scales

Alexis Comber & Paul Harris

Conference paper | First Online: 05 June 2023

146 Accesses

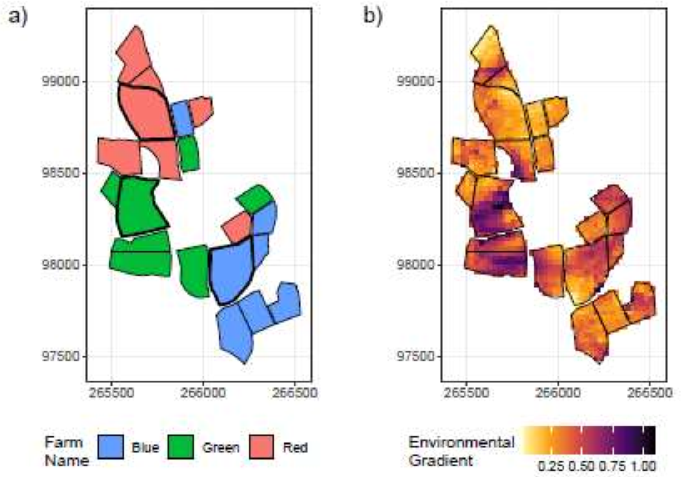
Part of the Lecture Notes in Computer Science book series (LNCS,volume 13912)

Local designs for optimal sensor placement on farm and for within-field (i.e., where to place a soil sensor).

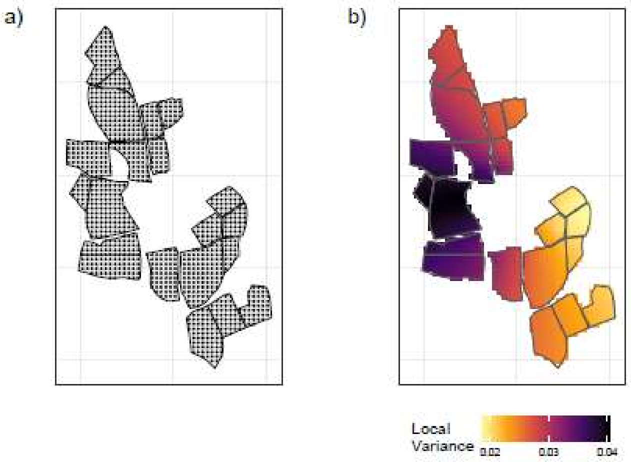
Cost-benefit analysis for the value of data and the implementation of associated re-designs (e.g., timely ways to discontinue low impact high resource collections).

Identify surrogates - low resource inexpensive data sets. Capture of error and uncertainty.

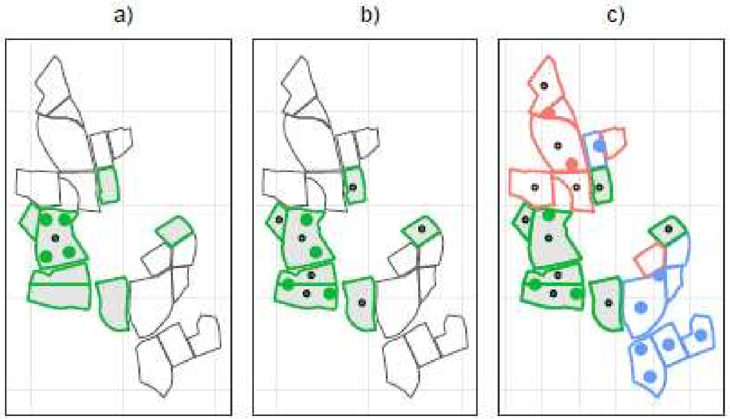
Global designs to optimise the 'hub and spoke' site configuration at the UK level (i.e., where to site additional experimental farm platforms).



(a) Green, Blue & Red Farms; (b) composite environmental gradient – topography & soil physics



(a) Potential sensor locations; (b) Local variance at those locations



(a) Green farm with 4 new sensors for field or (b) farm sensing; (c) all 3 farms sharing resources with 12 new sensors.

Black dots existing sensing capacity at field, farm or network scale

ROTHAMSTED RESEARCH

Thank you

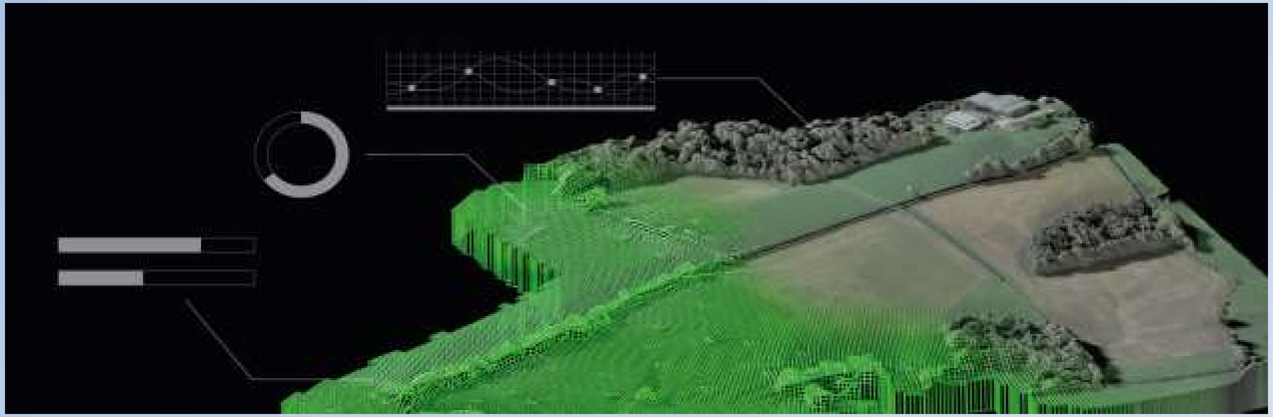
Extra Slides

Title Slides

The North Wyke Farm Platform NBRI: Its Science & its Digital Initiatives

Paul Harris, Adie Collins, Bruce Griffith, Phil Le Grice and many more

23/07/24



ROTHAMSTED RESEARCH North Wyke Farm Platform

Engineering and Physical Sciences Research Council
CIEL
Natural Environment Research Council
Biotechnology and Biological Sciences Research Council
ROTHAMSTED RESEARCH

Contributions from multiple project teams (as of 2024):

ROTHAMSTED RESEARCH

1. Data Platform - North Wyke Farm Platform NBRI (2023-28):

Debs Beaumont (biodiversity/field), Tegan Darch (data steward), **Bruce Griffith (farm lead/operations),** Jane Hawkins (biogeochemistry/data/website), Andy Jones (livestock/sheep), **Phil Le Grice (livestock/cattle/strategy),** Graham Leask (statistics), Nadine Loick (GHGs), Andrew Mead (statistics/design), Hazem Nureldin (software), Louise Olde (data/GHGs/water/sensors), Richard Ostler (data systems), Chris Powe (field/sensors), Maria Resendez-Sepulveda (field/surveys), Hadewij Sint (data systems/GIS), Helena Taylor (field/lab) & **Paul Harris (PI)**

2. RRes Science Support (2023-28):

Martin Blackwell (soils/water), Laura Cardenas (GHGs/soils), Gonzalo Irisarri (remote sensing), Andy Neal (soils), Jordana Rivero (grazing livestock, GHGs), Ian Shield (arable crops), **Adie Collins (water/NZRF science director)** & many more

3. Decision Support via Digital Shadows – 'Sensing Oats with APSIM' (SOAP) (UK & Australia Farms) (2023-26):

Prakash Dixit, Gonzalo Irisarri, Yunru Lai, Alice Milne, Keith Pembleton & **Paul Harris (PI)**

4. Decision Support via Digital Models / Twins – 'Resilient Farming Futures' ISP WP3 (Farm & Catchment) (2023-28):

Martin Blackwell, Kevin Coleman, Tegan Darch, Prakash Dixit, Gonzalo Irisarri, **Paul Harris (WP3 lead),** Annalisa Lanza, Andrew Mead, Helen Metcalfe, Richard Ostler, Simon Willcock & **Adie Collins (PI)**

5. Decision Support via Digital Twins – 'Biodiversity & Climate Crisis' with Alan Turing Institute (Farm) (2024-26):

Ireoluwa Fakeye, Paul Harris, Gonzalo Irisarri, Ellen Maas, Andrew Mead, Richard Ostler, Bader Ouliad & **Chris Baker (PI)**

The Farm-scale Data Platform

Increasing value of open data with increasing # of publications

ROTHAMSTED RESEARCH

- **To date: 70+ publications directly** using FP data
- **Many collections reaching maturity** (as 14 years in)
- **Plenty of FP hypotheses remain un-tested**
- **Opportunities for re-analysis with AI tools**
- **Wealth of supplementary info & tools**

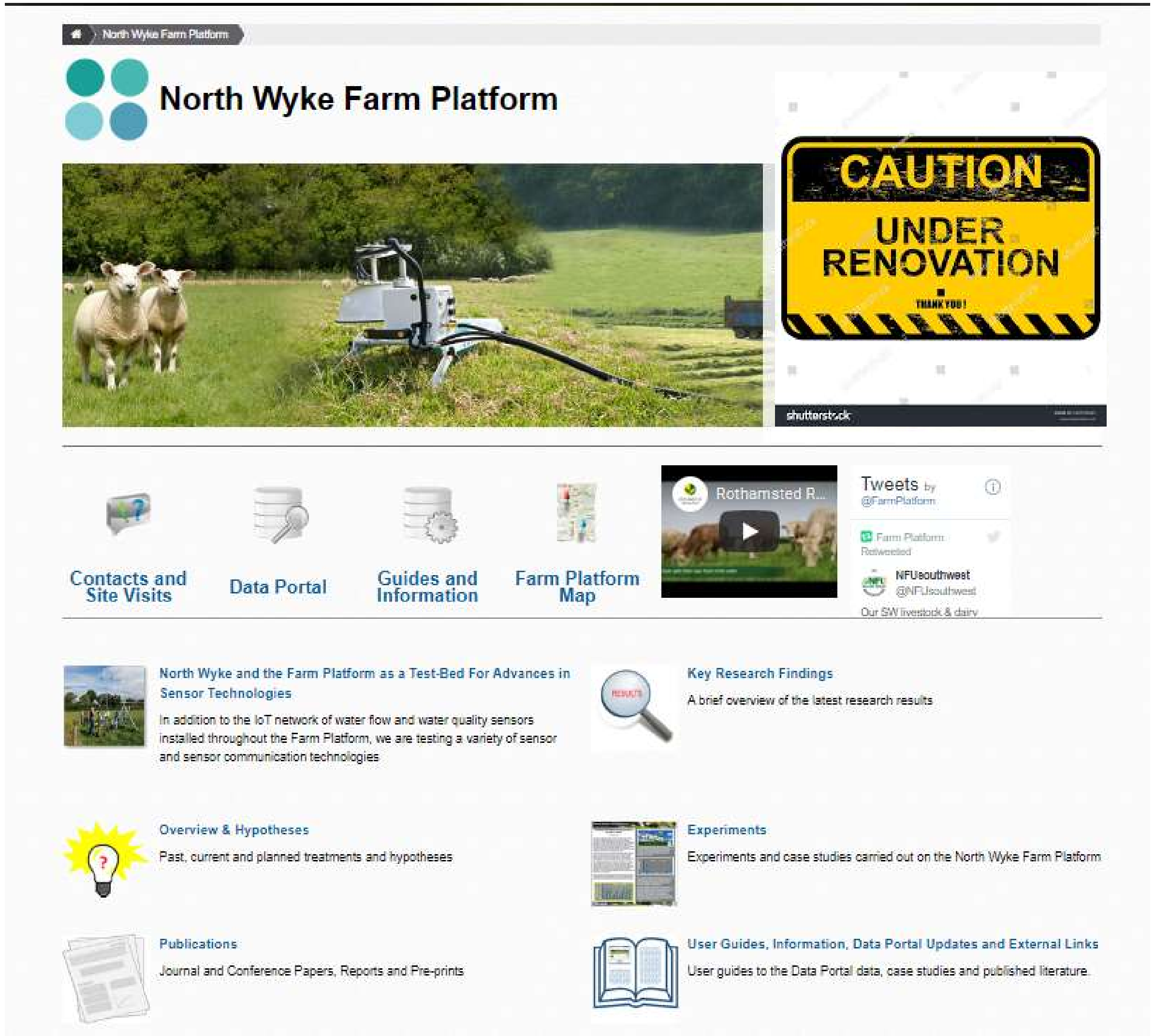
http://resources.rothamsted.ac.uk/north-wyke-farm-platform/publications

http://resources.rothamsted.ac.uk/north-wyke-farm-platform/overview-hypotheses

https://nwfp.rothamsted.ac.uk/

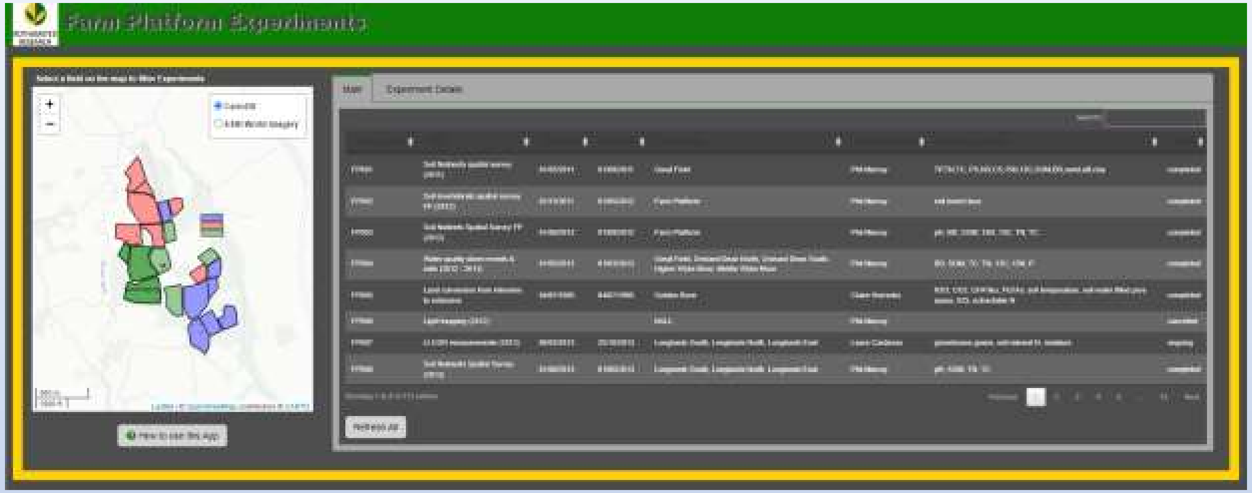
https://www.rothamsted.ac.uk/north-wyke-farm-platform

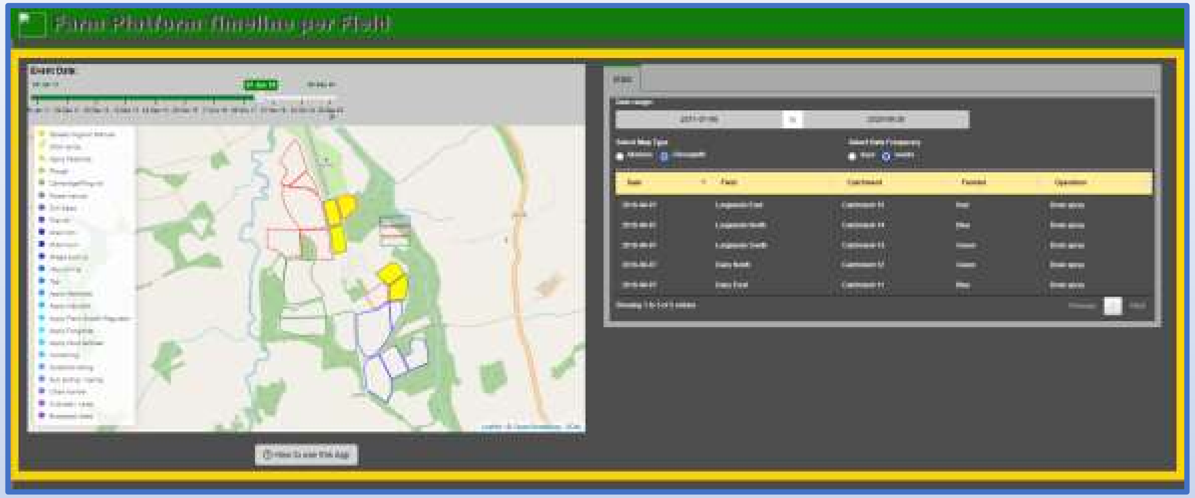
http://resources.rothamsted.ac.uk/farm-platform-national-capability/data-collections

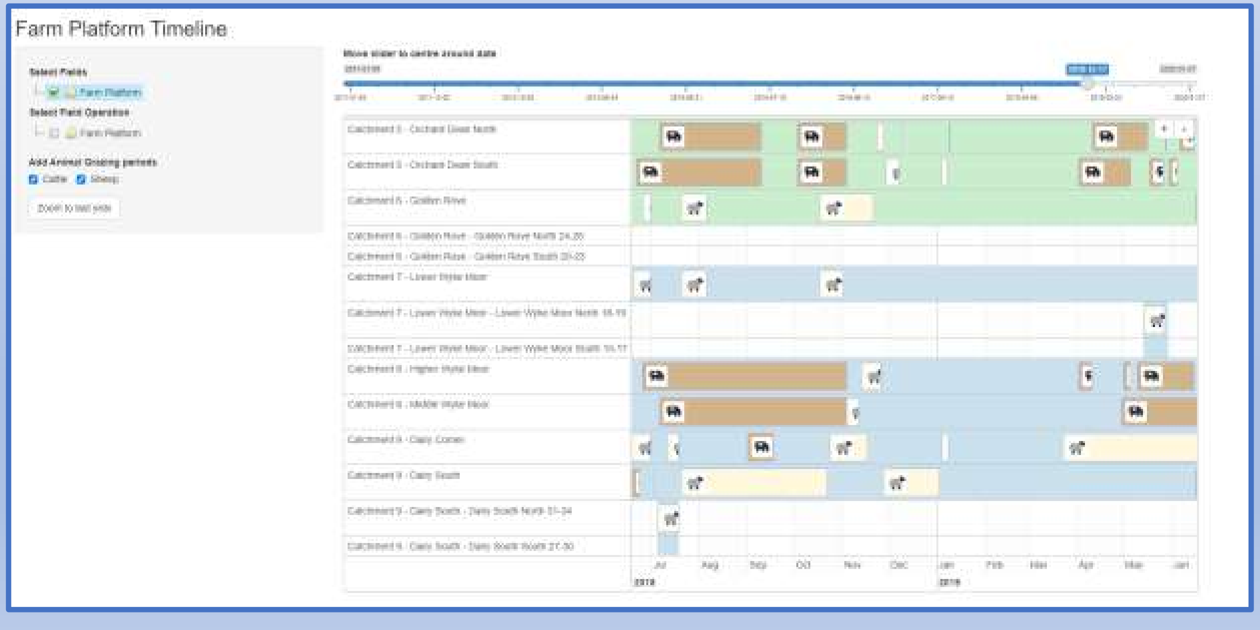


Serving internal & external use

NWFP: R-Shiny Apps:







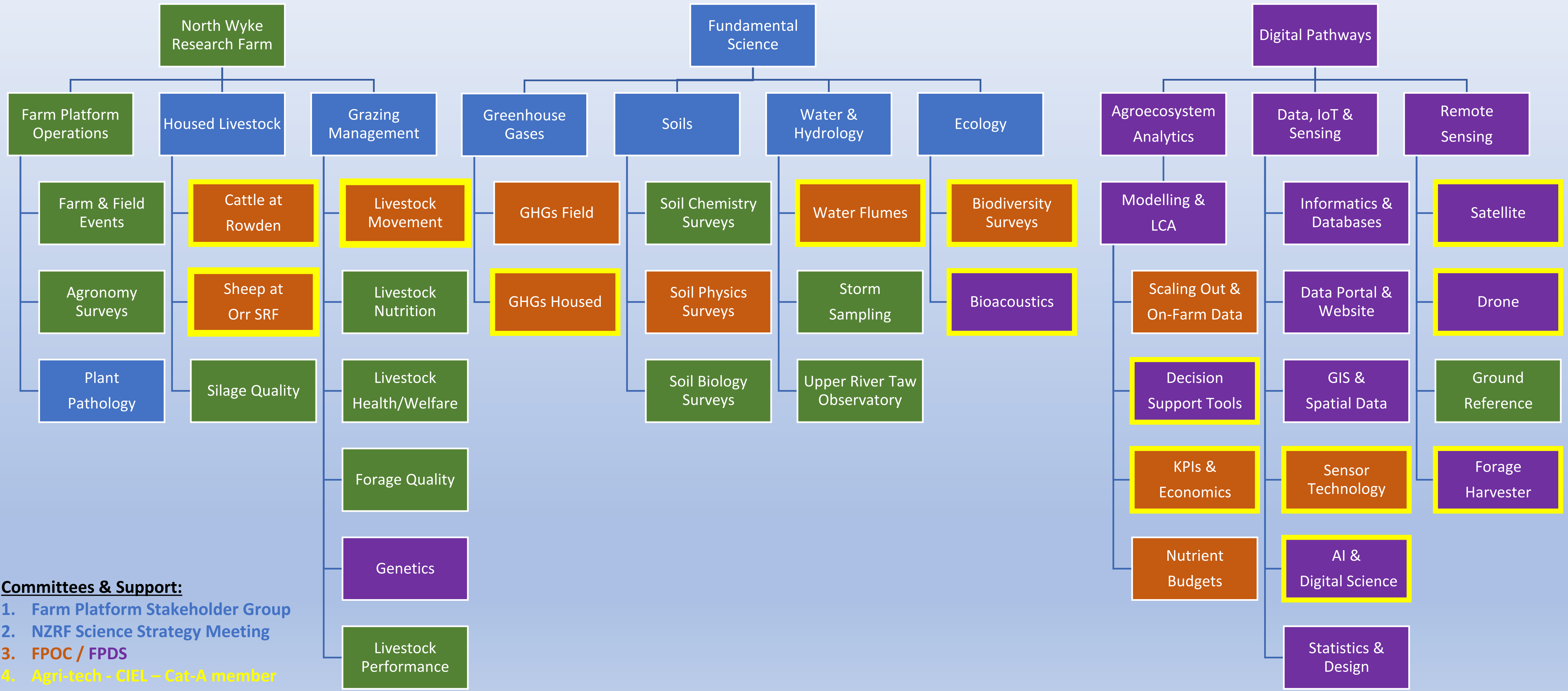
https://nwfp.shinyapps.io/FP_Experiments_App/
https://shiny.rothamsted.ac.uk/FP_Timelines_Map_App/
https://nwfp.shinyapps.io/NWFP_Timelines_App/

ROTHAMSTED RESEARCH

Interdisciplinary nature of the North Wyke Farm Platform – the NWFP organogram

Colour key:

Net Zero & Resilient Farming Science
Digital Science
Data Collection
Data Collection with Digital Science
Agri-tech Industry



Committees & Support:

1. Farm Platform Stakeholder Group
2. NZRF Science Strategy Meeting
3. FPOC / FPDS
4. Agri-tech - CIEL – Cat-A member
5. KE & Comms.

