

Agents and Telecoupling: Modelling Fire and Land Use

James Millington, King's College London



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Implications of Landscape Change for Wildfire Incidence and Risk in the SPA 56 'Encinares del Río Alberche y Cofio', Central Spain

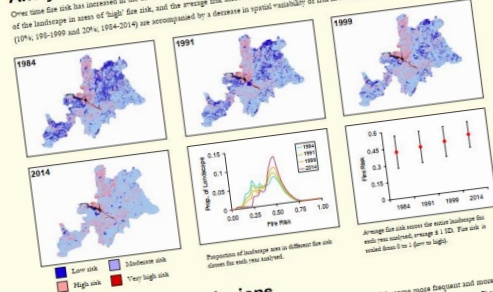
Millington, J.D.A.¹ Perry, G. L. W.¹ & Romero-Calcerrada, R.²
¹King's College London and ²Universidad de Alcalá

Analysing Changes in Fire Risk

Introduction & Methods

Socio-economic and political trends have led to changes in the structure and dynamics of many landscapes throughout the Mediterranean Basin. These changes have led to the accumulation of combustible biomass and may result in changes in fire risk. Three landscape maps were derived for the SPA 56 (Central Spain) from Landsat imagery for 1984, 1991 and 1999. These maps and multi-scale landscape complexity in 2004 of ~10 000 ha and in 2008 were of 10 000 ha. This research compares two maps.

1. The spatial distribution of forest land-uses was examined using multivariate regression analysis based on both topographic and socio-economic variables.
2. Fire risk values for these four landscapes were generated in a GIS using the methodology described by Salas & Cárdenas (1994). The model involves a quantification of the key factors determining the risk of fire ignition and subsequent spread.



Results & Conclusions

Exploring Future Fire Regimes in Serranía de Cuenca, Spain through an Integrated Fire Management Lens

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Introduction

Rural depopulation is a widespread challenge in mountainous Mediterranean regions. During recent decades, younger generations have migrated to urban areas, resulting in declining birth rates and aging population of rural areas. This demographic shift has led to significant socio-economic implications such as the loss of traditional livelihoods and local knowledge, which have historically contributed to the resilience and management of these landscapes. With abandonment of land-use practices the landscape has become densely vegetated resulting in increased fuel accumulation and continuity. When combined with increasing climate variability these changes amplify the probability of high-intensity wildfires, which threaten both the ecosystem and the livelihoods of those remaining.

Case Study – Serranía de Cuenca, Spain



Landscape Characteristics and Ecology

- Used mainly for agriculture (lowlands) and forestry which dominates in areas of higher elevations (Serranía).
- Traditional practices that remain within mountainous rural areas (but disappearing):
 - Transhumant pastoralism (e.g. seasonal)
 - Forestry (e.g. timber harvesting and resin collection)
 - Cattle farming
 - Mushroom and herb gathering
 - Forests dominated by...

An Ecological-Economic Model for Sustainable Forest Management: Modeling Deer Distributions from Local & Landscape Characteristics

J.D.A. Millington¹ (jmi@msu.edu), P. LeBouton², M.B. Walters^{1,2}, K.R. Hall¹, M.S. Matonis¹, E.J. Laurent¹, F. Lupi¹, S. Chen¹, J. Li¹

¹Center for Systems Integration and Sustainability, Michigan State University; ²Department of Forestry, Michigan State University; ³Department of Agricultural, Food and Nutritional Science, University of Alberta

1. Ecological-Economic Forest Model
 Forest Disturbance
 Timber harvesting and deer browsing are believed to be key disturbance agents affecting forest dynamics and habitat for deer, songbirds and other fauna in the Northern Hardwood forest landscapes of Michigan's Upper Peninsula.

Project Objectives
 We are developing an integrated simulation model to test hypotheses about the spatial interactions among forest dynamics, harvest patterns, deer, and songbirds habitat. We will use the model to investigate the mechanistic underpinnings of these coupled human-natural processes across multiple scales. The model will serve as a tool to aid management of forested systems for multiple resource objectives.