NWFP Data categorised by spatial & temporal coverage…

Coverage / Representation	Spatial or Operational unit	Temporal Frequency	Start	End	Coverage / Representation	Spatial or Operational unit	Temporal Frequency	Start	End
Grazing & arable farm management activities (e.g., fertilizer apps, ploughing)	Farm-scale	Variable	2011	Ongoing	Livestock (cattle) welfare (behaviour & health)	Individual animal	Weekly	2019	Ongoing
Housed livestock management activities	Farm-scale	Variable	2011	Ongoing	Eddy Covariance GHG (CH_4 & CO_2 from soil, plant & livestock).	Sited in 3 of 20 platform fields (CH_4 measured in 2 fields only)	30-minute	2017	Ongoing
Livestock performance (liveweight gain, condition scores)	Individual animal	2- to 4-weekly	2010	Ongoing	Eddy Covariance GHG (CH_4 & N_2O from soil, plant & livestock)	Addition of third CH_4 & single N_2O sensors	30-minute	2025	To start
Livestock performance (sales & carcase data)	Individual animal	End of life	2010	Ongoing	Citizen science app for wildlife sightings	Farm-scale	Intermittent	2022	2023
Livestock (cattle) performance (fat scanning)	Individual animal	2-scans per lifetime	2023	Ongoing	Bio-acoustic monitoring for biodiversity (birds, insects, bats) (x6 sensors)	Platform-scale	Continuous (1 week per month)	2023	Ongoing
Livestock (cattle) genomics & phenotypes	Individual animal	1-sample per lifetime	2018	Ongoing	Housed Greenfeed GHG (CH_4 & CO_2 from cattle)	Farm-scale (individual animal)	Variable	2017	Ongoing
Grazing crop quantity (silage cuts); RS ground reference	Field-scale	2-cuts per grazing season	2011	2020	Housed Greenfeed GHG (CH_4 & CO_2 from sheep)	Farm-scale (individual animal)	Variable	2022	Ongoing
'GrassCheckGB' extension; Un-grazed grass growth; RS ground reference	Off-platform ('Top Burrows' Met site)	Weekly	2018	2021	Forage Harvester (FH)	Within-field scale	Variable	2020	Ongoing
RS ground reference for ecosystem provisioning & plant communities	Field-scale	2-weekly	2024	Ongoing	Coordinated RS from Drone & Satellite with links to Forage Harvester	Within-field scale	Variable	2024	Ongoing
Grazing crop quality (forage)	Field-scale	2-weekly	2015	Ongoing	Water flow, physics and chemistry	Catchment-scale	15-minute	2012	Ongoing
Grazing crop quality (silage)	Farm-scale via Clamp / Bale	2-weekly	2015	Ongoing	Water flow, physics and chemistry ('bluemons' enhanced for Total C, N & P)	Catchment-scale	15-minute	2024	Ongoing
Arable crop quantity & quality (wheat, oats, beans)	Field-scale	Annual Harvest	2020	Ongoing	Soil Moisture (10cm) and Temperature (existing)	Field-scale (1 in 15 of 20 fields) (point sensors)	15-minute	2011	Ongoing
Fine-scale field surveys (soils & herbage nutrients, soil insects, vegetation)	Within-field level	Annual but intermittent	2012	Ongoing	Soil Moisture (10, 20, 30, 40 cm) and Temperature (enhanced)	Field-scale (3 in 20 of 20 fields + one extra) (point sensors)	15-minute	2024	Ongoing
Coarse-scale field surveys (soil & herbage nutrients)	Field-level (bulked samples)	Quarterly	2018	Ongoing	Rainfall (existing)	Field-scale (1 in 15 of 20 fields) (point sensors)	15-minute	2011	Ongoing
Above-ground biodiversity surveys (vegetation); RS ground reference	Transects across all 3 farms & into field margins / adjacent habitats	Bi-annual	2023	Ongoing	Rainfall (enhanced)	Field-scale (1 in 20 fields) (point sensors)	15-minute	2024	Ongoing
Above- & below-ground biodiversity surveys (soil insects); genetics (bioscan)	Sub-terranean traps	Campaign-style	2023	Ongoing	MET data	Platform-scale (Top Burrows) (point sensors)	15-minute	2011	Ongoing
Automated Chambers GHG (N_2O, CH_4 & CO_2 from soil & plant).	Campaign deployment for 3 fields at any given time	Sub 10-minute	2013	Ongoing					
Sampling for PBMs (Ksat, soil texture, soil-water retention curves)	Within-field level (not all fields)	One-off campaigns	2019	Ongoing					

Data by spatial / temporal coverage (green - good; blue - moderate; yellow - weak)

NWFP: Water & Gaseous Emissions

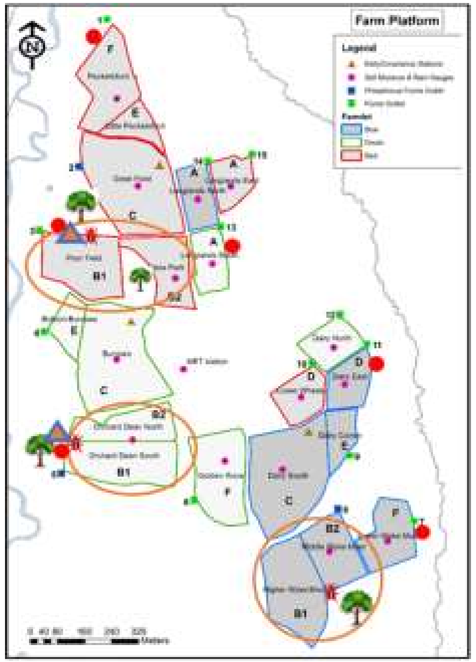
Water emissions the **'Jewel in the Crown'** that makes the NWFP globally unique
15 water flumes each measuring 15+ water physics & chemistry variables

Gaseous emissions both indoor & outdoor

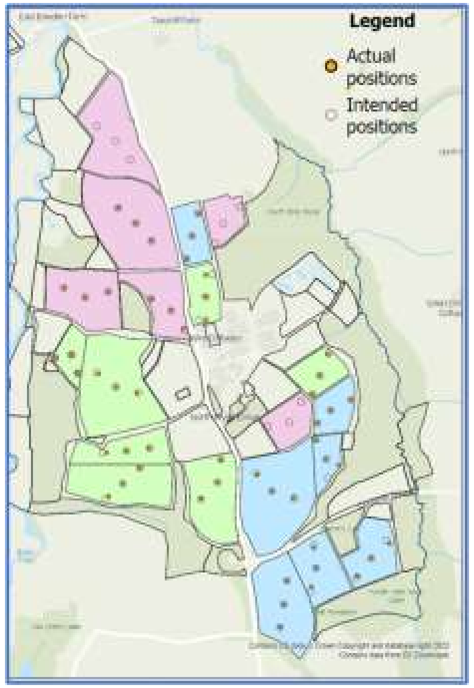
NWFP 2023-2028: Enhanced collections & digital workflows:

- **Biodiversity:** sensing for improved ecosystem characterisation (mixture of field and automated sampling – e.g., bioacoustic sensors x6)
- **Soil moisture and precipitation:** 61 SM sensors across 20 fields; 20 rain gauges. Key to Digital Twin of RFF ISP with links to URTO catchment
- **Remote sensing:** forage / combine harvester, drone with multiple sensors, satellite & ground-reference. For Digital Twin initiatives and model coupling
- **GHG eddy covariance:** 3rd CH_4 (plus release of N_2O data)
- **Livestock data:** (a) cattle genomics & phenotypes; (b) cattle welfare assessment; & (c) cattle meat quality
- **Digital workflows:** APIs, data repositories, data parcel DOIs, FP experiments data DOIs, data processing tools, website…

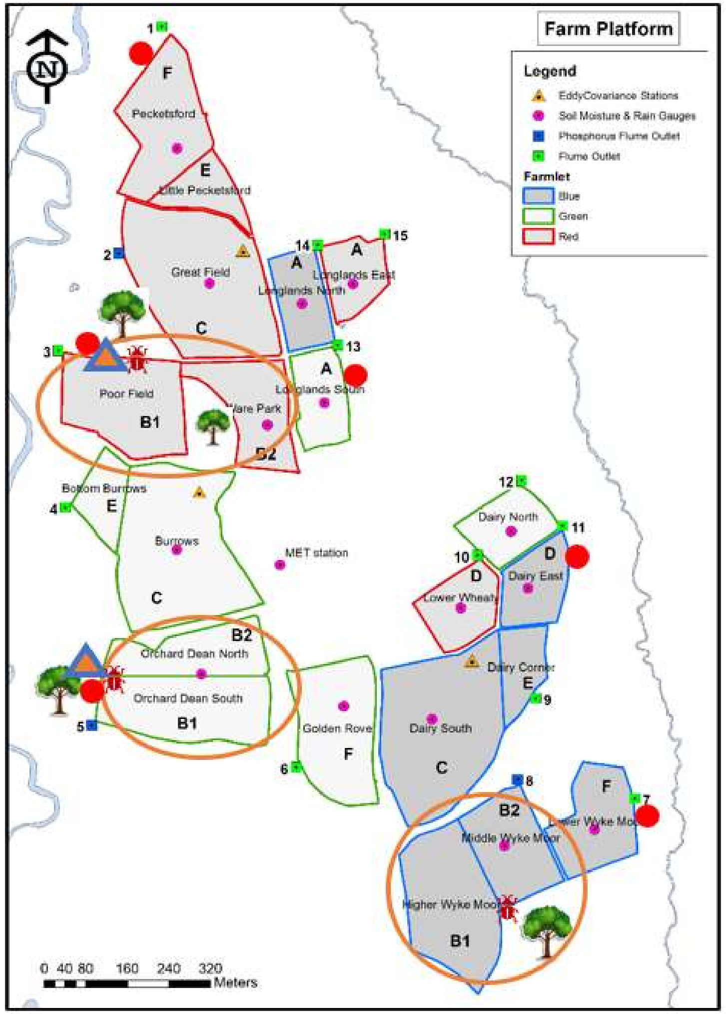
biodiversity

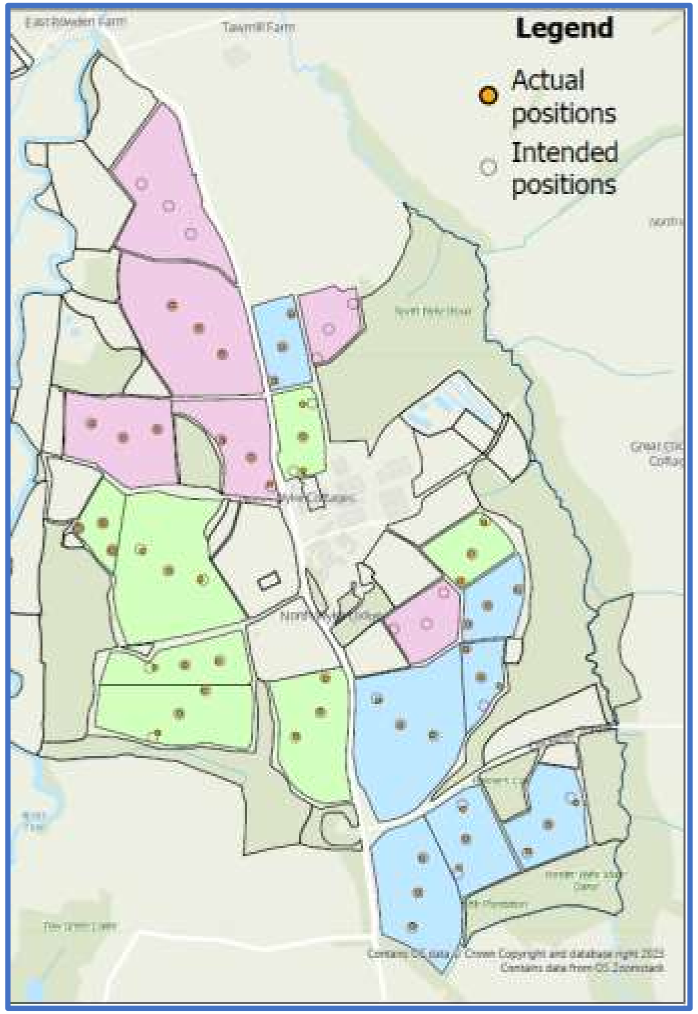


soil moisture



NWFP 2024: Progress for new collections:





Enhanced biodiversity sensing for improved ecosystem characterisation (mixture of field and automated sampling – e.g., bio-acoustic sensors)

Enhanced soil moisture and precipitation (60 SM sensors across 20 fields; 20 rain gauges). Key to resilience Digital Twin (of RFF ISP)

NWFP: Resources & Outputs

Core Funding - Biotechnology & Biological Sciences Research Council (BBSRC):

- 2010 setup: **approx. £3M +**
- 2012 onwards (3 grants): **approx. £12M** + (of which £3.2M is for 2023-28)

Capital Funding - BBSRC/NERC/CIEL:

- 2016 onwards: **approx. £3M +**

Staffing:

- 13 (approx. 9.5 FTE): Technicians in Data Science, Ecology, Livestock, Agronomy, Instrumentation, Drone Sensing, Lab & Field
- Data Systems/Science support (statistics, informatics, software engineering)

Wider Scientific Team:

RRes scientists – grazing, water/gas emissions, soils, modelling, remote sensing, etc.

From NC to NBRI:

As of 2023 NWFP is a **'UK National Bioscience Research Infrastructure'** (NBRI)

Along with Long-term experiments (RLTEs) and Insect Survey (RIS) NBRIs

Rothamsted is now a **'UK National Capability'**

BBSRC Reviews:

'Excellent' ratings in ALL BBSRC reviews since 2017

Outputs since set up:

FP experiments: **170+ (45% external)**

Publications (using data): **70+ (34% external lead)**

Data publications (outside of core) **15+**

Other publications: **70+**

Projects & collaborations: 30+ (from £50k to £1.35M)

Research-focussed events: **60+**

Industry-focussed events: **40+**

Media activities: **20+**

Data portal outputs (from 2016 start to 16/1/24):

Registered users: **402 (69% external to RRes)**

Measurements: **80+ million**

Downloads: **5865 (38% external to RRes)**

People outputs:

BSc/MSc projects: **25+**

PhD students: **20+**

Visiting researchers: **35+**

PDRAs: **30+**

People trained: **130+**

NWFP 2023-2028: Objectives realised via 3 workstreams:

A. <u>Systems Science through Measurement (45%):</u>
- ❑ Continue to build **unique & open long-term datasets**
- ❑ Manage data from **170+ FP experiments**
- ❑ Manage **FP's physical archive**

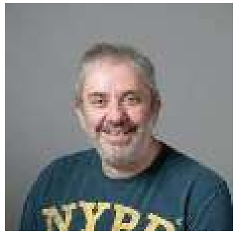
B. <u>Systems Science through Digitalisation (35%):</u>
- ❑ **Static & dynamic** digital processing tools
- ❑ **Upgrade of data systems: APIs, Repositories, FAIR**
- ❑ Detailed (living) **Data/Digital Management Plan**
- ❑ **Facilitate timely 'look-see' / 'PoC' projects**
- ❑ **Website re-vamp**

C. <u>Strategy (20%):</u>
- ❑ Promote the **Digital NWFP and its Manifesto (* update)**
- ❑ Develop links to **University BSc/MSc programmes (* update)**
- ❑ Implement **3rd System Change Period**
- ❑ **Facilitate co-development & leverage funding**
- ❑ **Lead FP strategy, FP steering group & partnerships**

<u>Each with own committee (working group), chair & ToRs</u>

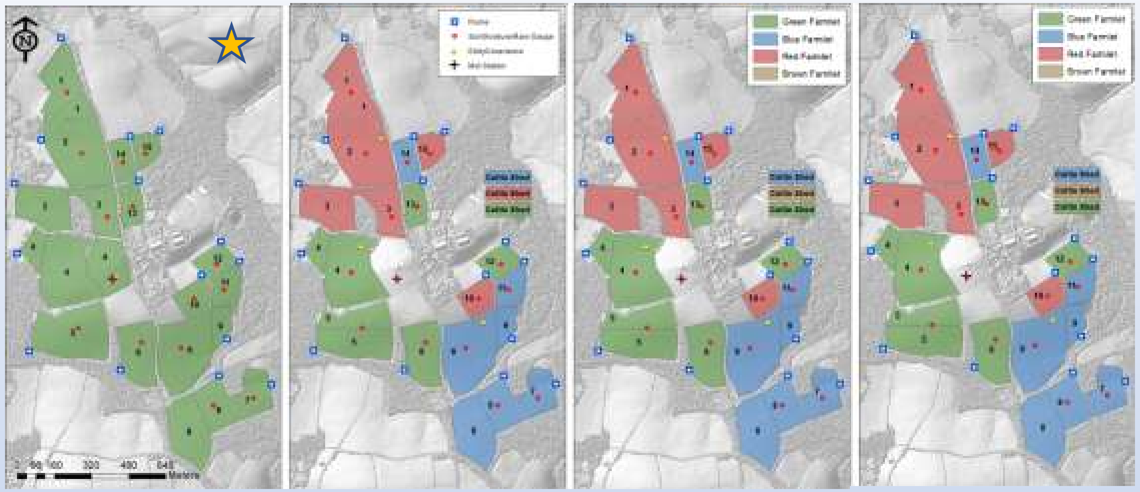
<u>Bruce Griffith (Co-I)</u>
(FP Operations Committee)

<u>Paul Harris (PI)</u>
(FP Digital Science)



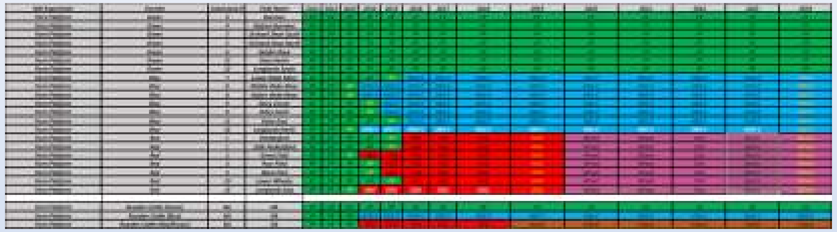
<u>Phil Le Grice</u>
(FP Strategy Group)

3rd System Change Decisions for the NWFP for 2025



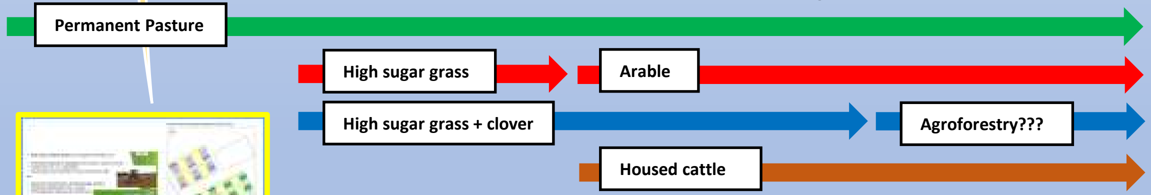
2010-13 | 2013-19 | 2019-24 | 2024-29*

New for 2024:
61 Soil moisture sensors
20 Rain gauges
6 Bio-acoustic Sensors
Enhanced RS ground-ref.
Enhanced GHGs
Enhanced livestock data



Cattle & silage

Sheep



System change timelines

Off-platform plot studies to inform system changes

What next?

- Stay as is?
- Change one farmlet?
- Time to change ‘Green’?
- Over-lapping system changes?
- Treat as 15 catchments?
- Treat as one farm – mixed farm?
- What to do with Brown, the indoor farm?
- Use farmland outside of FP?
- Use woodland outside of FP?
- Create 4 farmlets by re-introducing Top Burrows?
- GGR technologies; Agroforestry; Buffers?
- Sharing/sparing; Agrivoltaics?

Impact: North Wyke Farm Platform

Selected Impacts:

Improved estimates for soil erosion rates (Evans et al. 2017)

Improved estimates for livestock emissions (McAuliffe et al. 2018)

Farmer-friendly livestock KPIs (Jones et al 2021)

Improved system modelling for extreme events (Curceac et al. 2021)

Improved field to landscape run-off pollution forecasts for extreme events (Zhang et al. 2022)

Perspectives on unintended consequences of grassland to arable conversions (Blackwell et al. 2024)

Outputs:

Funded projects: 30+ (from £10k to £1.35M)

RRes ISP use: S2N, ASSIST, RFF, GH & AgZero+

Experiments (use as a facility): 150+ (45% external)

Direct publications (using data): 70+ (34% external lead)

BSc/MSc/PhD/VRW projects: 100+

Outreach Events: 100+

People trained: 130+

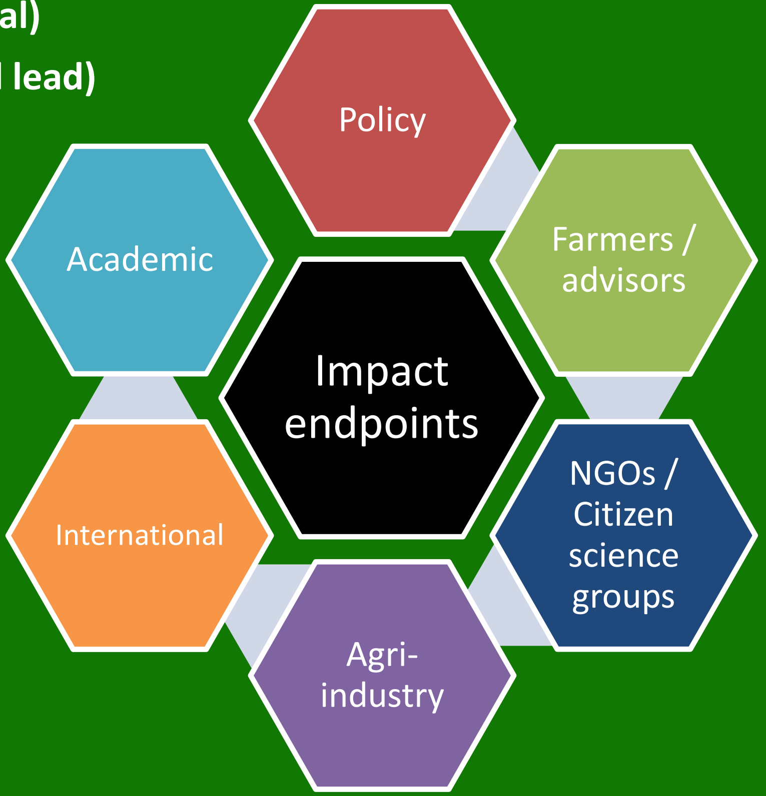
Media activities: 20+

<u>Data portal - increased use since 2016 deployment:</u>

Measurements: 80+ million

Downloads: 5800+ (38% external to RRes)

Registered users: 400+ (69% external to RRes)



On-going:

Developing *Demonstrator Digital Twins* for real world *On-Farm* roll-out

Instigation of 3rd System Change Period

Wider distribution of data (e.g. Hestia for LCA)

Data Parcels for Data Science BSc/MSc Students

NWFP 2023-2028: Recent FP experiments:

- Soil Carbon monitoring via drones and wet chemistry

Connectivity

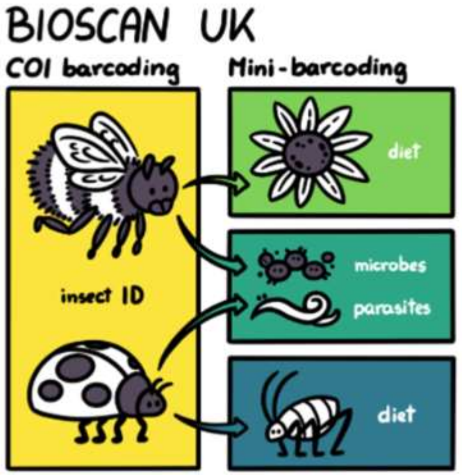
NWFP: Connectivity with Academia:

UK Institute/Charity/etc links:
- ❖ Quadram Institute, Norwich: shared NBRI initiatives (2024 ongoing)
- ❖ Alan Turing Institute: funded Farm Digital Twin project (2023 ongoing)
- ❖ Roslin Institute, University of Edinburgh: livestock genetics/omics, links to GE ISP (2024 ongoing)
- ❖ Welcome Sanger Institute: Bioscan - UK malaise trap network for arthropod DNA barcoding (2023-25)
- ❖ Ecological Continuity Trust (ECT): network of experimental sites (2018 ongoing)
- ❖ Donkey Sanctuary: sharing animal welfare system application (2024 ongoing)

UK University links:
- ❖ University of Oxford: Hestia, funded Defra ‘WRAP’ project for data sharing / LCA (2023 ongoing)
- ❖ University of Portsmouth: pilot sonification of data project (2024 ongoing)
- ❖ Reading University: model parameterisation and sampling (2024 on-going)
- ❖ University of Leeds: Leeds University Farm – PH visiting professorship (2020 ongoing)
- ❖ Lancaster University / Lancaster CEH: Digital Twin initiatives (2018 ongoing)
- ❖ Royal Agricultural College: Digital Twin initiatives using twinned experimental sites (2022 ongoing)

UK University links via student digital science programmes (BSc, MSc, PhD):
- ❖ Imperial College London: Computational Ecology with on-site sampling (2024 ongoing)
- ❖ Cambridge University: funded Sensors CDT Team Challenge (2024 ongoing)
- ❖ Bangor University: Visualisation with fixed data parcels (2023 ongoing)
- ❖ University of Leeds: Visualisation with fixed data parcels (2023 ongoing)
- ❖ giCentre, City University of London: Visualisation with fixed data parcels (2023 ongoing)
- ❖ St Andrews University: Visualisation of Animal Movement (2024 ongoing)

International links:
- ❖ Global Farm Platform (GFP) network: multiple experimental livestock farms (2014 ongoing)
- ❖ Juelich University, Germany: soils Digital Twin with Bayer (2024 ongoing)
- ❖ University of Southern Queensland: funded BBSRC partnering award – modelling & RS (2023-26)
- ❖ eLTER Agroecology network: expert panel membership (2023 ongoing)

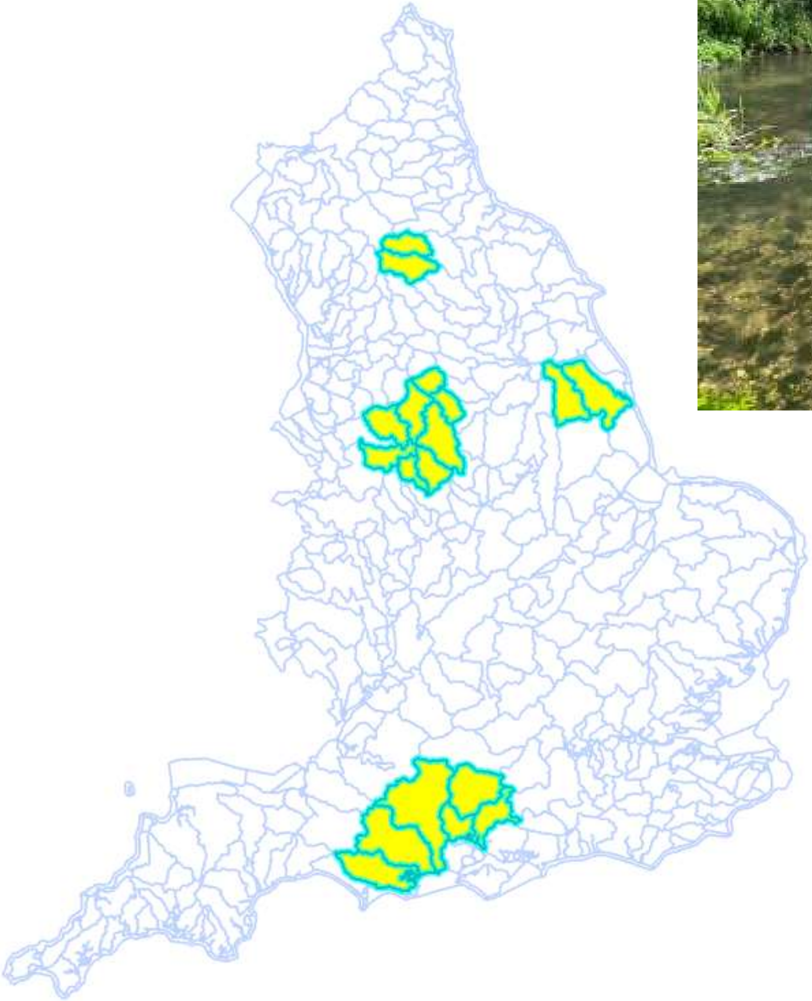



The Imperial College students get training in parasitology analysis from Dr

NWFP: Connectivity with farmers:

Growing strategic partnership:

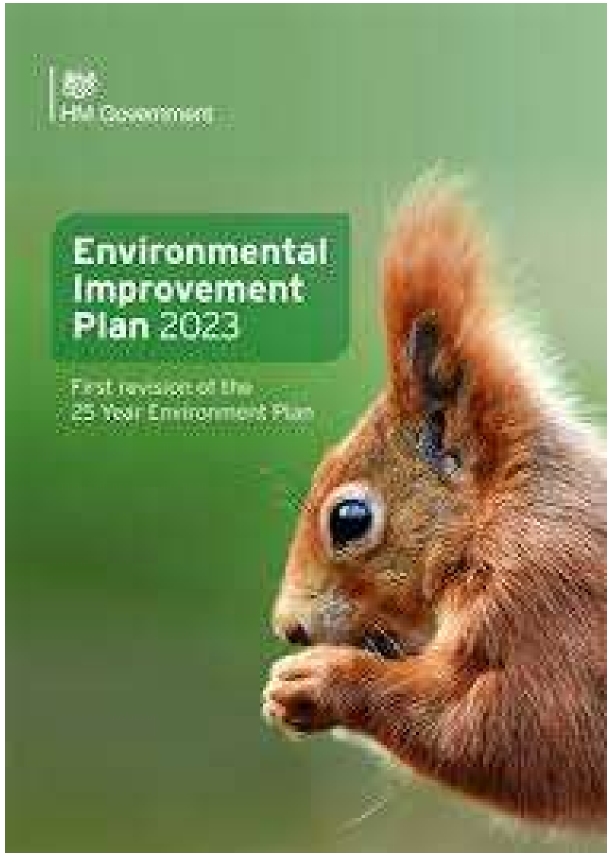
- With GWCT and Environmental Farmers Group (EFG)
- ~1000 commercial farmers
- Network visiting the NWFP to understand the impacts of extreme weather
- Installing on-farm labs for farmer self-monitoring of resilience of regulating services (for water) to extreme weather events



NWFP: Connectivity with policy:

New management targets in the Environment Improvement Plan:

- Reducing the water pollution from farms
- Feasibility of targets examined using NWFP data and process-based modelling (PBM)



The Data Platform:
NWFP Biodiversity Focus

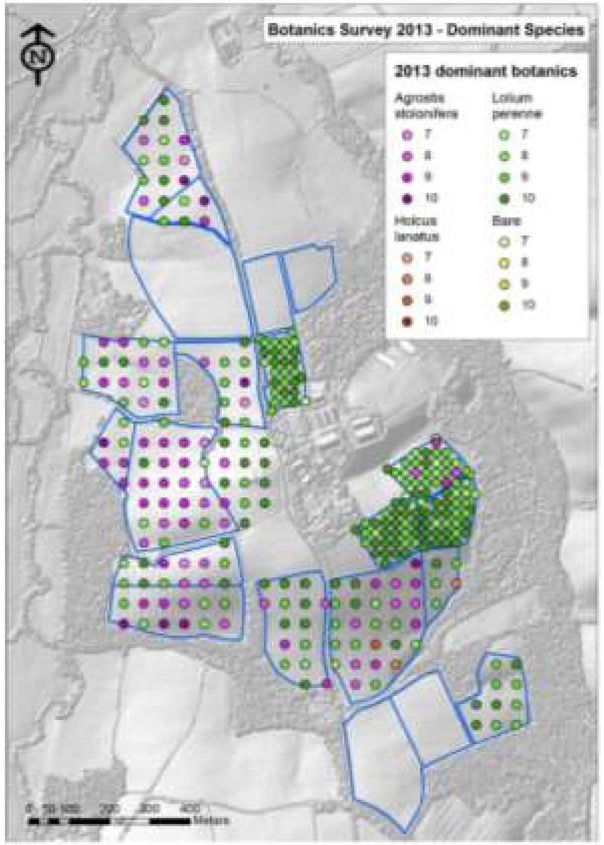
ROTHAMSTED RESEARCH

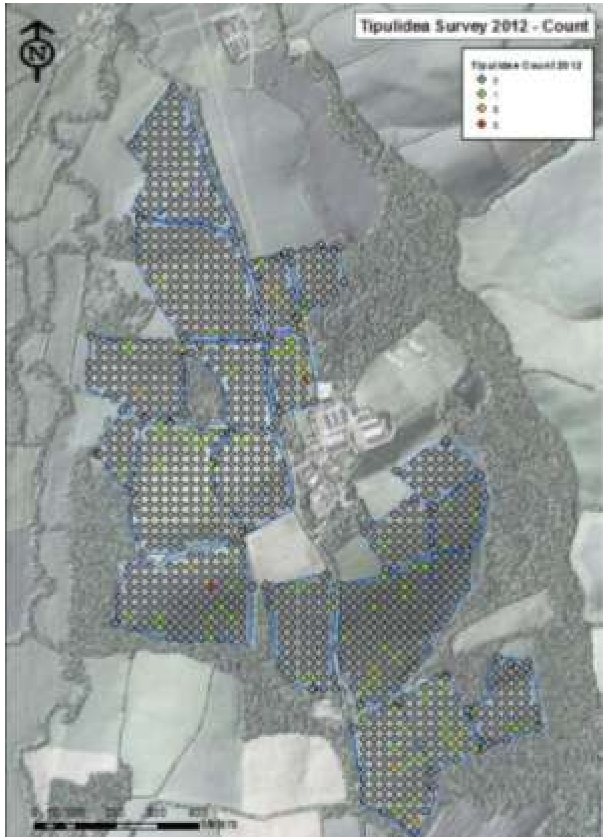
NWFP Biodiversity monitoring: Past, present & future.

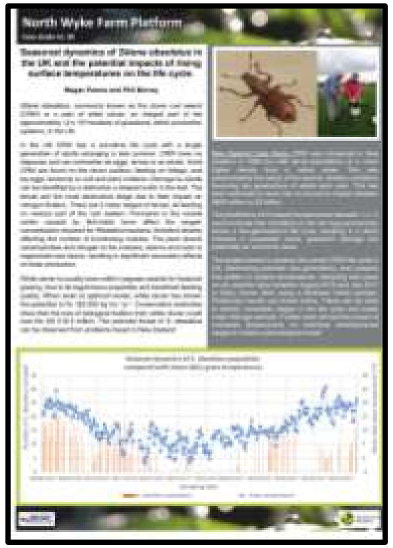
March 2024

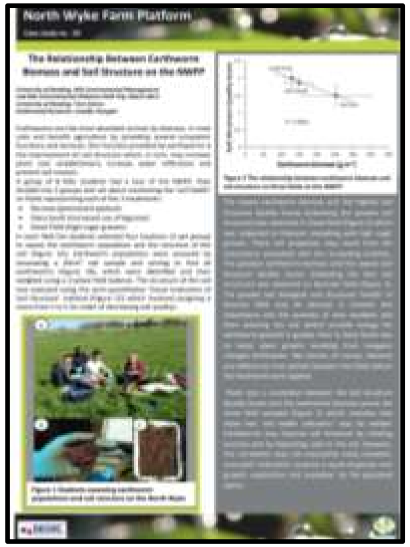
Debs Beaumont

Past biodiversity surveys & projects









High Resolution 25 & 50m sampling grids

- ❑ Botanical composition (2013, 2016, 2018 & 2021)
- ❑ Soil fauna (2012 & 2013)

Projects

http://resources.rothamsted.ac.uk/north-wyke-farm-platform/experiments

Current Biodiversity observations & projects

ROTHAMSTED RESEARCH

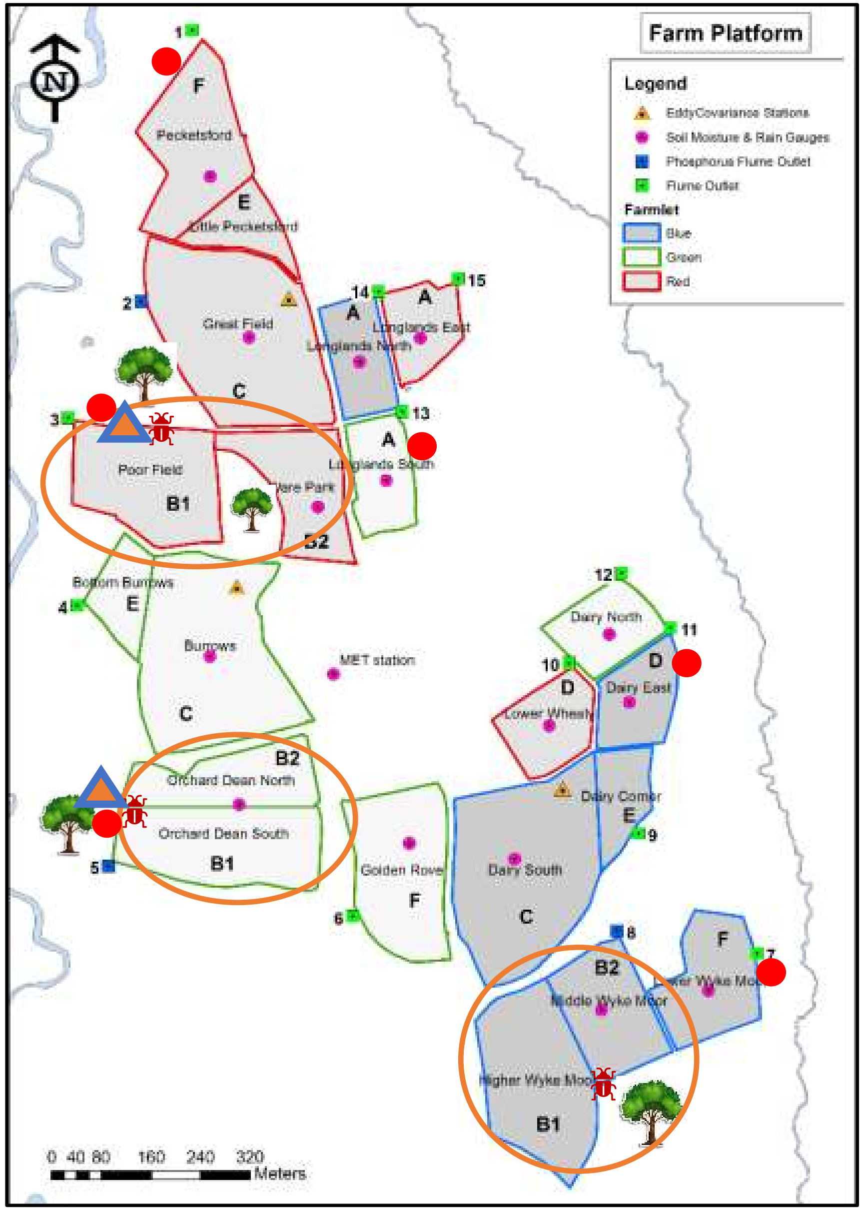
1. AgZero+
Towards sustainable, climate-neutral farming

Biodiversity monitoring using AgZero+ protocols (2023-2025):

6 NWFP fields monitored (2 in each treatment)

4 monitored woodland areas ('non-cropped areas')

3 Baited Dung beetle trap locations 2023



2. The BIOSCAN project

UK malaise trap network: arthropod DNA barcoding (2023-2025).

2 Malaise traps deployed in NWFP field margins (one permanent pasture (green) , one arable (red) treatment). Deployed for one 24hr period per month.

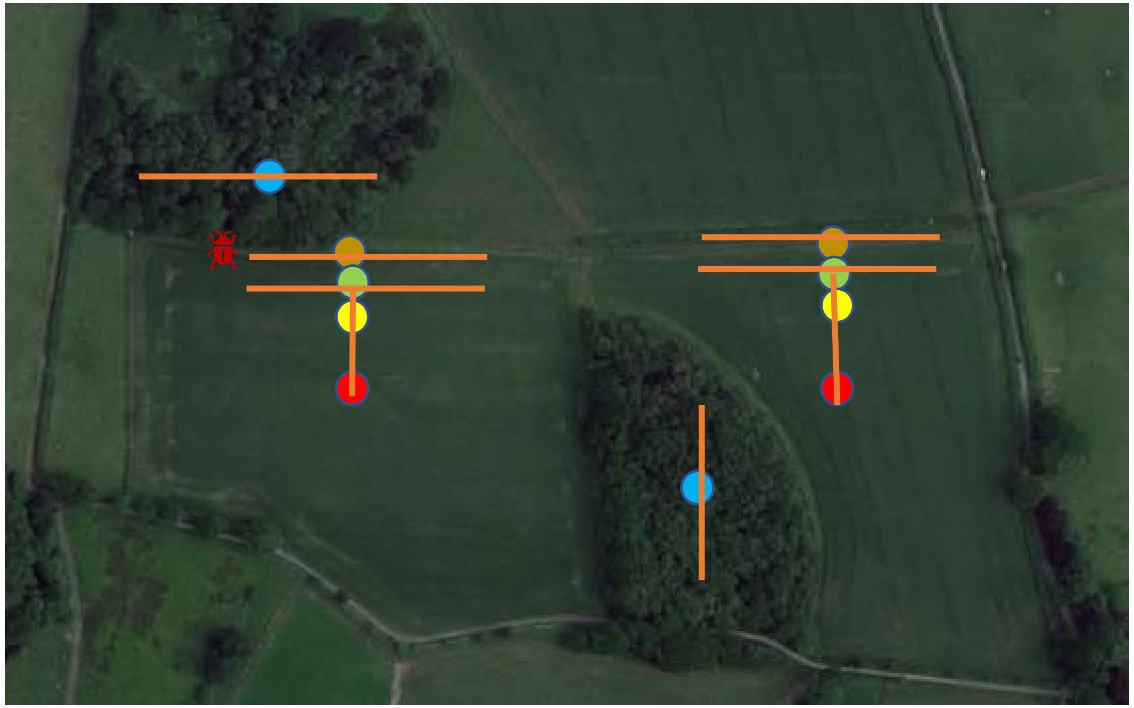
3. Ecoacoustic monitoring

(Oct 2022-)

6 recorders (ultrasonic) in NWFP margins (2 in each treatment). Recorders deployed for one week per month.

AgZero+ Project

Sampling locations



- Field boundary (FB)
- Field margin (FM, if present)
- Field edge (FE)
- Field centre (FC, 50 m)
- Non-cropped (N)
- Baited Dung beetle trap
- Pollinator & plant community 50m transects

Measurement	Method	Location
Beetles	Pitfall traps	FB, FE, FC, FM, N
Pollinators	Transect	FB, FC, FM, N
Pollinators & parasitoids	Pan/water traps	FE, N
Plant community	Transect	FB, FC, FM, N
Weed seedbank	Soil cores (15cm)	FE, FC
Dung beetles	Baited dung traps & hand sorting	FE/whole field

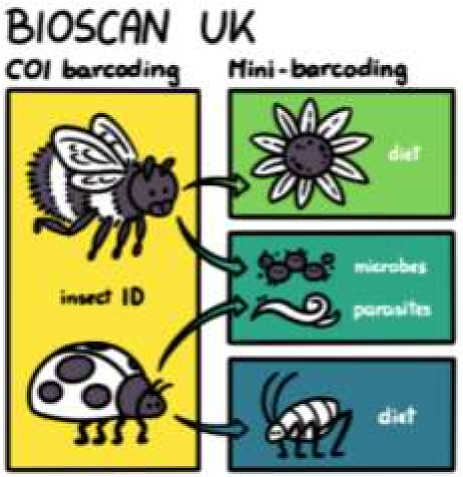
Extra measurements (6 fields):

- ❑ High resolution 50m grid plants (DOMIN scale)
- ❑ Earthworm count and biomass (five 20 x 20 x 20 cm pits within each field plus 1 pit in FM)

Wellcome Sanger Institute

The Bioscan UK Project

ROTHAMSTED RESEARCH



Background

- ❑ Studying the genetic diversity of arthropods across the UK over a 5-year period.
- ❑ Sequence data will provide a baseline characterisation of arthropods species diversity over space and time.
- ❑ Develop methods to target additional DNA barcodes to reveal potential interactions (pollination, diet, parasites).
- ❑ Form a foundational resource for DNA-based biomonitoring in UK.

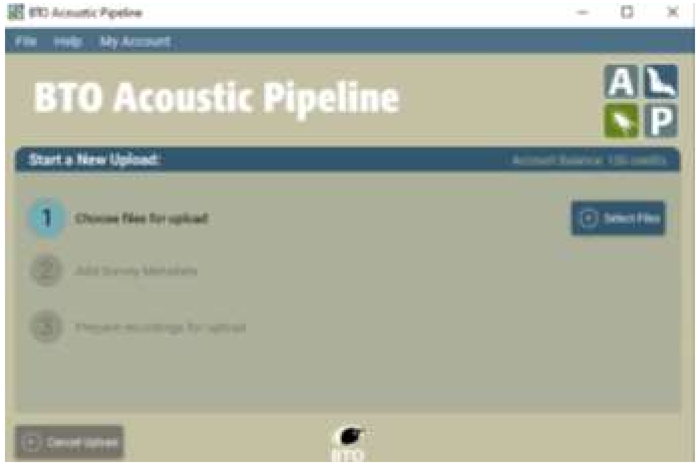
NWFP

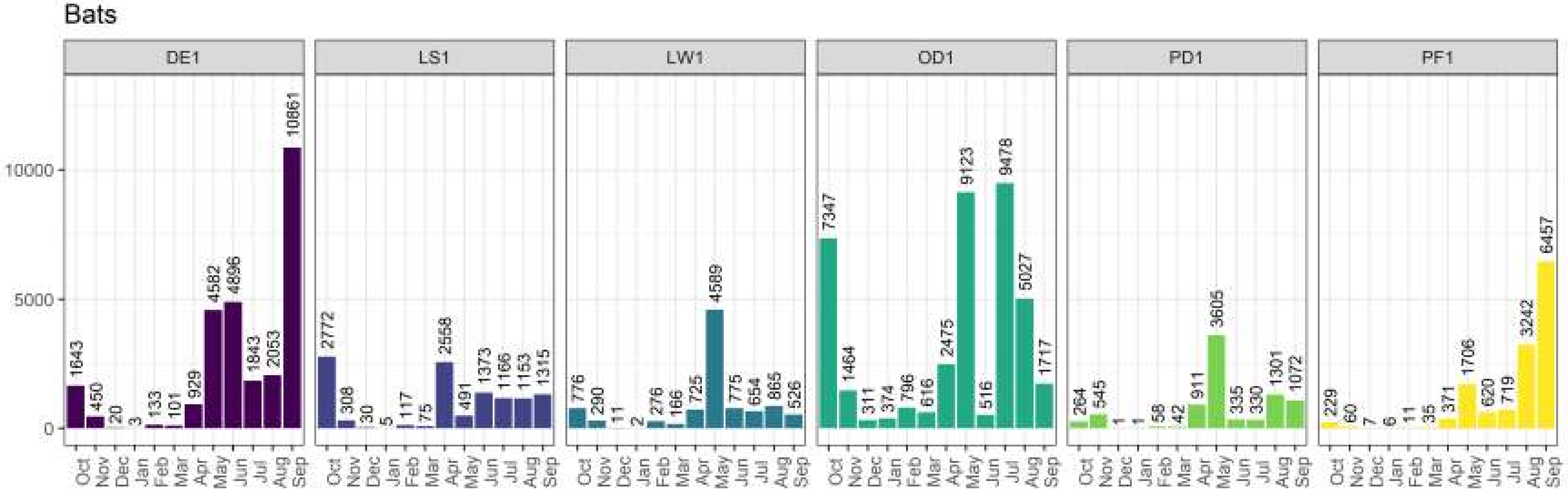
- ❑ Start date: Jan 2023
- ❑ **2** Malaise traps:1 **permanent pasture**, 1 **arable**.
- ❑ Deployed monthly for 24 hrs.
- ❑ >10,000 specimens plated.

Part of the global BIOSCAN initiative 'building a complete library of life'.

Acoustic monitoring

- Start date: Oct 2022
- **6** Song Meter Mini Bat Ultrasonic recorders Deployed in NWFP margins:
  2 permanent pasture, 2 arable, 2 legumes
- Deployed monthly for 7 days (30 mins before sunset until 30 mins after sunrise).
- 'Raw' wav files archived for future data mining
- Wav files uploaded to BTO Acoustic Pipeline

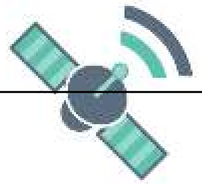




Possible future initiatives

ROTHAMSTED RESEARCH

Test-bed for advances in biodiversity monitoring



Surveillance Stations

- ❑ Automated traps with high resolution cameras & develop identifying tools (machine learning).
- ❑ Ecoacoustics: both audible & ultrasonic. Individual species, above and below ground & soundscapes.
- ❑ Bioaerosol samplers: collect airborne particles (viruses, bacteria, fungi, pollen).
- ❑ Phenocams.

Sampling & survey campaigns

- ❑ Soil biodiversity & functionality - soil metagenomics.
- ❑ Impacts on water quality - eDNA (NWFP flumes and wider landscape, River Taw).
- ❑ Ground truth sampling - to support remote sensing, AI and modelling development.
- ❑ Biodiversity within livestock - pathogens, pests plus beneficial microbes.

<u>Long term goals</u>

1. Integrated biodiversity surveillance and its application for a wide range of research and policy requirements.
2. Use data streams to help develop models to predict impacts of management and climate changes.
3. Develop a farm network using standardised protocols.

Possible research questions

ROTHAMSTED RESEARCH

- Is there variation in ecological composition, function and ecosystem resilience across management gradients?
- How do species, communities and ecosystem processes change in space and time?
- Do high-diversity soil communities compared to low-diversity soil communities lead to productivity gains and buffer against extreme weather events?
- How do changes in soil microbiome translate into spatial and temporal trends in soil function?
- Which farming system is the most sensitive to drought and wet periods and how do ecosystem responses cascade through the system?

Student Projects:
Data Parcels & other initiatives

Visualisation projects:

Computational Ecology projects:

Sensor Engineering projects:

Analytical Snippets:

Analytical snippet # 3: Visualisation – e.g., sketchy rendering

Geophysical Research Abstracts
Vol. 18, EGU2016-17395, 2016
EGU General Assembly 2016

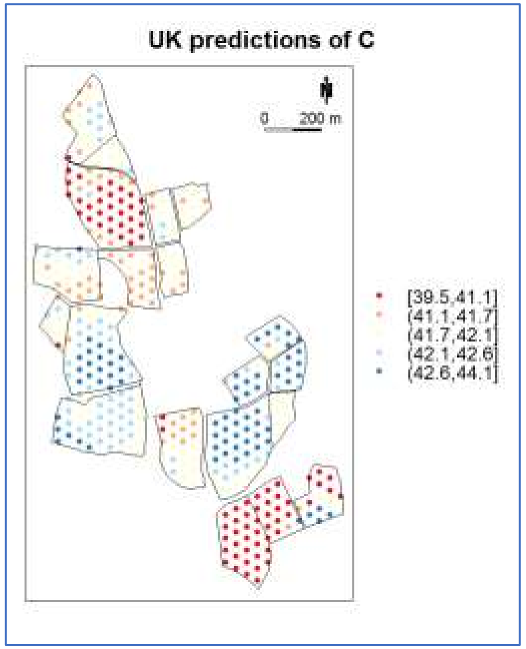
Visualizing uncertainties with the North Wyke Farm Platform Data Sets

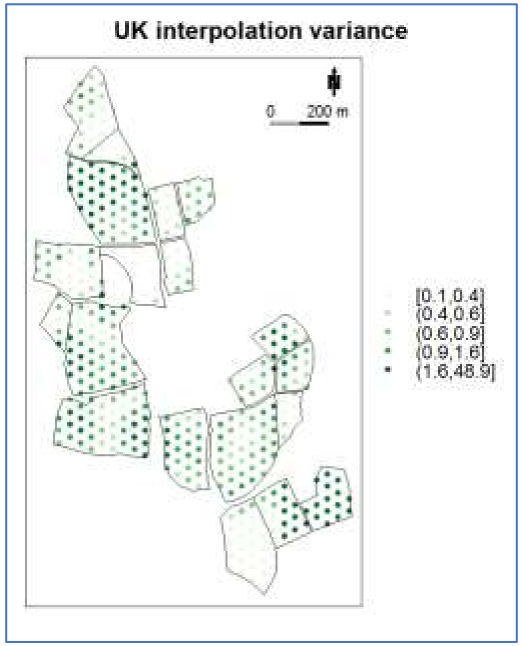
Paul Harris (1), Chris Brunsdon (2), and Michael Lee (1)
(1) Rothamsted Research, North Wyke, UK (paul.harris@rothamsted.ac.uk), (2) National Centre for Geocomputation, Maynooth University, Ireland (christopher.brunsdon@nuim.ie)

Spatial sketchy rendering techniques for visualizing uncertainties associated with a systems-based agricultural experiment

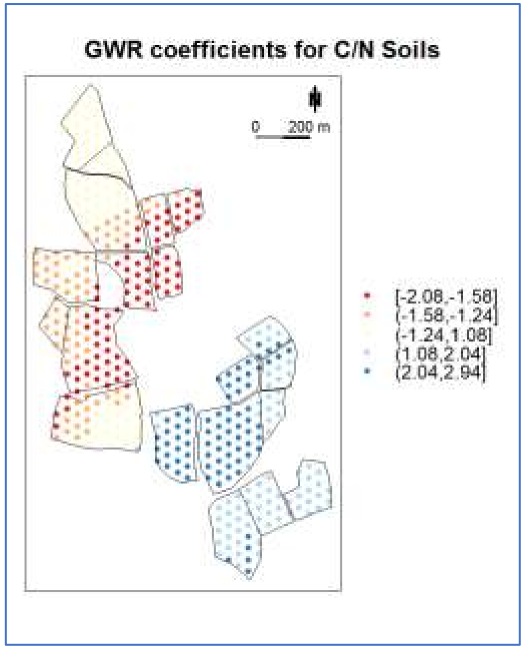
Crisp
&
Certain

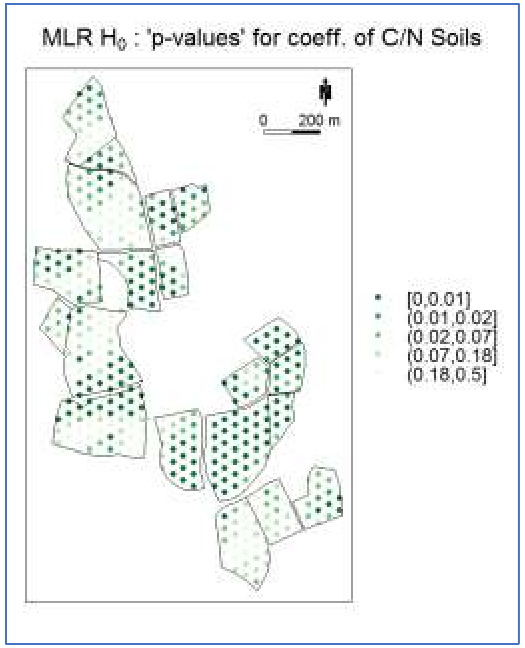
Sketchy
&
Uncertain

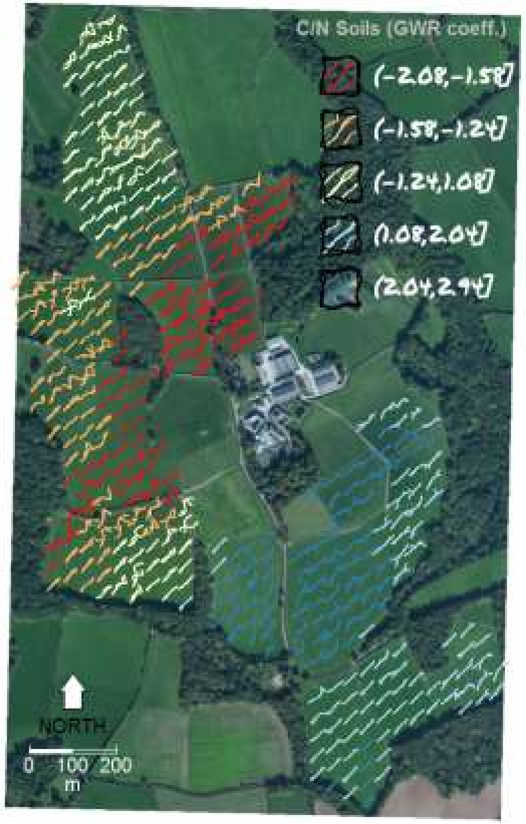




Universal kriging *for mapping total Carbon predictions & their uncertainties (via interpolation variance not kriging variance)*







Geographically Weighted Regression *for Plant species diversity = f(C/N soils): Are local coefficients significantly different to those from global regression?*

Analytical snippet # 4: Linking system processes: e.g., soils to plants to livestock

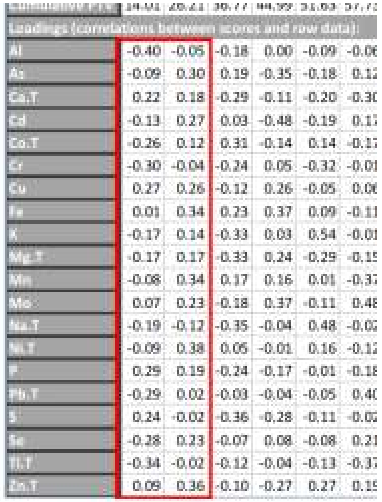
ROTHAMSTED RESEARCH

- This study: Explore & classify the **multivariate process** of soil micronutrients dataset at the 3-farm scale

- **Initial steps to characterize** the full space-time process:
  - Inform **future sample campaigns** for soils micronutrients *and* **plant micronutrients** concurrently
  - Dynamic links to **animal movement and grazing behaviour (livestock-based sensors)**
  - Dynamic links to animal performance data - **health, weight gain and well-being (livestock-based sensors)**
  - Dynamic links to **crop growth, biomass and vegetation characteristics (species)**
  - **Use of drone/satellite-based remote sensing data** linked to livestock-based sensors through **IoT low-cost sensor network**
  - All with **space-time data mining, machine learning, statistical** models for data fusion

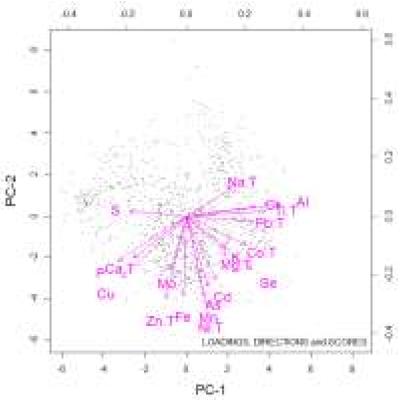
- **End point:** optimize within-pasture and across-pasture livestock grazing that efficiently manages (soil & plant) micronutrients so that:
  - Livestock feeding requirements would be less reliant on diet supplements (e.g., **human-edible ones**)
  - Livestock **health & meat quality** is improved
  - **But not at** the expense of **sustainable targets**
  - Develop **space-time analytical tools for precision livestock farming**

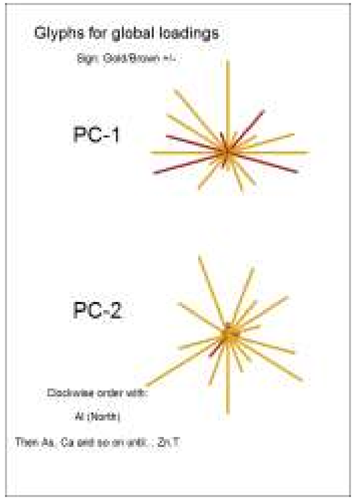
Mapping local PCA loadings for Soil Micronutrients



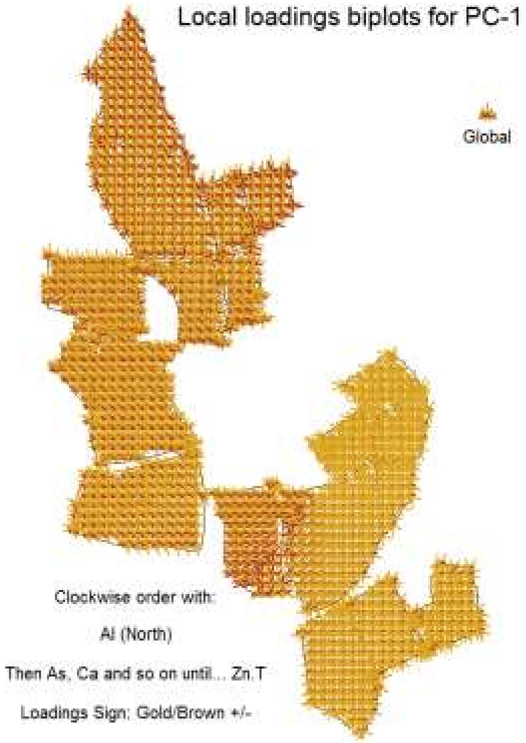
Cumulative Var %	14.01	26.21	36.77	44.99	51.63	57.7
Loadings (correlations between scores and row data):						
Al	-0.40	-0.05	-0.18	0.00	-0.09	-0.06
As	-0.09	0.30	0.19	-0.35	-0.18	0.12
Ca.T	0.22	0.18	-0.29	-0.11	-0.20	-0.30
Cd	-0.13	0.27	0.03	-0.48	-0.19	0.17
Co.T	-0.26	0.12	0.31	-0.14	0.14	-0.17
Cr	-0.30	-0.04	-0.24	0.05	-0.32	-0.01
Cu	0.27	0.26	-0.12	0.26	-0.05	0.06
Fe	0.01	0.34	0.23	0.37	0.09	-0.11
K	-0.17	0.14	-0.33	0.03	0.54	-0.01
Mg.T	-0.17	0.17	-0.33	0.24	-0.29	-0.15
Mn	-0.08	0.34	0.17	0.16	0.01	-0.37
Mo	0.07	0.23	-0.18	0.37	-0.11	0.48
Na.T	-0.19	-0.12	-0.35	-0.04	0.48	-0.02
Ni.T	-0.09	0.38	0.05	-0.01	0.16	-0.12
P	0.29	0.19	-0.24	-0.17	-0.01	-0.18
Pb.T	-0.29	0.02	-0.03	-0.04	-0.05	0.40
S	0.24	-0.02	-0.36	-0.28	-0.11	-0.02
Se	-0.28	0.23	-0.07	0.08	-0.08	0.21
Tl.T	-0.34	-0.02	-0.12	-0.04	-0.13	-0.37
Zn.T	0.09	0.36	-0.10	-0.27	0.27	0.15

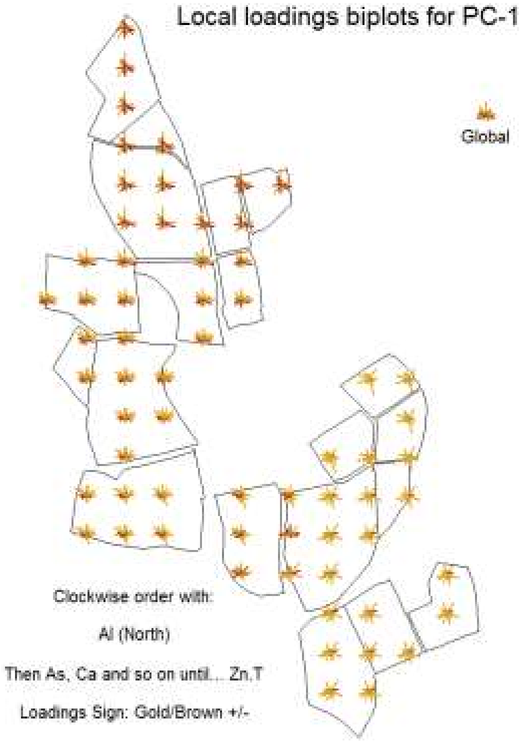
Global case

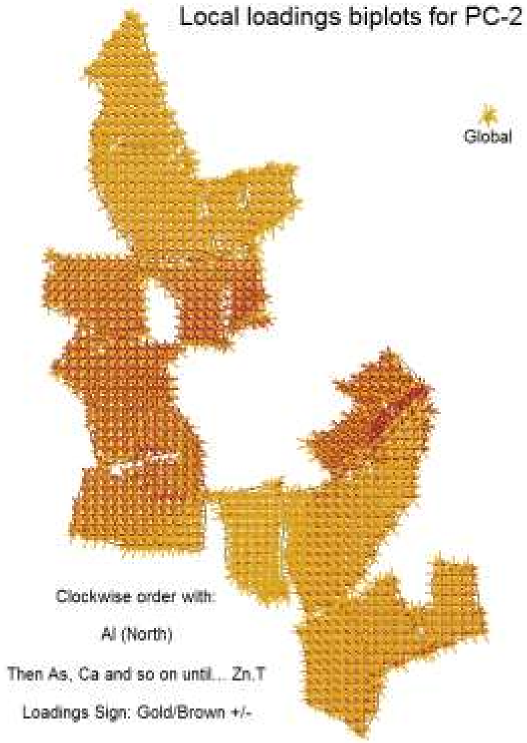


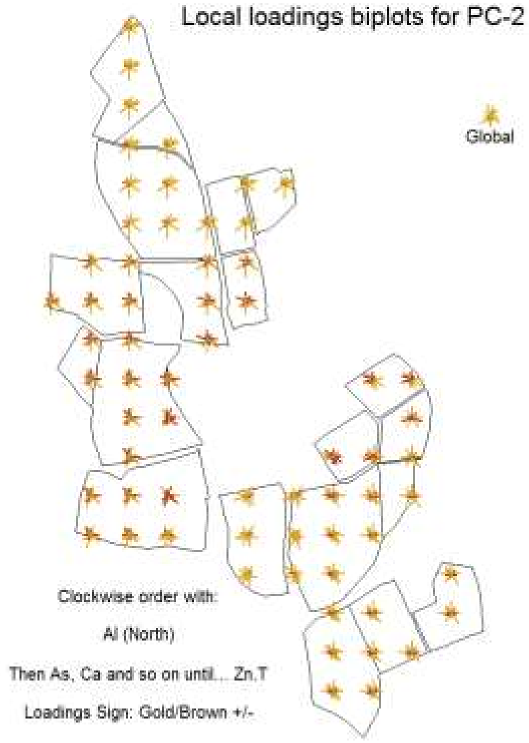


Local case on 25m and 100m grids

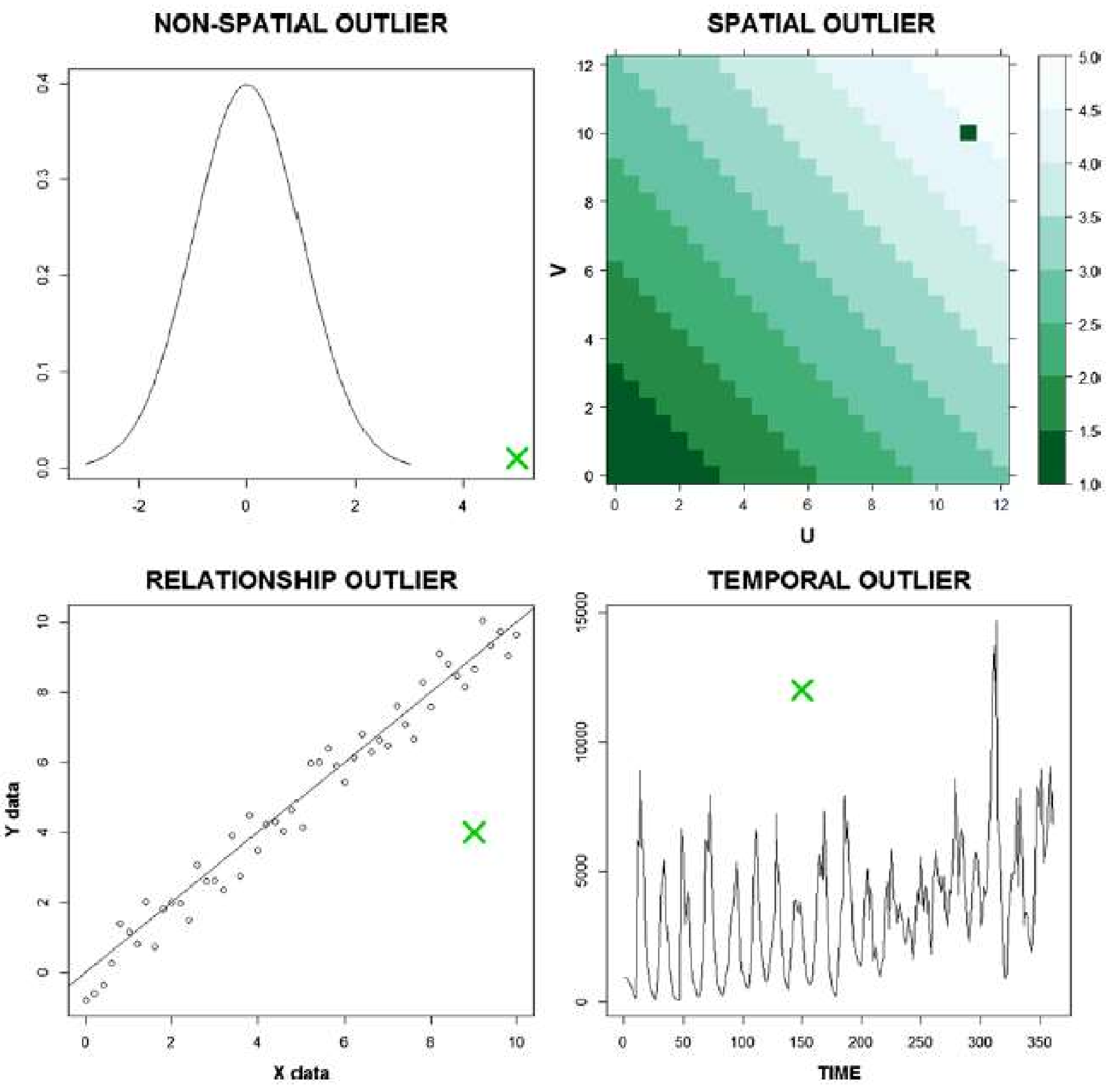








Analytical snippet # 5: Analyses for ‘Out of Ordinary’



Title: Statistical data mining for the out of the ordinary in agroecosystems

The volume, variety and velocity of data created through this experiment is overwhelming, the so-called “big data” problem, with different modes of acquisition, different measured variables, different data models (e.g., random fields, streaming data), some relating to fluxes, and different sampling frames in time. This proposed research aims to link these NWFP datasets to mine the data and the implicit relations statistically, for anomalies, non-linearities and non-stationarities. The research goals are: (a) to detect data that are in error (but have already passed a standard quality control (QC) exercise) and thus provide a highly advanced and sophisticated QC; and (b) to detect highly unusual events/characteristics in valid data that have never been considered before – events/characteristics that could be of great significance in advancing our understanding of grassland systems. Goal (a) strengthens the validity (and reduces uncertainty) of standard models that would be typically applied to the NWFP data when analysing differences among the three management regimes. Goal (b) is focused on discovery and is in line with modern machine learning/deep learning approaches to handling big data. This goal relates to ecological theory concerning extreme events, which this project will advance through considering extremes in terms of highly unusual combinations of driving variables. We propose a full range of statistical, machine learning and deep learning techniques each encompassing various multivariate, spatial, temporal, spatio-temporal, scale and extreme-value effects. New statistical/learning methodologies will result, reflecting the novel nature of the NWFP experiment itself. Opportunities for novel visualisation methods are planned, along with proposals for the re-direction of sampling resources to improve the information to cost trade-off efficiency of the NWFP experiment.

- **Hidden relationships / structures in the database**
- **Hidden extremes and hidden anomaly detection**

Challenges & Lessons Learned

NWFP: Challenges and Lessons Learned

A. Organisational Structure - interdisciplinary: science, data science, computer science, sensor engineering, etc.

B. Design - trade-offs, replication, interventions, process / measurement scales in time & space, optimisations, etc.

C. Treatments / Systems / Land use - severity, legacy effects, length & timings, overlapping system changes, time to return to baseline, etc.

D. Confounders - weather, soil class, topography, enterprise history, treatment history, etc.

E. Collections - relevance, spatial & temporal unit, baseline data, data for model inputs / validation, etc.

F. Data quality - basic / advanced QC, feedback loops to improve data quality

G. Analytical Toolkits - physics-based (& emulators), statistics-based, ML/DL-based, hybrids, etc.

H. Capture of uncertainties - measurement, missingness, scale, prediction, simulation, model parameters, etc.

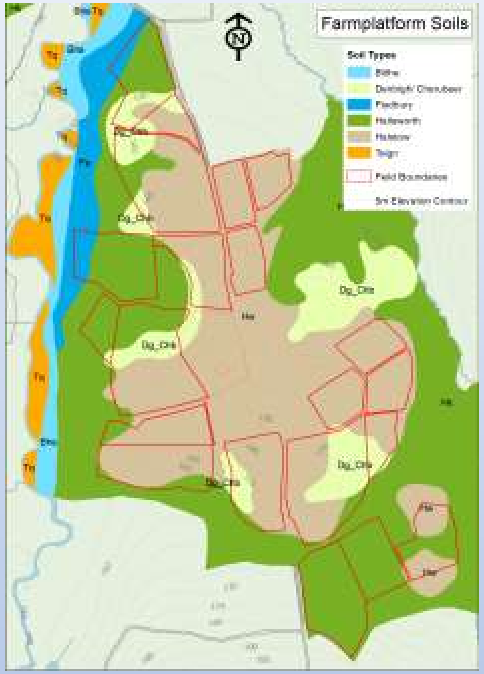
I. Geographies - fit to research farm (hubs), real farm (spokes), supply chain networks, external data (e.g. EO data)

J. Optimal use of resources - staff, capital grants, cost-benefit analyses, timely review and revision

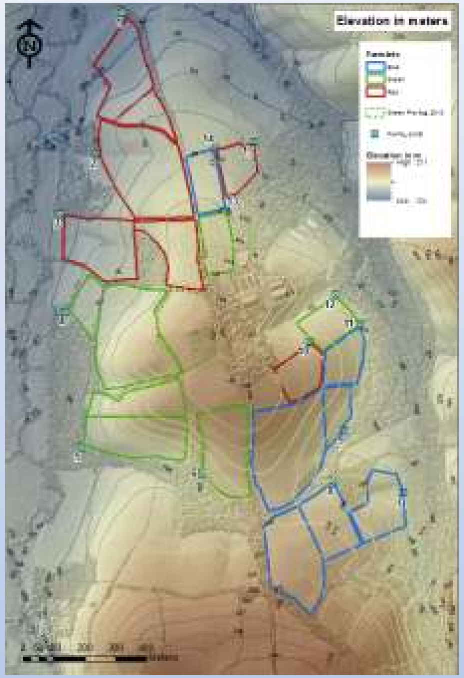
K. Stakeholders and co-development - identify and promote engagement

L. Planned outputs for impact - have a route map for this from the outset – tailored to different stakeholders

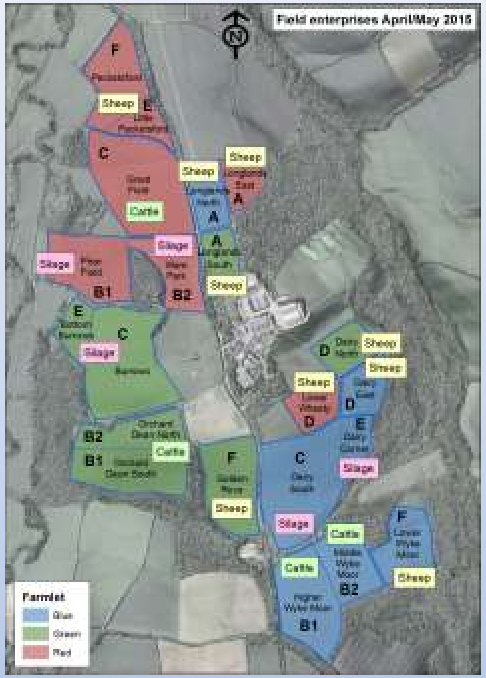
Spatial analysis on the NWFP - context/confounders, treatments & scale



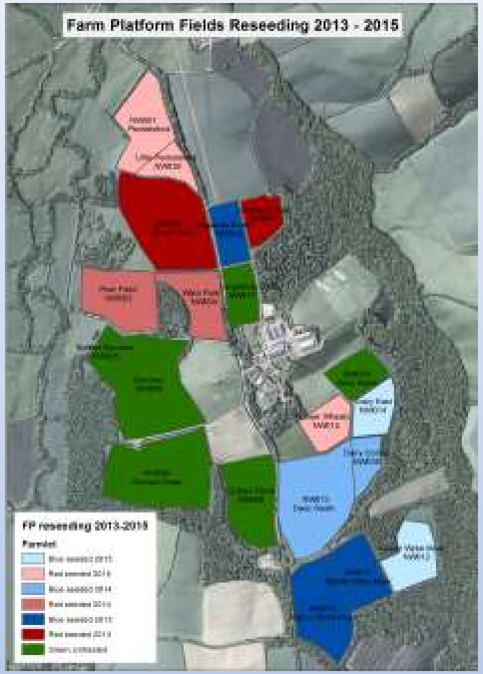
Soil class



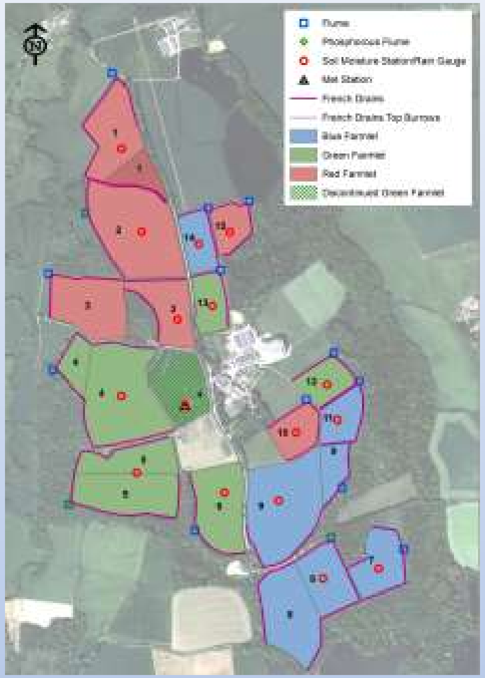
Topography



Enterprise history



Ploughing history



Treatments & Legacy

Also…

- Within-field/catchment grazing system history
- Fertilizer application history (& other field events)
- Meteorological/climate history
- Indirect/direct consequences of the NWFP experiment itself?

The NWFP experiment works best at the catchment or field scale

Spatial analysis works OK at the single within-field scale

But is awkward at the NWFP-wide & within-field scale!!

The Interdisciplinary 'A to B' for Transforming Farm-scale Data to Digital Platforms for Decision Support

1. Data Capture

A

- Field Collections & Lab analyses
- Land management & contextual Data
- Survey & External Data
- Remote Sensing
- In-situ & proximal sensing

2. Data Systems & Architecture

- Scalability, High Performance & Cloud Computing
- APIs & Data Communication
- Software Engineering
- Databases & platforms
- Data processing & QC

3. Serving the (Digital) Community

- FAIR data
- Documentation & Metadata
- Community coding (Github; Galaxy)
- Metrics of Use
- FAIR code

4. Agroecosystem Science

- Water / GHG emissions
- Soils (biology, chemistry & physics)
- Biodiversity & Ecology
- Crops & livestock
- Socio-Economics

5. Regular Review & Revision

- Cost Benefit Analysis for each component
- Prevailing Policy
- Scientific Literature & Debate
- Zeitgeist & Blue Sky
- Resource Costs

6. Data Science for Current Status

- Design & Re-design
- Matching Process & Data Scale
- Optimisation & Evaluation
- Machine & Deep Learning
- Statistical Inference & Uncertainty

7. Up-skilling & Ensuring Longevity

- Management Buy-in
- In-house Research Awards
- Culture Change
- Sabbaticals & Placements
- Mentoring, Training & Best Practice

8. Stakeholder Co-development

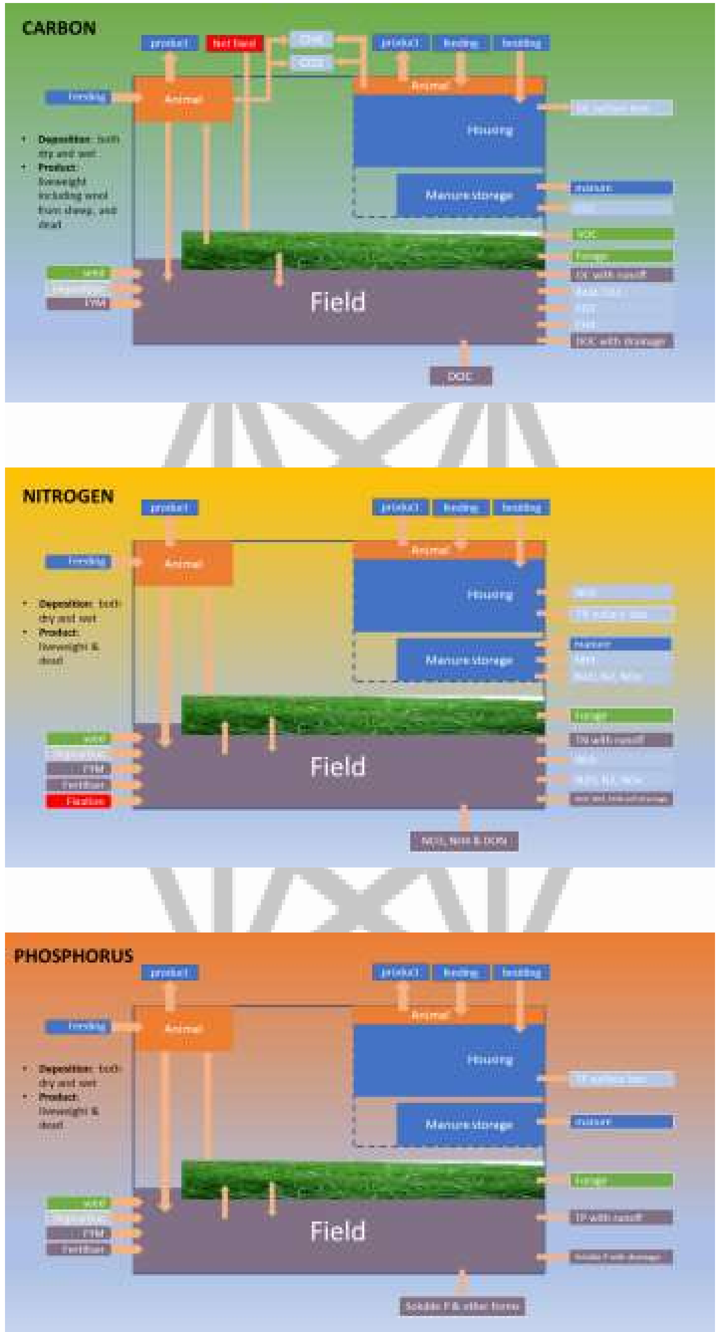
- Industry & Academia Sensor Engineering
- Agriculture Industries
- Policy & Government
- Environmental Organisations
- Academia with Digital Excellence

9. Digital Platforms for Forecasting

B

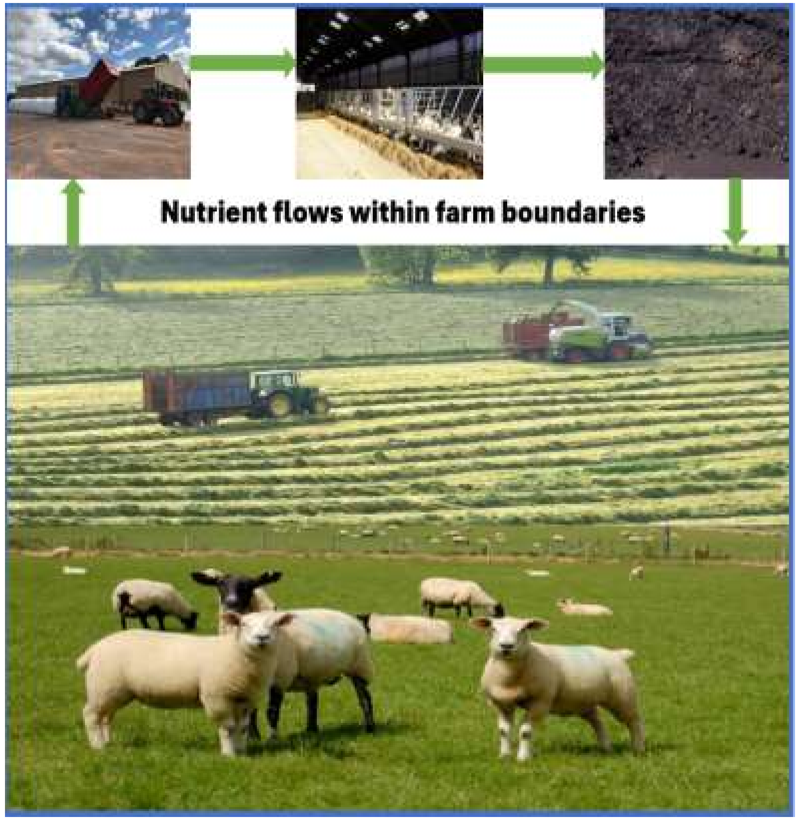
- Decision Support & Risk
- Digital Twins & Risk
- Hybrids & Ensemble models
- Back- & fore-casting
- Model simulation – internal & external calls

Process-based Models on the NWFP



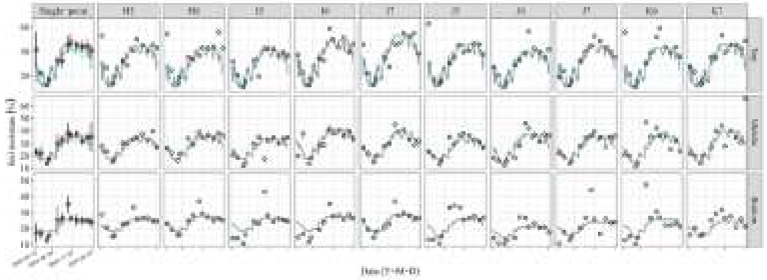
BUT – many farm processes are complex & difficult to simulate:

E.g.: Simulating nutrient budgets (Wu et al. in prep.)

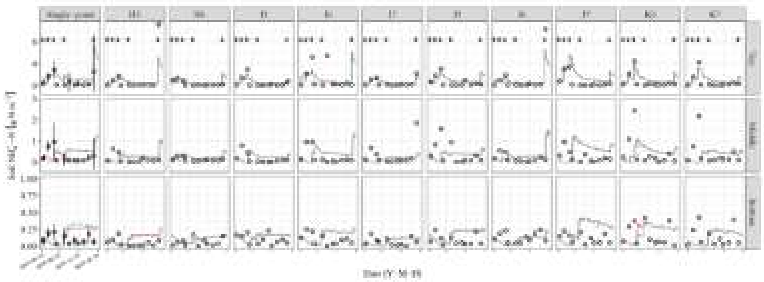


Thus, only indirect / limited validation

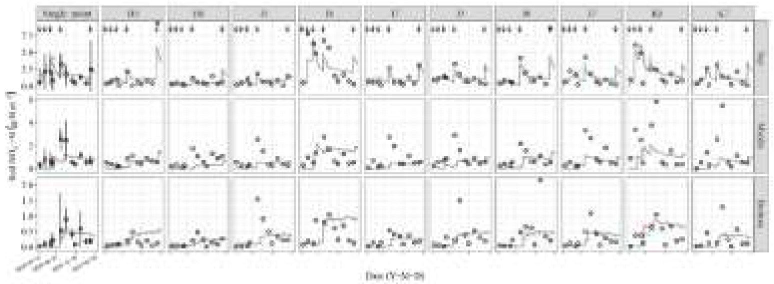
Soil moisture



Soil ammonium



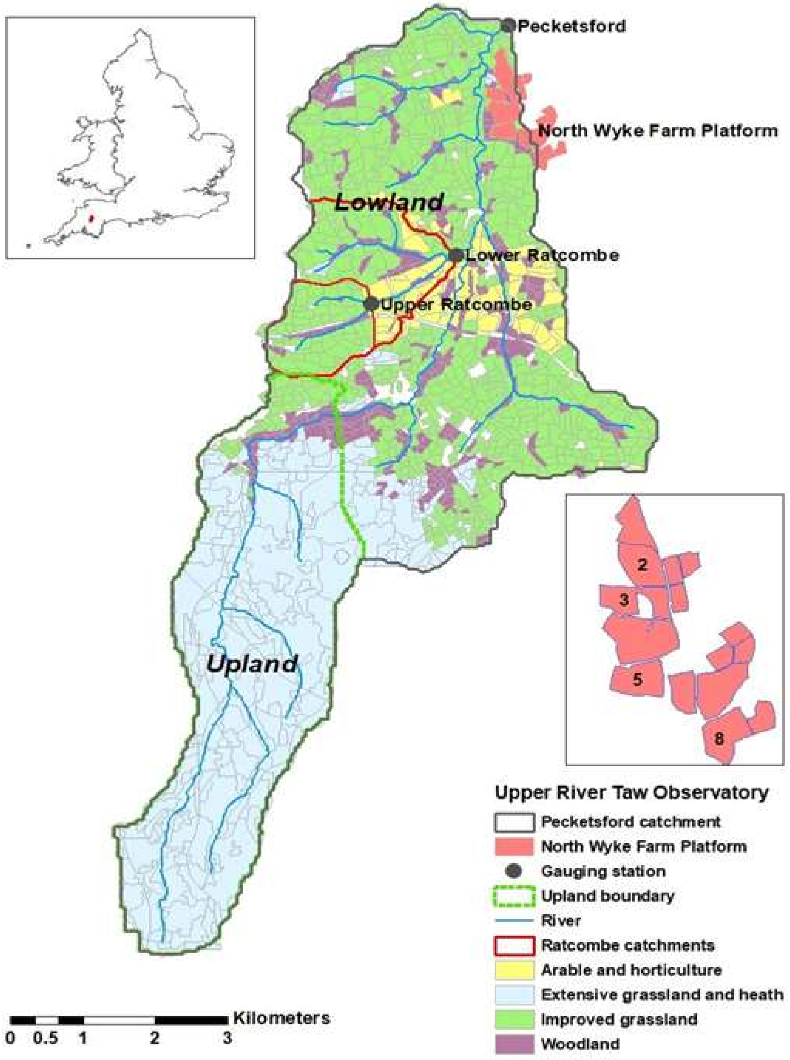
Soil Nitrate



Lui et al. (2023)

Little in common with Data-Driven Models (DDMs)

Forecasting: Ensemble PBMs using Upper River Taw Observatory (URTO)



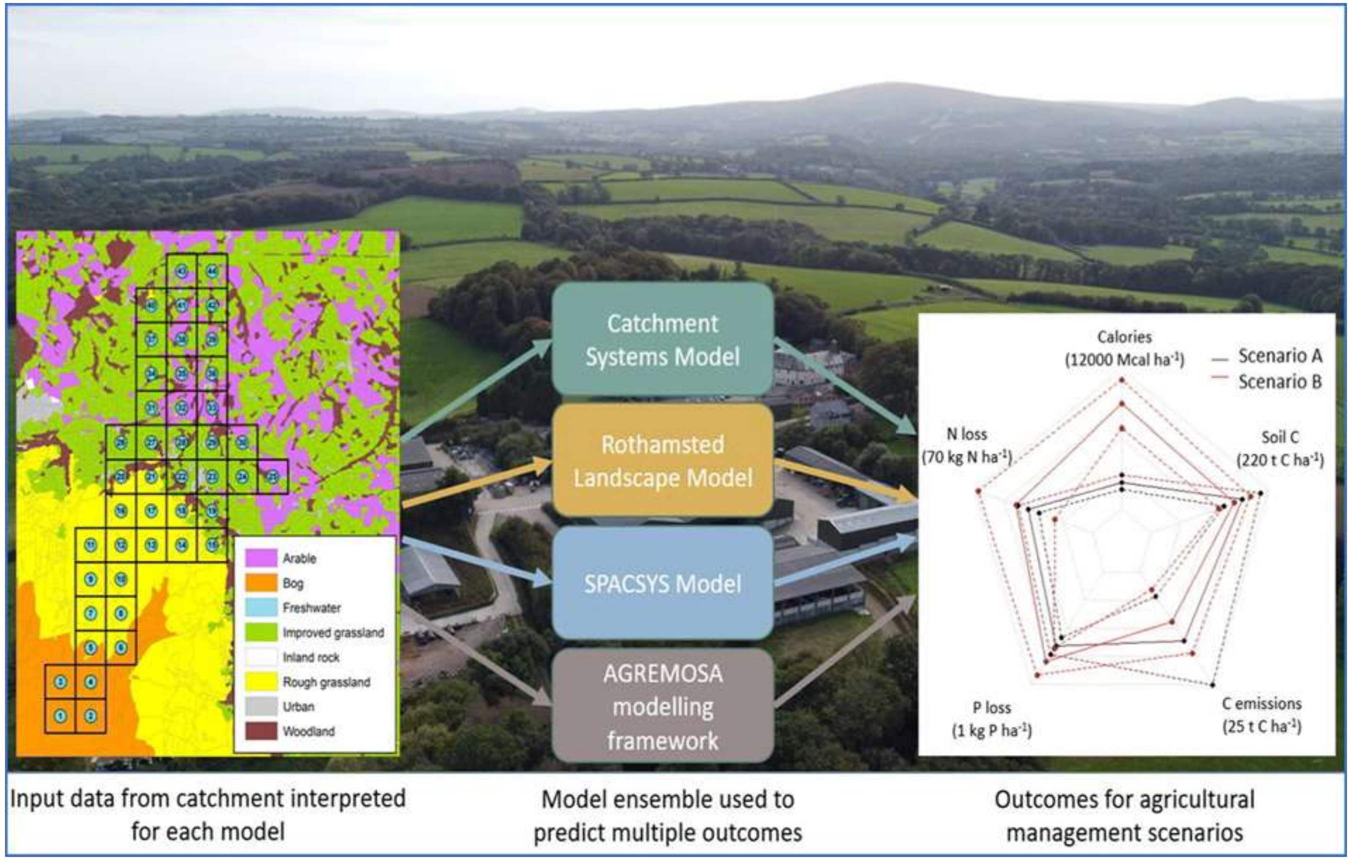
NWFP sits at edge of URTO

Science of the Total Environment

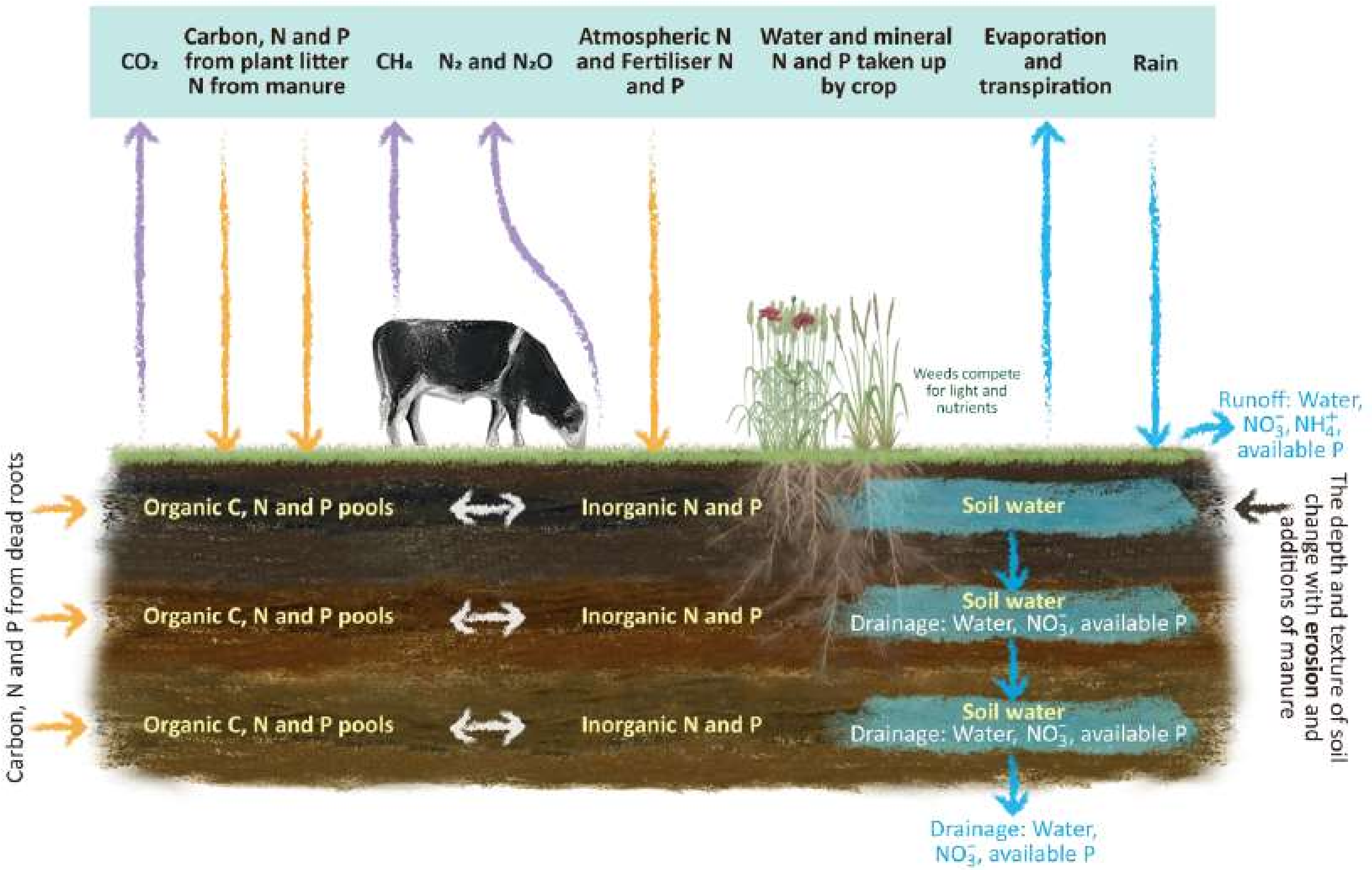
journal homepage: www.elsevier.com/locate/scitotenv

Exploring the effects of land management change on productivity, carbon and nutrient balance: Application of an Ensemble Modelling Approach to the upper River Taw observatory, UK

Kirsty L. Hassall[a], Kevin Coleman[b,1], Prakash N. Dixit[b,1], Steve J. Granger[c], Yusheng Zhang[c], Ryan T. Sharp[b], Lianhai Wu[c], Andrew P. Whitmore[b], Goetz M. Richter[b], Adrian L. Collins[c,1], Alice E. Milne[b,a,1]



Rothamsted Landscape Model:

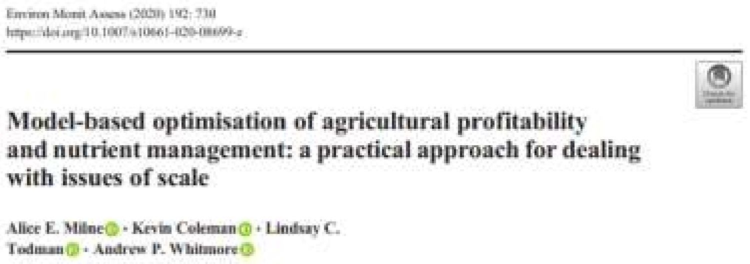


The Rothamsted Landscape Model is a suite of interacting process-based modules that simulate soil processes, (including soil organic matter, soil nutrient and water dynamics), livestock production and crop growth and yield, including interactions with arable weeds. The model is spatially explicit with adjacent pieces of land (fields or watercourses) linked to simulate spatial movement of nutrients, water (and in the future pests).


Science of the Total Environment

The landscape model: A model for exploring trade-offs between agricultural production and the environment

Kevin Coleman [a], Shibu E. Muhammed [a], Alice E. Milne [a,*], Lindsay C. Todman [a], A. Gordon Dailey [a], Margaret J. Glendining [b], Andrew P. Whitmore [a]


Environ Monit Assess (2020) 192: 730
https://doi.org/10.1007/s10661-020-08699-z

Model-based optimisation of agricultural profitability and nutrient management: a practical approach for dealing with issues of scale

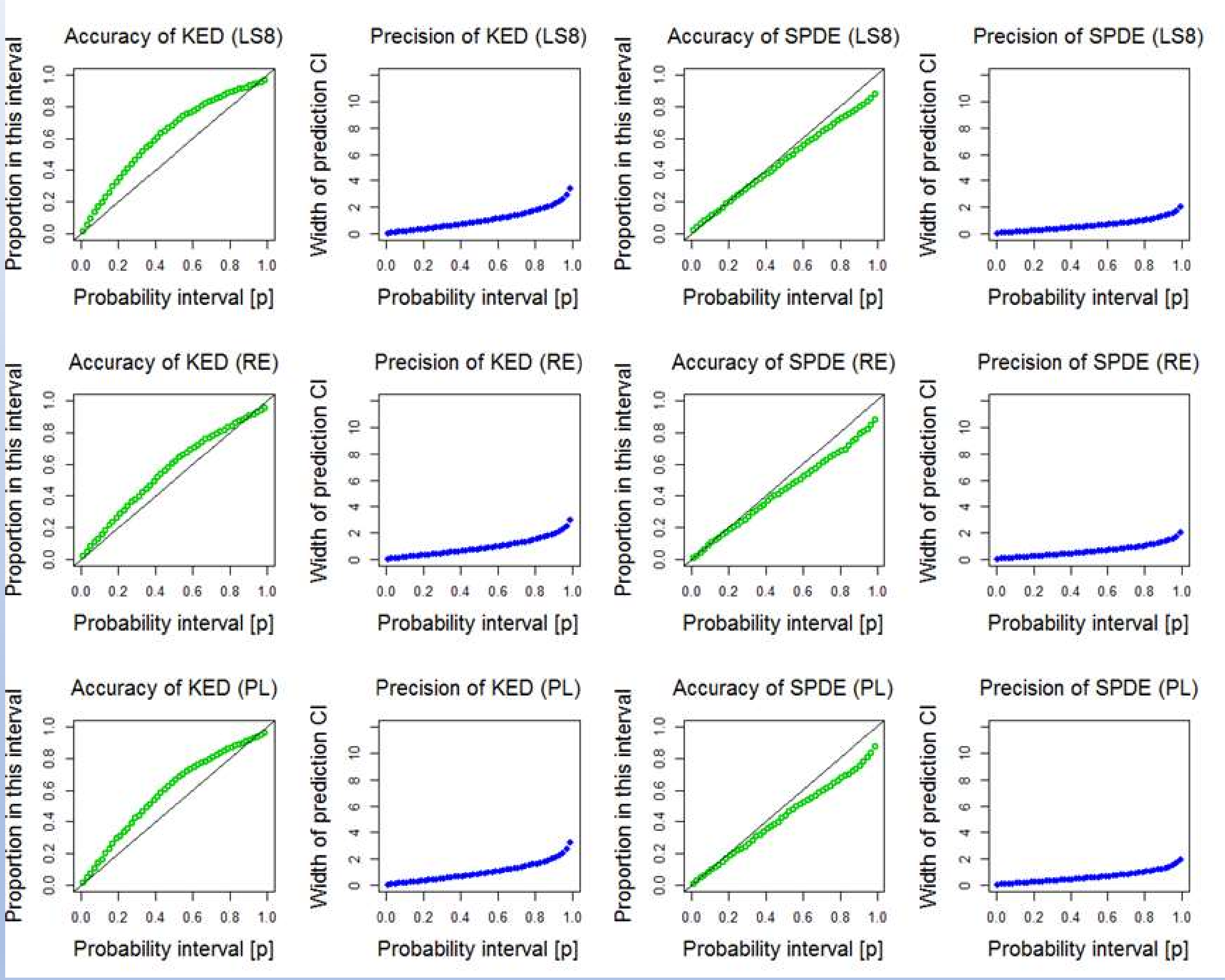
Alice E. Milne · Kevin Coleman · Lindsay C. Todman · Andrew P. Whitmore

Latest Updates:

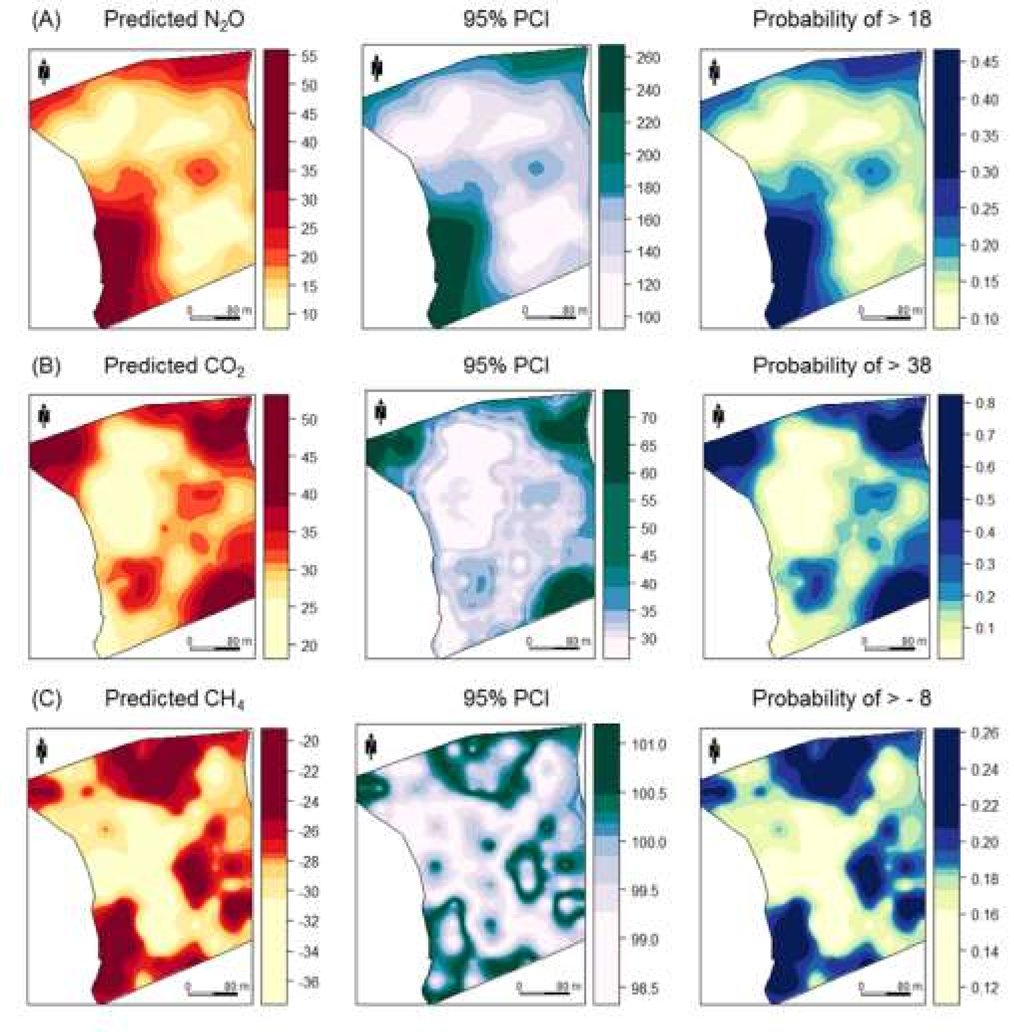
- Improved root growth model
- Dynamics of metals/micro-nutrients in soil and crops
- Impacts of tillage on soil erosion
- Pathogen dynamics: take all
- Improvements to RothC will be incorporated

Data-Driven Models for Capture of Prediction & Forecast Uncertainty

In-sample **assessment of prediction uncertainty:** *Out-of-sample* **forecast uncertainty & threshold exceedance:**



Spatial prediction using 2 DDMs & 3 different satellite products



DDM spatial forecasts for pasture GHGs

Farm Digital Twins

Farm-scale Digital Twin and its Modular Framework

Stakeholder Platform
- User Identification
- User Requirements
- Road Testing
- Community Development
- Open Source
- Outreach & Training

Data Collection
- Sample Design
- Farm Events & Observations
- Remote Sensing Data
- External Data
- PBM Input Data
- Measurement Uncertainty

Data Management
- Storage & Processing
- Quality Control
- Semantics & Interoperability
- Data Capture Latency
- Data Pre-processing & Fusion
- Pre-processing Uncertainty

Analytical Toolbox
- PBM Toolkit
- DDM Toolkit
- Data Assimilation
- PBM Emulators
- Hybrids
- Prediction Uncertainty

Forecasting & Scenarios
- Sustainable, Resilient or Net Zero?
- Short-term warning / Long-term forecasts
- Climate Scenarios
- Management & Land Use Scenarios
- Economic & Social Scenarios
- Forecast Uncertainty

User Interface
- Interactive Visualisation
- Decision Support & Risk
- Model Performance Toolkit
- Ensemble Specification
- Scale of Decisions & Refresh
- Adaptive Sample Re-design

Other
- Security & Privacy
- Energy Consumption Efficiency
- Sensor Communication & Engineering
- Technology Transfer
- Fit to Farm Digital Twin Networks
- Impact Stories

Impact: RRes Digital Twins

Expected impacts:

Management and land use decision support

Long-term forecasts coupled with short-term warnings

For stakeholders at the Farm-, Regional- & National-scale

Digital Twins for Resilience, Sustainability, Net Zero,…

* Each with bespoke modelling framework

Existing components:

Environmental sensors on the NWFP-NBRI – est. 2010

Ground reference on NWFP for remote sensing

Process-based modelling (PBMs) on the NWFP

Hybrids (PBMs with DDMs) for extremes on the NWFP

Upper River Taw Observatory (URTO) - for RFF ISP

In development:

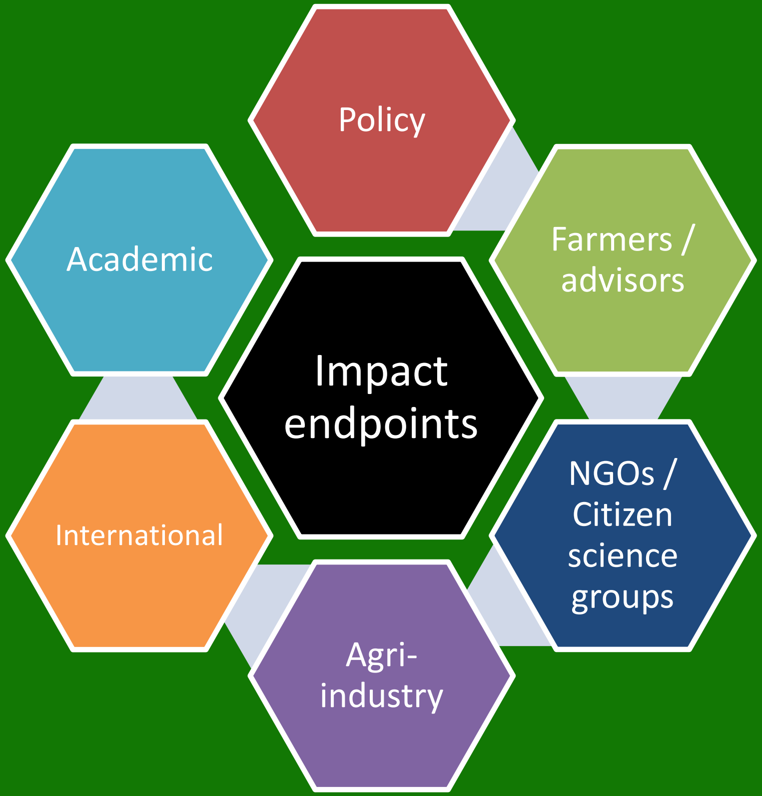
Digital workflows from NWFP-NBRI & URTO

Automated PBMs, Hybrids & Emulation

Sensor network design – what, where & when?

Digital Twin Architectures (Software)

Coupled Large Language Models / Semantic Querying



Next steps?

Imagery and plant phenotyping

Bespoke sensors with AI

Biodiversity challenges

Disease & pests

Indoor farms

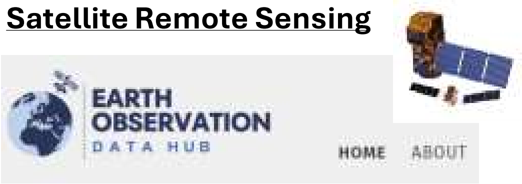
And more…

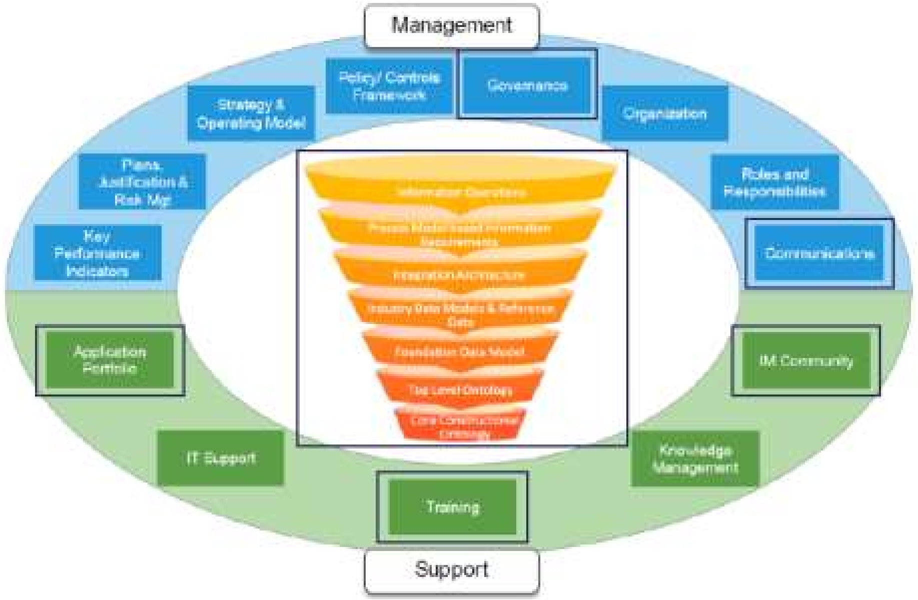
Co-development and User Cases for roll-out to real farms

Digital Twin IMF for Land Use Change

Information Management Framework

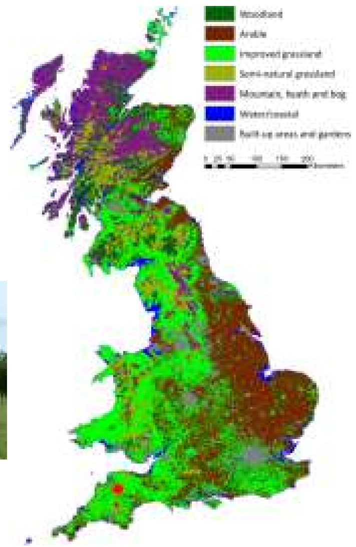
Satellite Remote Sensing



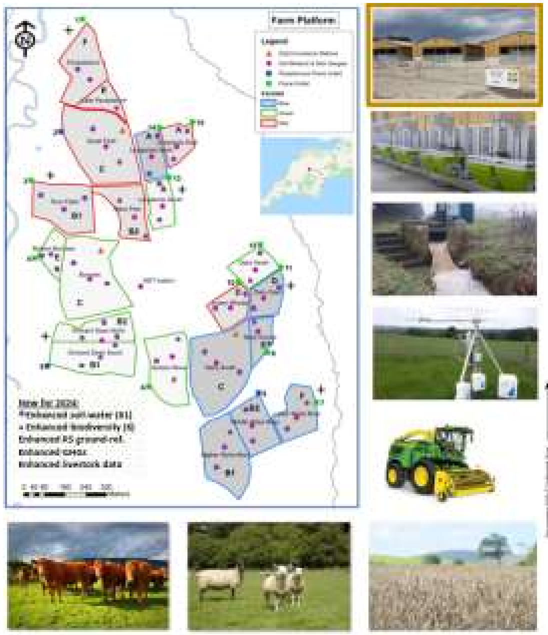


NOC (2022)

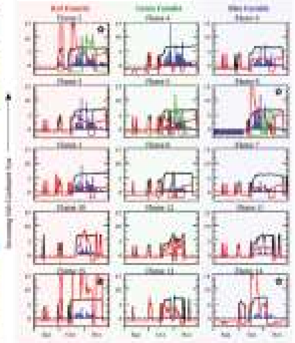
Land Use Change



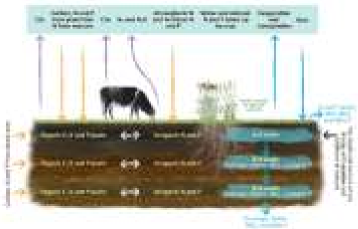
North Wyke Farm Platform



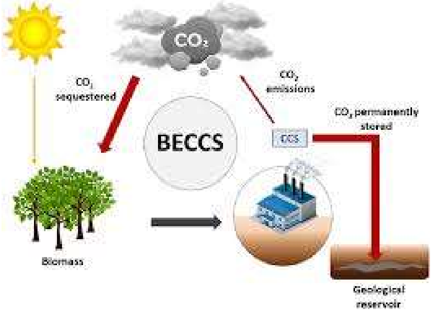
Nutrient leaching



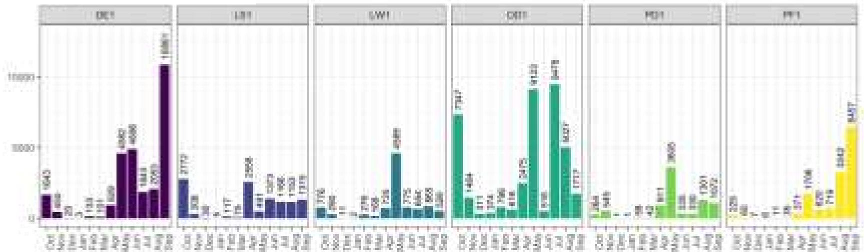
Rothamsted Landscape Model



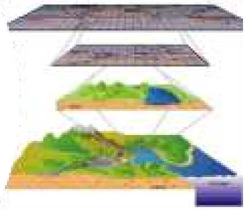
Bioenergy with Carbon Capture & Storage



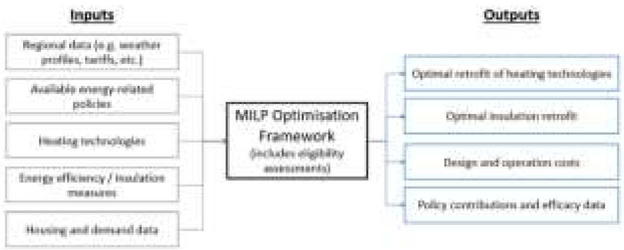
Bat counts (bioacoustics)



mesoclim in R



Models for Solar & Wind Generation



Farm Digital Twins: Dashboards

The ‘What if’ Dashboard for Resilient Farming: Red-DT with three alternative weather scenarios:

The ‘What if’ Dashboard for Net Zero Farming: Green-DT with combined management / weather scenarios:

The 'What if' Dashboard for Decision Making at Scale: Blue-DT with combined management / weather scenarios:

The ‘What if’ Dashboard: Red-DT with combined management / weather scenarios:

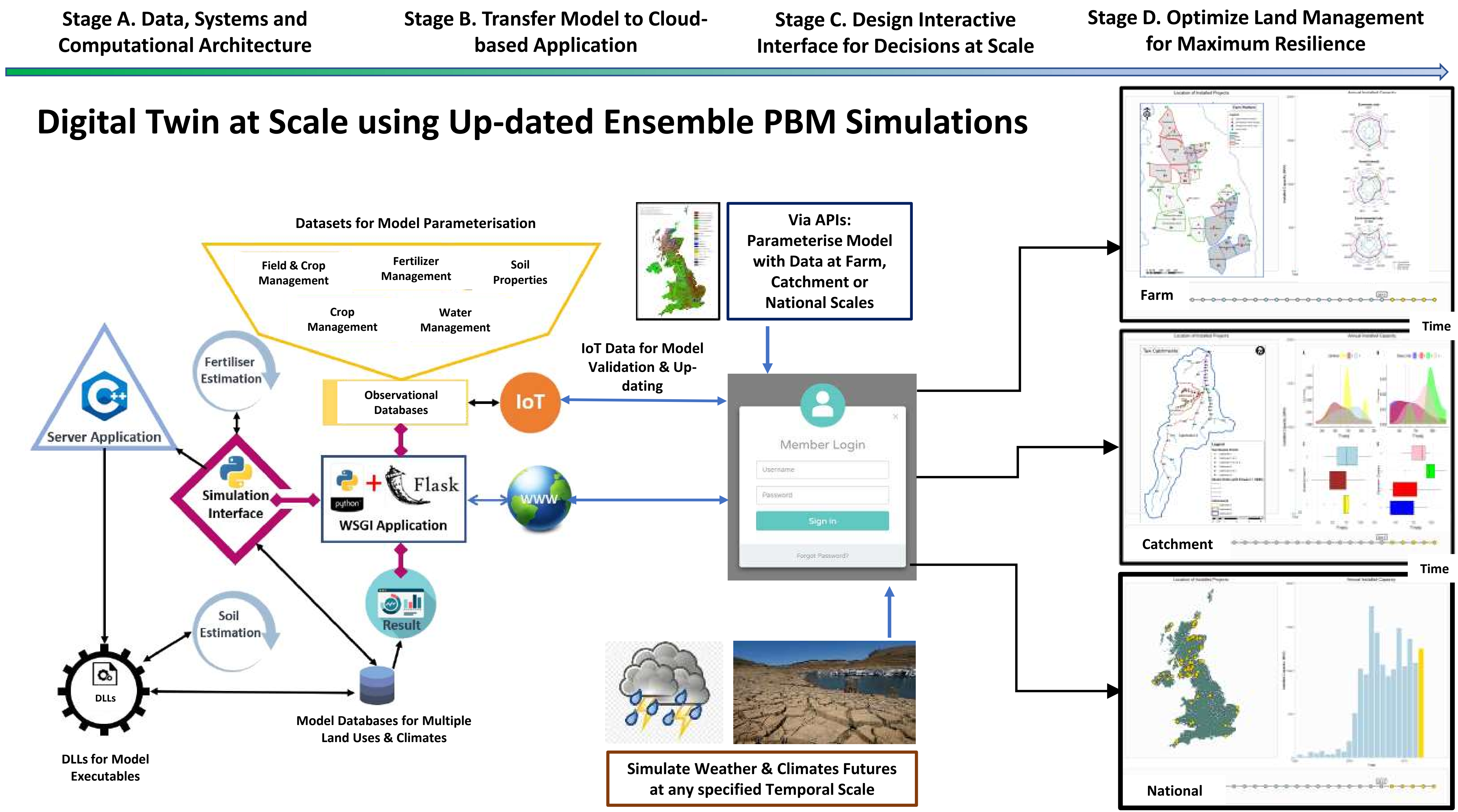
Sustainability – Resilience – Net Zero – Scale Farm Network – Scale Regional – Scale National

Digital Twins for Adaptive Design

Analytical snippet # 1: Adaptive forecasts with adaptive design

Analytical snippet # 2: Adaptive spatio-temporal forecasts with adaptive design

Farm Digital Twins: Other Representations

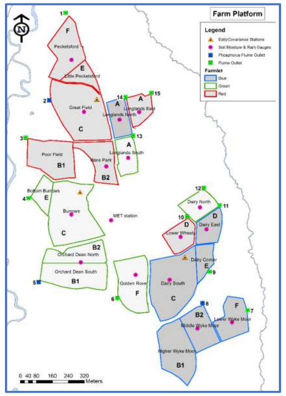

Stage A. Data, Systems and Computational Architecture
Stage B. Transfer Model to Cloud-based Application
Stage C. Design Interactive Interface for Decisions at Scale
Stage D. Optimize Land Management for Maximum Resilience
Digital Twin at Scale using Up-dated Ensemble PBM Simulations
Datasets for Model Parameterisation
Field & Crop Management
Fertilizer Management
Soil Properties
Crop Management
Water Management
Via APIs: Parameterise Model with Data at Farm, Catchment or National Scales
IoT Data for Model Validation & Up-dating
Fertiliser Estimation
Server Application
Observational Databases
IoT
Simulation Interface
python
Flask
WSGI Application
WWW
Member Login
Username
Password
Sign in
Forgot Password?
Result
Soil Estimation
DLLs
DLLs for Model Executables
Model Databases for Multiple Land Uses & Climates
Simulate Weather & Climates Futures at any specified Temporal Scale
Farm
Time
Catchment
Time
National

Mock-up of Web-based Digital NWFP using Modern Data Science Tools (2018)

ROTHAMSTED RESEARCH

Component system:
- ❑ Can bolt on other portals
- ❑ E.g. Interactive AI
- ❑ E.g. Advanced Visualisation

1. Portal - NWFP v2.0 (the real data)



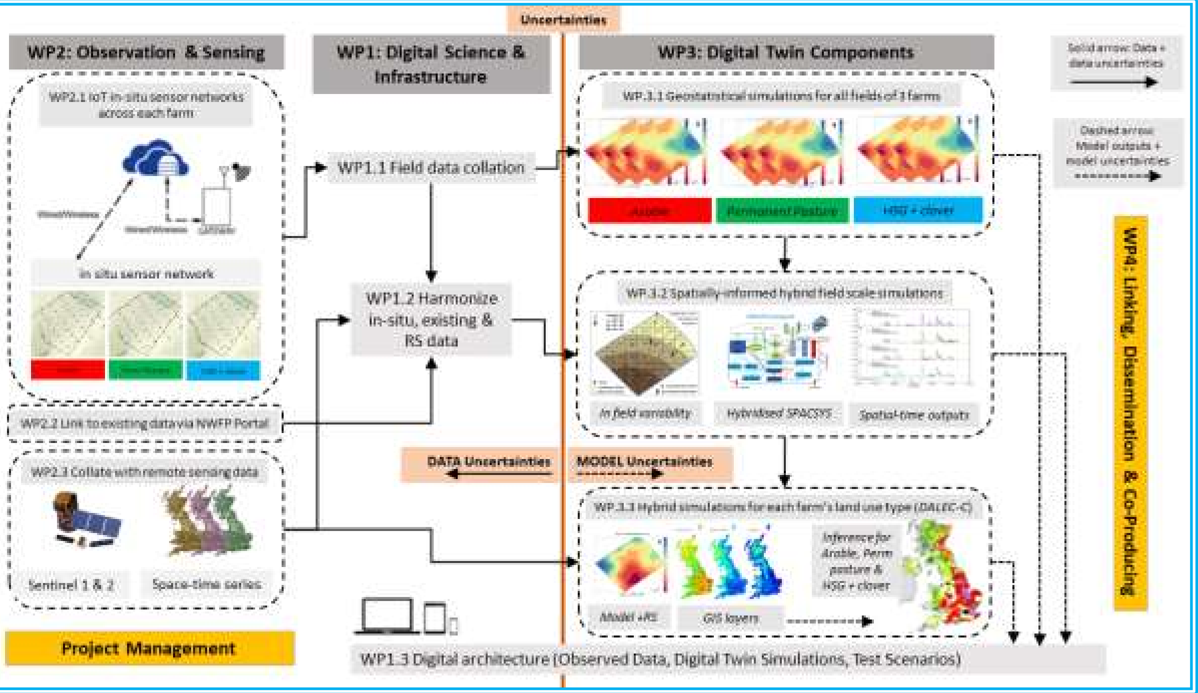
'Real time' data platform capturing open data through use of IoT

Extend NWFP collections for:
- ❑ Water Use Efficiency
- ❑ Soil fauna & biodiversity
- ❑ Pests & disease
- ❑ Etc.

Strengthen links to:
- ❑ Upper Taw (nested catchments)
- ❑ Local farmer networks (spokes)
- ❑ Other data hubs (GFP)

Strengthen links to:
- ❑ External Monitoring
- ❑ External Research
- ❑ Industry
- ❑ Data Science & IoT groups

3. Digital Twin: Simulations conditioned on real data (from NWFP v2.0)



- ❑ Open code
- ❑ Simulations from field to farm to landscape with Remote Sensing components
- ❑ Simulate metrics, nutrient cycling, LCA, Productivity, Emissions, etc.
- ❑ Project to Climate Change, Land Use Change

Digital Twins Options:
- ❑ Network of networks
- ❑ Research sites (UK & GFP sites)
- ❑ Regional & Local farmer networks
- ❑ Supply chain thru to the supermarket

2. Portal for generic data science tools

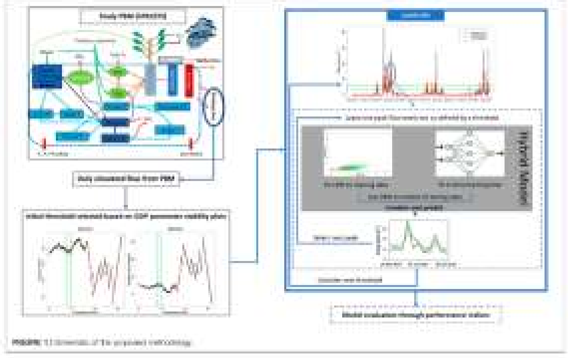
- ❑ Open code
- ❑ Data fusion & harmonization
- ❑ Up & down scaling
- ❑ Infilling
- ❑ Optimisations
- ❑ High performance Computing
- ❑ Visualisation
- ❑ Quality Control & Assurance

- ❑ NWFP github site
- ❑ See https://www.ceh.ac.uk/ukscape

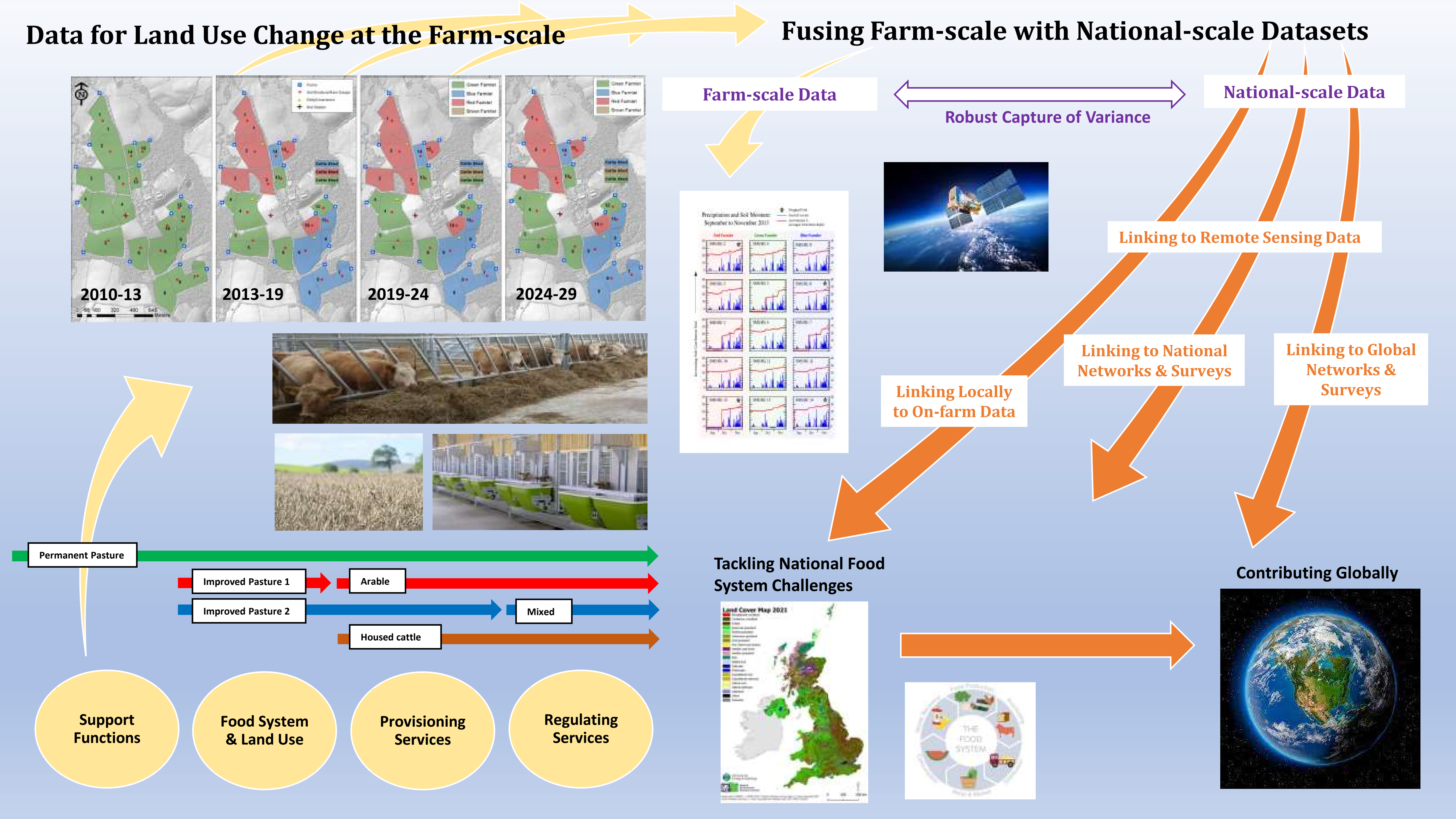
4. Portal for "Resilience due to shock events and extremes"

- ❑ Hybrids with open code
- ❑ High-dimensional anomalies
- ❑ Non-stationarities in space & time
- ❑ GWmodel (for 'locally unusual')
- ❑ Extreme value theory

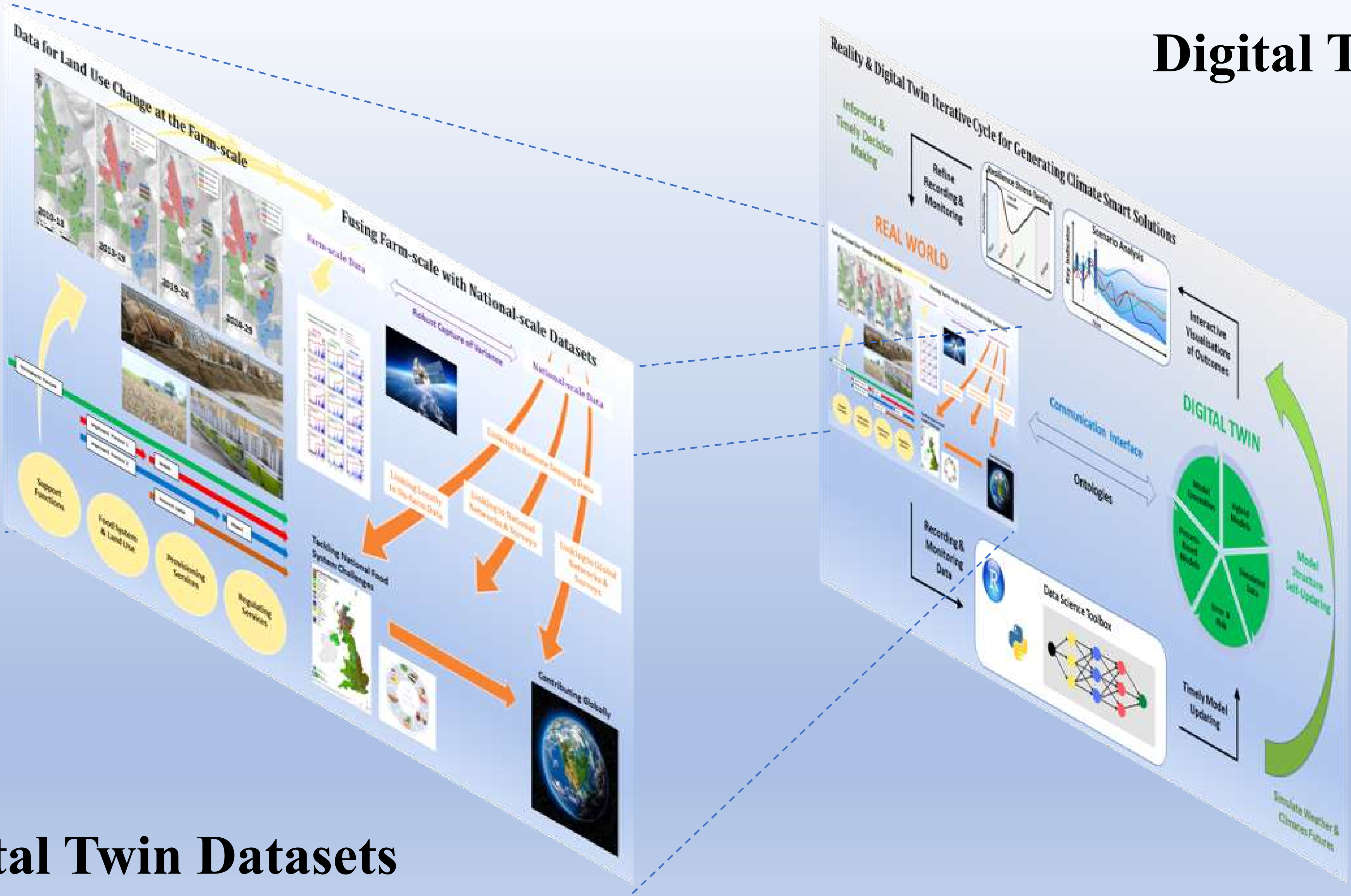
- ❑ "Tipping Points"
- ❑ "Perfect storms"
- ❑ "Black Swan" events



- ❑ Drive & fuel new RESEARCH HYPOTHESES


Data for Land Use Change at the Farm-scale
Fusing Farm-scale with National-scale Datasets
2010-13
2013-19
2019-24
2024-29
Farm-scale Data
Robust Capture of Variance
National-scale Data
Linking to Remote Sensing Data
Linking to National Networks & Surveys
Linking to Global Networks & Surveys
Linking Locally to On-farm Data
Permanent Pasture
Improved Pasture 1
Arable
Improved Pasture 2
Mixed
Housed cattle
Tackling National Food System Challenges
Land Cover Map 2021
Contributing Globally
Support Functions
Food System & Land Use
Provisioning Services
Regulating Services

Digital Twin



Digital Twin Datasets

GitHub:

AT RRES DT Project

Add status update

Gantt | Task List | Progress | My Tasks - by Date | My Tasks - by Type | + New view

Filter by keyword or by field

	Title	Assignees	Status	Start Date	Target Date	Task Type
32	Papers DT Advances #47		Todo	Aug 1, 2024		Publications

+ Add item

Digital Twin Models 13

	Title	Assignees	Status	Start Date	Target Date	Task Type
33	DT via (PBM/DDM) Hybrids #45	andrewmead107, ...	Todo	Sep 1, 2024	Mar 1, 2025	Digital Twin Models
34	Continuous training for DDMs #41	andrewmead107, E...	In Progress	Feb 1, 2024		Digital Twin Models
35	DT via DDMs #43	andrewmead107, E...	Todo	Sep 1, 2024	Mar 1, 2025	Digital Twin Models
36	Document challenges for PBM set-up #31	edvlmaas	In Progress	May 1, 2024	Oct 31, 2025	Digital Twin Models
37	Digital Twin Models #75	edvlmaas	In Progress	Feb 1, 2024	Oct 31, 2025	Digital Twin Models
38	Automate PBM model calibration #90	edvlmaas	Todo	Oct 1, 2024	Feb 28, 2025	Digital Twin Models
39	Investigate PBM software modification for GPU compatibility #91	edvlmaas	Todo	Aug 1, 2024	Sep 30, 2024	Digital Twin Models
40	DT via PBMs #40	edvlmaas, Erayoluw...	In Progress	Mar 1, 2024	Oct 31, 2025	Digital Twin Models
41	Ensemble PBMs #33	edvlmaas and oulai...	Todo	Sep 1, 2024		Digital Twin Models
42	Emulators of PBMs #35	Erayoluwa and harv...	On hold			Digital Twin Models
43	DDMs - for DT with Adaptive Sensor Designs #48	harvid50	On hold			Digital Twin Models
44	DDMs - Digital Realisations of NWFP #49	harvid50	On hold			Digital Twin Models
45	Data Assimilation #68	harvid50 and oulaidb	Todo	Jul 1, 2024		Digital Twin Models

+ Add item

Coupled RRes Projects

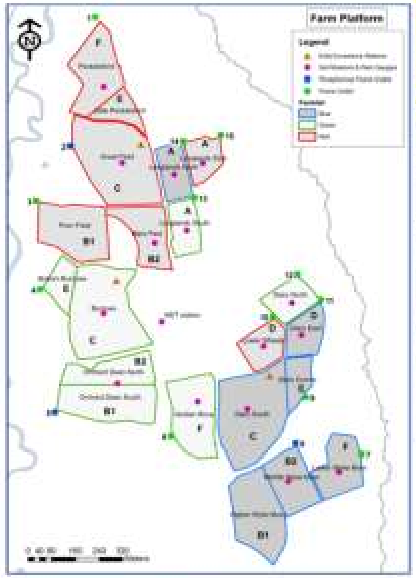
Wider Rothamsted Programme:

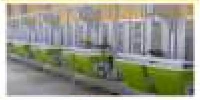
Decision Support via Farm, Catchment & National-scale Digital Twins

The NWFP-NBRI: an ideal demonstrator platform for farm-scale Digital Twins

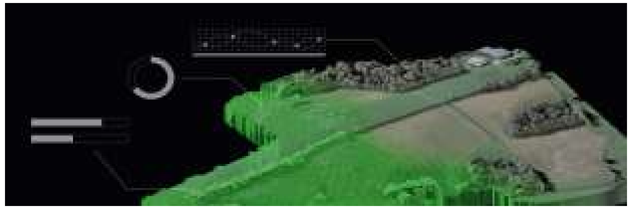
- ❑ **Data & Infrastructure: North Wyke Farm Platform (BBSRC - RRes NBRI)**
- ❑ **Enhancements: Capital Awards (CIEL, BBSRC, NERC)**
- ❑ **Research: Resilient Farming Futures (BBSRC - RRes ISP)**
- ❑ **Research: AI and DTs - Biodiversity & Climate Crisis (EPSRC - ATI with RRes)**

- ❖ **Linked to UKRI Digital Twin Network + hub**
- ❖ **Linked to MSc, PhD & Visiting Researcher projects at RRes**
- ❖ **Linked to BBSRC ‘PBMs with EO’ - UK / Australia partnering award (SOAP)**





<u>New for 2024:</u>
60 Soil moisture sensors
20 Rain gauges
6 Bio-acoustic Sensors
Enhanced RS ground-ref.
Enhanced GHGs
Enhanced livestock data



Engineering and Physical Sciences Research Council · CIEL · Natural Environment Research Council · Biotechnology and Biological Sciences Research Council · ROTHAMSTED RESEARCH

Timelines for RRes Digital Twin Proposals and Projects

1. PhD - Extremes PBM/ML/Stats hybrids in DTs (2016-2020) - finished
2. x2 ‘DIGGERS’ DT proposals - PoC across 3 research farm fields - Leeds, RRes, Bangor (2018 + 2019) - failed
3. The North Wyke Farm Platform RRes NBRI (2023-28) - funded
4. Resilient Farming Futures (RFF) RRes ISP WP3 - Farm and catchment scale DT only with soil moisture focus (2023-28) - funded
5. UK / Australia partnering award (SOAP) - APSIM PBM with Remote Sensing - DT with model assimilation (2023-26) - funded
6. PhD - Anomalies in DTs (2023-27) - funded
7. Alan Turing Institute - Environment & Sustainability Grand Challenge - Farm and national scale DT (2023-25) - funded
8. DT Network+ (2023-26) - funded
9. ‘AI-SUST’ - DTs for Land, Freshwater & Marine using same AI framework - Bangor (2023) - failed
10. NSF ‘Swick’ - DTs for US, UK & Canada (2023) - failed
11. Visiting researcher – VPMs, PBMs with Remote Sensing (2023-24) – self-funded
12. Visiting researcher - Emulators and VPM (2024) – self-funded
13. Hestia DEFRA - WRAP (LCA & ontologies) (2024-26) - funded
14. PhD - Sample design for DTs (2024-2028) – candidate selected
15. FAB-DT (emulators) – NERC TWINE call (2024-25) - failed
16. Land Surface DT (DT designs) - LUNZ call (2024-27) - failed
17. Land Use DT - LUNZ call (2024-27) - failed
18. Extension of SOAP - DT modelling from satellite imagery (2024-2028) – failed
19. Land Use Change DT – UKRI/Defra (2024-27) in review

UK-Australia project: Remote Sensing coupled with APSIM PBM

Sensing Oats with APSIM (SOAP):

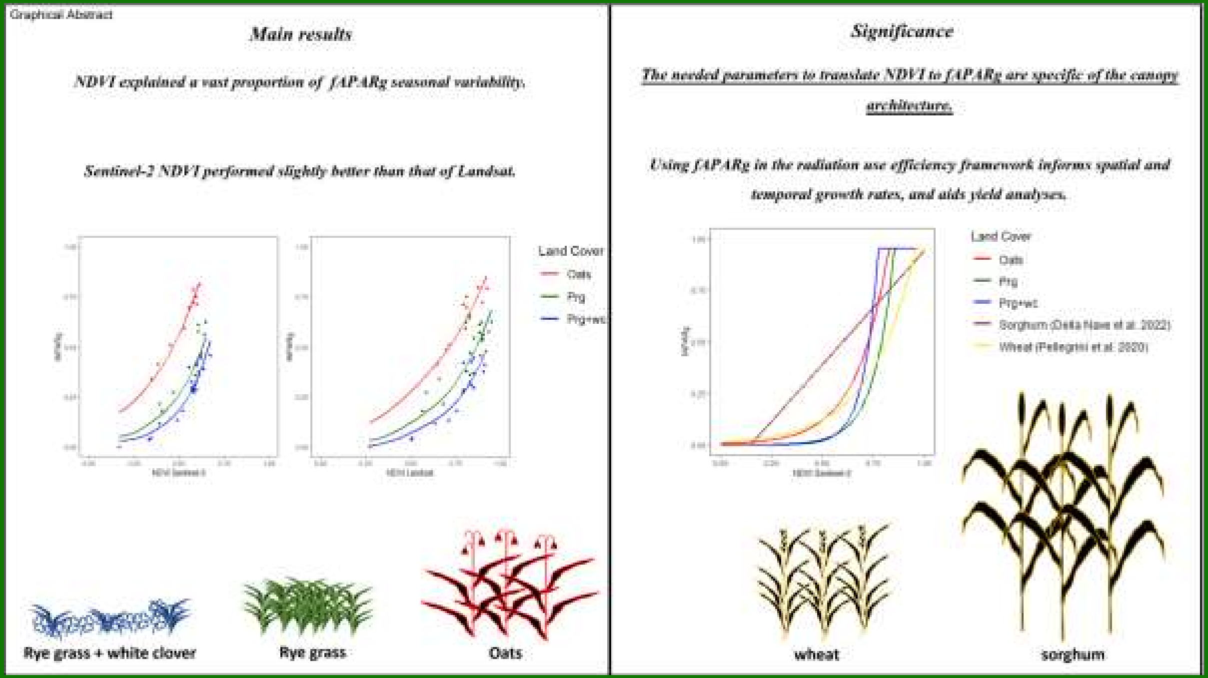
Hybrids for combining Remote Sensing with the APSIM process-based model

A BBSRC International Partnering Award

UK & Australia (University of Southern Queensland)

Using NDVI to predict fAPARg for different pastures & crops

fAPARg a more intuitive Remote Sensing index for crop monitoring



Biotechnology and Biological Sciences Research Council

University of Southern Queensland

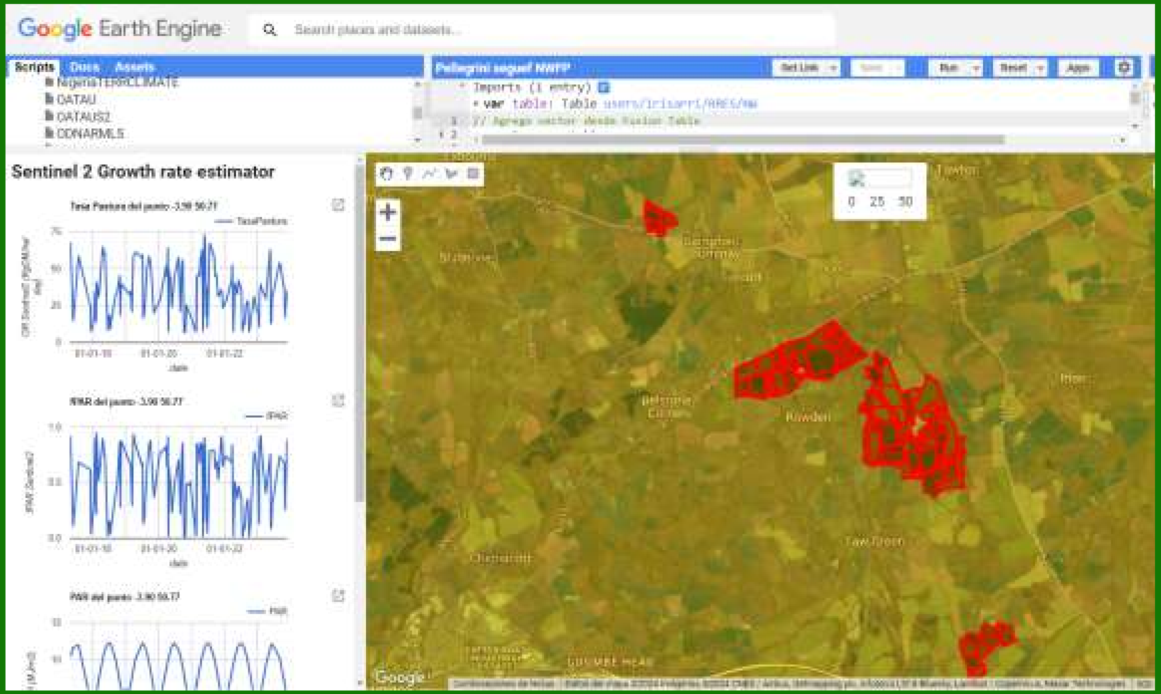
Remote Sensing Snippet:

Through Landsat and Sentinel-2 remote sensing data we can accurately estimate fAPARg, a crucial factor for monitoring crop & pasture canopies

Empirical models linking fAPARg to NDVI are used but models are lacking for temperate pastures

Especially models for wheat & oats

Integrating fAPARg into NDVI web tools provides on-line crop management strategies



Developing an open Google Earth Engine (GEE) app, that will allow any user to access growth rate predictions based on remote sensing data

Impacts:

The GEE app will allow stakeholders (policy makers, farmers) to track & monitor the Ag landscape at any scale in the UK

Similar rollout of GEE app in Australia

On-going work:

APSIM training workshops conducted in UK & Australia

APSIM a core model of the RFF ISP

Hybrids of remote sensing / APSIM in development

Links to co-development of APSIM-based Digital Twin projects in UK & Australia

International Projects: Visiting Research Workers


UNDER CONSTRUCTION
COMING SOON

Sustainability Metrics

SUSTAINABILITY METRICS

A	B	C	D	E	F	G
	Dairy	**Beef**	**Lamb**	**Pork**	**Chicken**	**Eggs**
Social	Training	Lameness	Nutrient density and profile	Worker health and safety/retention -	Pododermatitis	Feather score
	Responsible Antibiotic Use Objectives	Respiratory disease	Macro nutrients	Biosecurity	Hock burn	Keel bone damage
	Open farm Sunday	Mortality	Antibiotic reduction (particularly focusing	Animal health and welfare	Quality of life assessment	Mortality
	Face time a farmer	Opportunity to express natural behaviour	Supporting YFC farmers	Amino acids per kg? Use the metrics	Opportunity to express natural behaviour	Opportunity to express natural behaviour
	School Visit	Quality of life assessment	Vitamin / mineral compostion	Tail biting	Campylobacter	Quality of life assessment
	Positive contribution to community	Antibiotic usage	Lameness	Lesions scoring	Salmonella	Antibiotic usage
	KPIs (and allocate point and minimum threshold)		Mastitis	Lameness	Antibiotic usage	Salmonella free
	Red Tractor		Opportunity to express natural behaviour	Opportunity to express natural behaviour		
	Lameness		Quality of life assessment	Quality of life assessment		
	Mastitis		Mortality	Antibiotic usage		
	Cow longevity		Mutilations (tail docking/castration/mulesing)		Public engagement	Public engagement
	Quality of life assessment				Colleague/student training	Colleague/student training
	Opportunity to express natural behaviour				Living wage	Living wage
	% calves with viable market					
	Striving for sustainability for next gen					
	SDDG specific pool of known farmers					
Environmental	Soil	Carbon sequestered by the landscape	LFA's utilised - area coverage?	Carbon measure (per sow or per kg)	Trees planted	Trees planted
	Trees / hedges	Wormer and flukicide usage	Amount of hedgerows / trees	Land Use (per kg)	Ammonia emisisons	Ammonia emissions
	Biodiversity (novel initiatives e.g. bee hot	Concentrate sustainability	Amount of land in SSSI's, protected lands	Air emissions (per kg) - Ammonia,	Carbon footprint	Carbon footprint
	Rain water harvesting? Bore Holes	Slurry management	Herbal leys / wild flower leys?	Water use (per kg) - drinking, washing,	Feed sustainability	Feed sustainability
	Water Use Plan	Carbon footprint	Carbon sequestered by the landscape	Slurry removals per kg? (odour and		Range biodiversity (incorporates trees/foliag
	Nutrient Management Plan		Leaf marque accredited	Carbon measure of feed (per kg pigmeat		Wormer usage
	Plastic policy / recycling		Methane / Nitrogen / Carbon emissions			Red mite control strategy
	Renewables		Wormer and flukicide usage			
	Soya use in feed		Sheep scab control strategy		Habitats created	Habitats created
	Ammonia Output (measured using tool)		Concentrate sustainability		Wildlife hosted	Wildlife hosted
Economic	Productivity KPIs (e.g.lifetime daily yield)	Age at slaughter	Supporting British farmers - development	Kg/sow/year	FCR	Eggs per hen housed
	AAFC	DLWG	Lambs hitting spec - projects and initiativ	Profitability - p/kg (SPP-COP/kg	Total mortality	Seconds %
	Calving index	Feed cost of production/kg	TtD bonus payments	Community economic benefit?	Total rejects	FCR
	Maximising value from calves born	Calving %	YFC bonus payments	Mortality rate (all stages)	DOAs	Mortality
	Feed cost of production/litre	Renewable energy produced	Lambing %	Sow lifetime productivity - pigs/sow/life	Renewable energy produced	Renewable energy produced
	Renewable energy produced	Carbon sequestration income (e.g. tree pl	Lamb survival %	FSA post mortem outcomes	Carbon sequestration income (e.g. tree pl	Carbon sequestration income (e.g. tree plant
	Carbon sequestration income (e.g. tree pl	Environmental stewardship income	Ewe replacement rate	Renewable energy produced	Environmental stewardship income	Environmental stewardship income
	Environmental stewardship income		Renewable energy produced	Carbon sequestration income (e.g. tree planting, carbon capture technology)		
			Carbon sequestration income (e.g. tree pl	Environmental stewardship income		
			Environmental stewardship income			

Weighting


Ecological Indicators

Review

When to use what: Methods for weighting and aggregating sustainability indicators

Table 2
Common methods for indicator weighting (primarily based on Nardo et al. (2005), OECD (2008), Hermans et al. (2008), and Mikulić et al. (2015)).

Method Name	Type	Examples	Formulas	Benefits	Drawbacks
Equal weighting	Equal weighting	Human Development Index (UNDP, 1990) Genuine Savings (WorldBank, 1999)	$\omega_i = \omega$, $i = 1, \ldots, m$, where ω_i is the weight of the i^{th} indicator and ω a constant used as the weights for all the indicators	Simple, replicable and straightforward.	No insights into indicator relationships; risk of double weighting.
PCA/FA	Statistic-based	Environmental Sustainability Index (Sands and Podmore 2000) The 2006 European e-Business Readiness Index (Pennoni et al., 2006)	$\omega_i = r_j(l_{ij}^2/E_j)$ $i = 1, \ldots, m$; $j = 1, \ldots, n$ where r_j is the proportion of the explained variance of factor j (or the intermediate composite j) in the data set, l_{ij} the factor loading of the i^{th} indicator on factor j and E_j the variance explained by the factor j	Reduces the risk of double weighting, classifying ungrouped indicators.	Dimensions of sustainability are unpredictable, and weights may differ from reality.
Benefit of the doubt approach (BOD)	Statistic-based	Meta-index of Sustainable Development (Cherchye and Kuosmanen 2004) Macro-economic performance evaluation (Melyn and Moesen 1991)	$\omega_c = \arg\max_{\omega_{c,i}} \frac{\sum_{i=1}^{m} \omega_{c,i} I_{c,i}}{\max_{I_{ij} \in \{\text{studied units}\}} \sum_{i=1}^{m} \omega_{c,i} I_{j,i}}$ s.t. $\sum_{i=1}^{m} \omega_{c,i} I_{j,i} \le 1$, $\omega_{c,i} \ge 0$ $\forall i = 1, \ldots, m$; $\forall j = 1, \ldots, n$ where $\boldsymbol{\omega}_c$ is the weight vector of unit c, $\omega_{c,i}$ the weight of the i^{th} indicator of unit c, $I_{c,i}$ the normalized score of the i^{th} indicator of unit c, and $I_{j,i}$ the normalized score of the i^{th} indicator of the j^{th} unit	The processes of weighting, aggregation, and index construction are efficiently integrated. Weights are selected to maximize the index for each unit.	Results may not be comparable and lack transparency. A multiplicity of solutions exists.
Regression analysis (RA)	Statistic-based	National Innovative Capacity (Porter and Stern 2001)	$\omega_i = \beta_i$, $i = 1, \ldots, m$ where β_i is the regression coefficient of the i^{th} indicator	Results can be used for updating or validating weights.	Either multi-collinearity among indicators or an improper dependent variable may lead to poor results.
Unobserved component models (UCM)	Statistic-based	The aggregate governance indicators (Kaufmann et al., 1999)	$\omega_i = \frac{\delta_i^{-2}}{1 + \sum_{i=1}^{m} \delta_i^{-2}}$ $i = 1 \ldots, m$ where δ_i is the variance of the i^{th} indicator	The processes of weighting, aggregation, and index construction are efficiently integrated. Statistical significance can be expressed when conducting comparisons.	Results are sensitive to outliers. Problems of identification may occur if indicators are highly correlated. Reliability and robustness of the model may be lost when adequate data are not available.
Budget allocation (BAL)	Public/Expert opinion-based	The Eco-indicator 99 (Goedkoop and Spriensma, 2001) Overall Health System Attainment (Murray et al., 2000)	–	Transparent and explicit.	Measuring urgency instead of importance; region-specific.
Public opinion (PO)	Public/Expert opinion-based	Concern about environmental problems Index (Parker, 1991)	–	Transparent and participatory.	Measuring concern instead of importance; region-specific.
Analytic hierarchy process (AHP)	Public/Expert opinion-based	Composite sustainability performance index (Singh et al., 2007) Index of Environmental Friendliness (Puolamaa et al., 1996)	$\mathbf{A}\boldsymbol{\omega} = \lambda\boldsymbol{\omega}$ where $\mathbf{A}$ is the comparison matrix, λ the largest eigenvalue of $\mathbf{A}$, and $\boldsymbol{\omega}$ the weight vector as well as the eigenvector corresponding to λ	Has a hierarchical structure that is in line with the structure of sustainability frameworks. Simple and flexible. Providing consistent verification operation. Available for both quantitative and qualitative data.	Requirement of a high number of pairwise comparisons. Inconsistency and cognitive stress may exist if there are too many indicators in each cluster.
Conjoint analysis (CA)	Public/Expert opinion-based	Indicator of quality of life in the city of Istanbul (Ülengin et al., 2001)	$\omega_i = \frac{\partial P(I_1, \ldots, I_m)}{\partial I_i}$ where $P(I_1, \ldots, I_m)$ is the preference function defined by researchers and I_i the i^{th} indicator	Results can be easily used for making sustainability plans. Available for both quantitative and qualitative data.	Requires a large sample of respondents. Has complicated estimation process.

Also Fuzzy set theory with AHP & Ideal Point Variants (Saaty 2008)

Uncertainties associated with combining metrics:

- Bayesian Approaches
- Fuzzy Set
- Dempster-Shafer
- Possibility theory

(e.g. Su et al. 2019; Wang et al. 2019)

Aggregation

X. Gan et al.

Table 3
Common methods for indicator aggregation (based mainly on Munda and Nardo (2005), Beliakov et al. (2007), OECD (2008), and Pollesch and Dale (2015)).

Common methods for aggregation	Examples	Formulas	Benefits	Drawbacks
Additive aggregation	Environmental Performance Index (Esty et al., 2006) Well Being Index (Prescott-Allen 2001)	$SI = \omega_1 I_1 + \omega_2 I_2 + \ldots + \omega_m I_m = \sum_{i=1}^{m} \omega_i I_i$ where SI is the sustainability index, ω_i the weight of the i^{th} indicator, and I_i the normalized score of the i^{th} indicator.	Transparent and simple. Easy to execute sensitivity analysis and uncertainty quantification.	Rigorous prerequisites exist, such as mutually preferentially independence.
Geometric aggregation	Living Planet Index(Loh et al., 1998; Loh et al., 2005)	$SI = I_1^{\omega_1} I_2^{\omega_2} \ldots I_m^{\omega_m} = \prod_{i=1}^{m} I_i^{\omega_i}$ where SI is the sustainability index, ω_i the weight of the i^{th} indicator, and I_i the normalized score of the i^{th} indicator.	Transparent and simple. Can be used for all kinds of ratio-scale variables.	Rigorous prerequisites exist, such as mutually preferentially independence.
Non-compensatory aggregation methods	Index for "Social Multi-Criteria Evaluation"(Munda 2004)	Rank($Unit_i$) $s.\ t.\ \varphi_* = \max \sum e_{jk}$ $i = 1,\ldots,n$ where Rank ($Unit_i$) is the overall ranking of the n researched units, φ_* the corresponding score of the final ranking of the researched units, and e_{jk} the generic element of the outranking matrix.	No ad hoc restrictions.	Computational problems may be caused by the increasing number of units or indicators. Losing information on the intensity of sustainability.

The use of the Canberra metrics to aggregate metrics to sustainability

Humberto S. Brandi · R. J. Daroda · A. C. Olinto

Quadrant Test

Public Health Nutrition: 18(13), 2488–2497
doi:10.1017/S1368980015000579

Which functional unit to identify sustainable foods?

Gabriel Masset, Florent Vieux and Nicole Darmon*
Mixt Research Unit NORT (Nutrition, Obesity and Risk of Thrombosis), Institut National de la Recherche Agronomique 1260 INRA, Institut National de la Santé et de la Recherche Médicale 1062 INSERM, Aix-Marseille Université, F-13385 Marseille, France

Which functional unit to identify sustainable foods

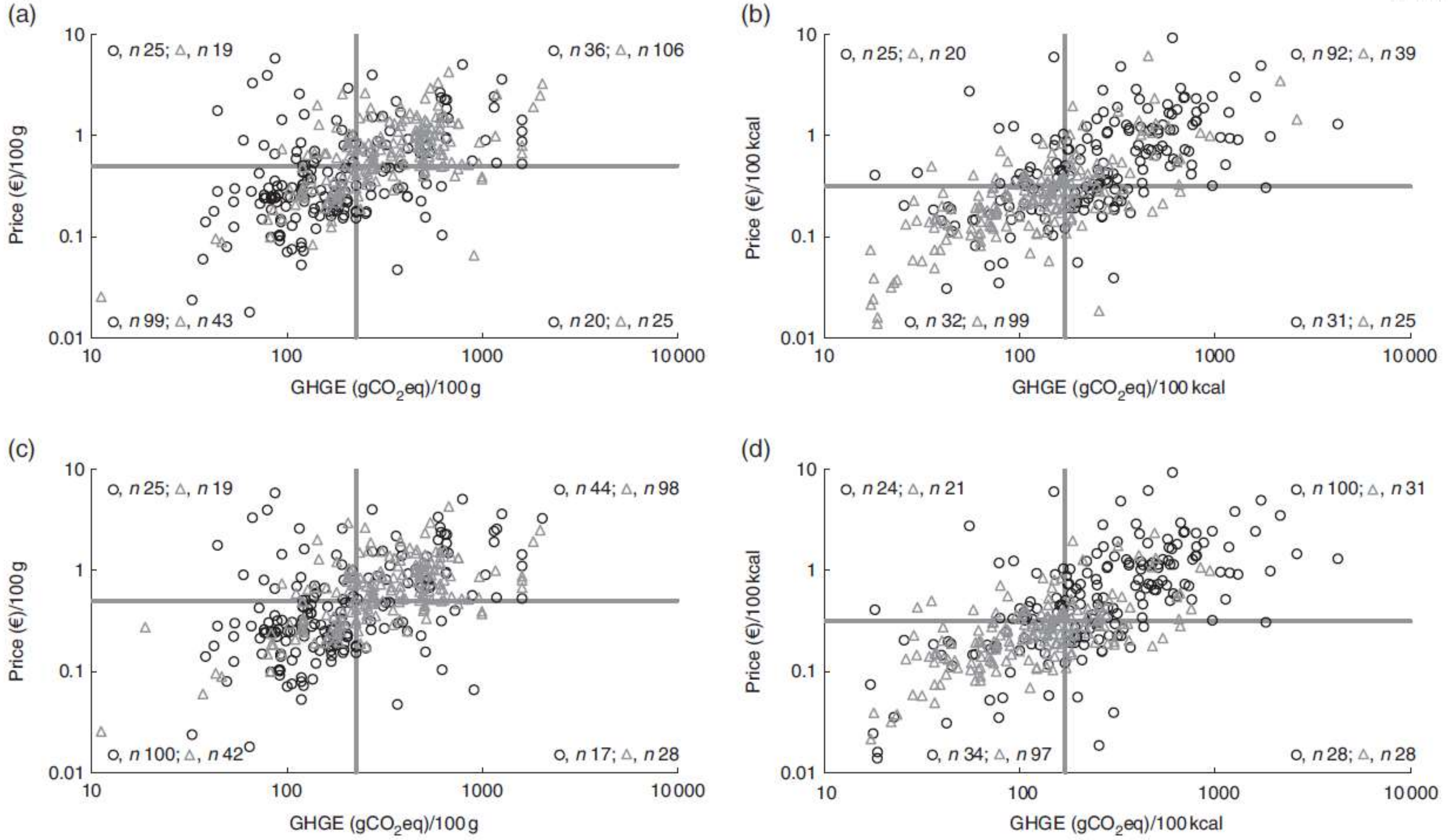
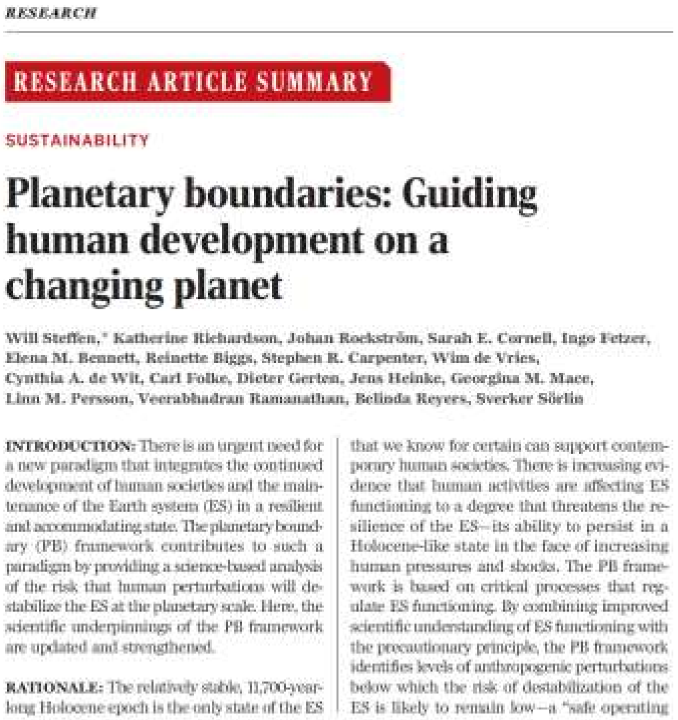


Fig. 2 Scatter plots representing food price (in Euros) *v.* food greenhouse gas emissions (GHGE; in grams of CO_2 equivalents), using either a 100 g (a, c) or a 100 kcal (b, d) functional unit. 100 kcal = 420 kJ. The Ofcom (a, b) and SAIN/LIM (c, d) nutrient profile scores were used to identify healthier (O) and less healthy (Δ) foods; ——, medians. The total number of foods is 373. The SAIN/LIM was based on the SAIN,LIM nutrient profiling model[44]; Ofcom refers to the UK Ofcom nutrient profiling model[45]

Planetary Boundaries



RESEARCH

RESEARCH ARTICLE SUMMARY

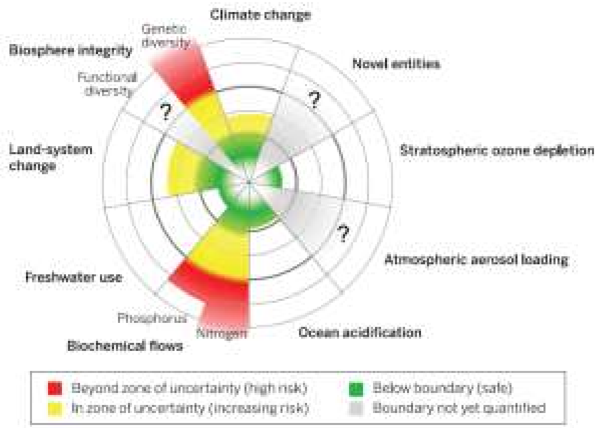
SUSTAINABILITY

Planetary boundaries: Guiding human development on a changing planet

Will Steffen,* Katherine Richardson, Johan Rockström, Sarah E. Cornell, Ingo Fetzer, Elena M. Bennett, Reinette Biggs, Stephen R. Carpenter, Wim de Vries, Cynthia A. de Wit, Carl Folke, Dieter Gerten, Jens Heinke, Georgina M. Mace, Linn M. Persson, Veerabhadran Ramanathan, Belinda Reyers, Sverker Sörlin

INTRODUCTION: There is an urgent need for a new paradigm that integrates the continued development of human societies and the maintenance of the Earth system (ES) in a resilient and accommodating state. The planetary boundary (PB) framework contributes to such a paradigm by providing a science-based analysis of the risk that human perturbations will destabilize the ES at the planetary scale. Here, the scientific underpinnings of the PB framework are updated and strengthened.

RATIONALE: The relatively stable, 11,700-year-long Holocene epoch is the only state of the ES that we know for certain can support contemporary human societies. There is increasing evidence that human activities are affecting ES functioning to a degree that threatens the resilience of the ES—its ability to persist in a Holocene-like state in the face of increasing human pressures and shocks. The PB framework is based on critical processes that regulate ES functioning. By combining improved scientific understanding of ES functioning with the precautionary principle, the PB framework identifies levels of anthropogenic perturbations below which the risk of destabilization of the ES is likely to remain low—a "safe operating



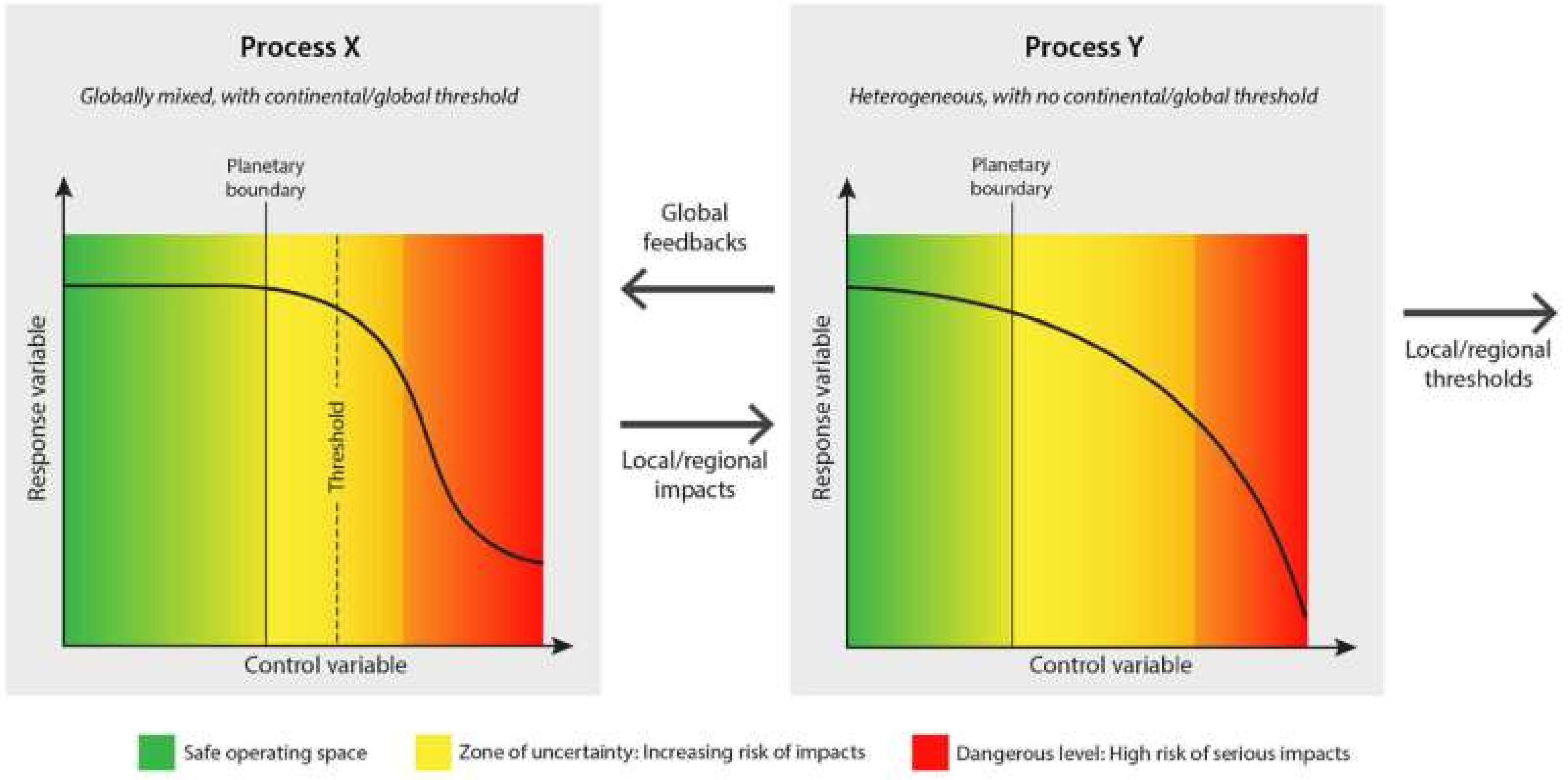


Fig. 1. The conceptual framework for the planetary boundary approach, showing the safe operating space, the zone of uncertainty, the position of the threshold (where one is likely to exist), and the area of high risk. Modified from (1).

Visualisation

https://computingforsustainability.com/2009/03/15/visualising-sustainability/

Spatial examination of variable contributions to a multi-dimensional composite index by a geographically weighted non-negative principal components analysis

Narumasa Tsutsumida[*,1], Dausuke Murakami[2], Takahiro Yoshida[3], Tomoki Nakaya[4], Binbin Lu[5], and Paul Harris[6]

In review IJGIS

[1,*] Graduate School of Global Environmental Studies, Kyoto University, Japan
[2] Department of Data Science, Institute of Statistical Mathematics , Japan
[3] Center for Global Environmental Studies, National Institute for Environmental Studies, Japan
[4] Graduate School of Environmental Studies, Tohoku University, Japan
[5] School of Remoting sensing and information engineering, Wuhan University, China
[6] Sustainable Agriculture Systems North Wyke, Rothamsted Research, UK
[*] Email: naru@kais.kyoto-u.ac.jp

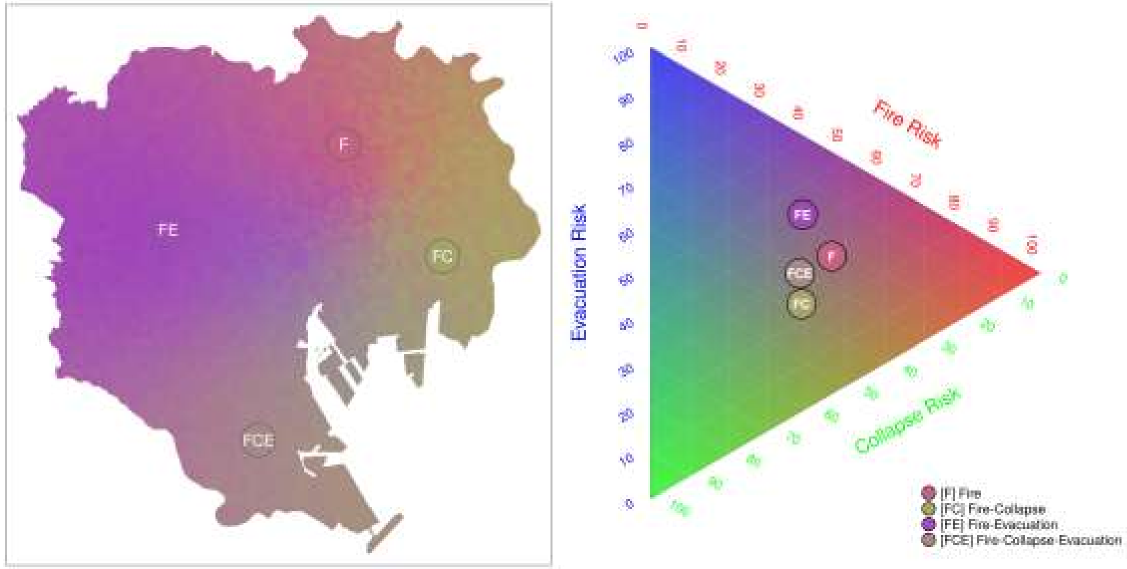


Figure 8. RGB composite map of PC-1 loadings of GW non-negative PCA. Labels stand for strongly contributing variables with F: Fire, FC: Fire-Collapse, FE: Fire-Evacuation, and FCE: Fire-Collapse-Evacuation.

Rothamsted Research Structure

Strategic Themes (Directorates or Departments)

ROTHAMSTED RESEARCH

Harpenden site – arable farming – home to LTEs

North Wyke site – livestock – home to NWFP

Research: 5-year funding cycles delivering strategic programmes

2017 to 2023

Designing Future Wheat (DFW) – JIC led

next generation of wheat germplasm for sustainable and productive agriculture.

Tailoring Plant Metabolism (TPM)

designing novel traits that improve the nutritional or industrial value of crops

Soil to Nutrition (S2N)

mechanistic understanding of nutrient use efficiency and productivity from soil to food

Achieving Sustainable Agricultural Systems (ASSIST)

innovative systems that increase food production while reducing the environmental footprint

Smart Crop Protection (SCP)

gene to landscape approach for more targeted and sustainable control of insect pests, weeds and diseases

2023 to 2028

Green Engineering (GreEn)

Growing Health (GH): Bio-inspired solutions for healthier agroecosystems

Resilient Farming Futures (RFF)

Delivering Sustainable Wheat (DSW) (JIC led)

AgZero+ (CEH led: BBSRC-NERC funded from April 2022)