Integrated Simulation Model Structure
 The model structure shows the interactions between Forest Dynamics, Deer Population, and Songbird Population. Forest Dynamics includes Timber Harvesting, Deer Browsing, and Songbird Foraging. Deer Population includes Deer Recruitment, Deer Mortality, and Deer Density. Songbird Population includes Songbird Recruitment, Songbird Mortality, and Songbird Density.

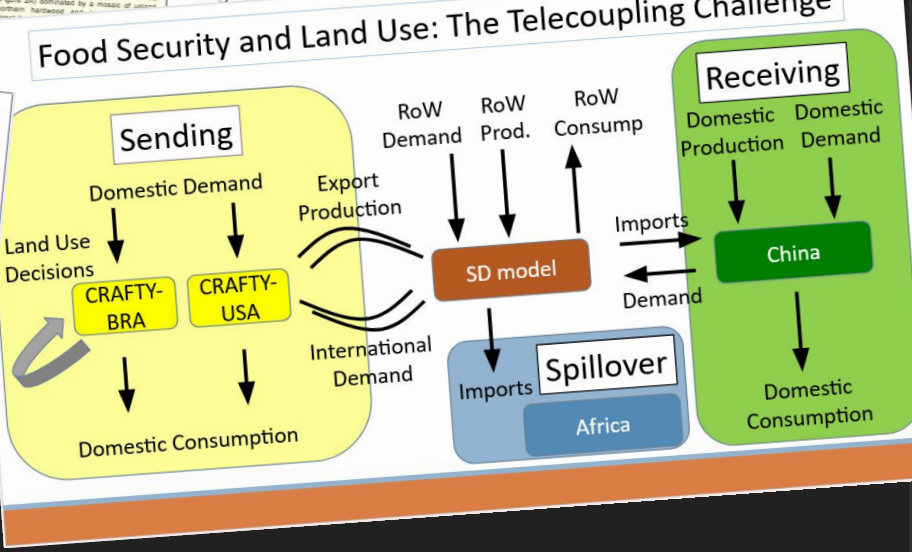
2. Modeling White-Tailed Deer Distribution
 a) Regional Patterns
 We can predict the counter deer pellet groups in ten 0.02 ha transects (20m x 10m) arranged in a bow-tie configuration around the vegetation sample site. These deer pellet survey data serve as a proxy for deer-level vegetation.

b) Sub-Regional Predictors
 Using transect-level data we identified an inverse relationship between distance to continuous forest and maximum transect-level deer density (Figure 4). Deer density is highest in forested areas and lowest in open areas.

c) Stand-Attribute Predictors
 To improve predictive power we examined stand-attribute data from the Michigan DNR Forest Division. Stand attributes include:

- Canopy cover class (see legend of Figure 5 for example colors)
- Stand basal area
- Distance to the nearest forest edge

Stand-Attribute Data Improve Predictions
 The best multiple linear regressions for the 0.125 km² (Table 1) and 0.05 km² (Table 2) LDCs include stand basal area and minimum distance to forest edge. These models explain ~42% and ~50% of the variance in deer density estimates respectively.





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- **Ol Perkins:** Agent-based modelling of human fire globally
- **Viera Ukropcova:** Corporate & financial actors in telecoupling
- **Amos Chege Muthiuru:** Managing protected African savannas
- **Monika Moreu Vicente:** Spanish social-ecological systems
- **Verena Achterberg:** Forest transition in the Atlantic Forest

Take Home Messages

Data on human behaviour is vital for understanding our sustainability challenges... but it is expensive

- **Case Study Data** are out there, but for large extents are likely sparse, non-uniform, varied and incomplete
- **Fuzzy Cognitive Maps** useful for summarising understanding of feedbacks (but private institutions often means low sample size)

A clear theoretical framing is needed to specify the categorisations, quantifications and decisions made when constructing models from these data

WHAM!

The Wildfire Human Agency Model

Ol Perkins, James Millington, *et al.*



Project Homepage

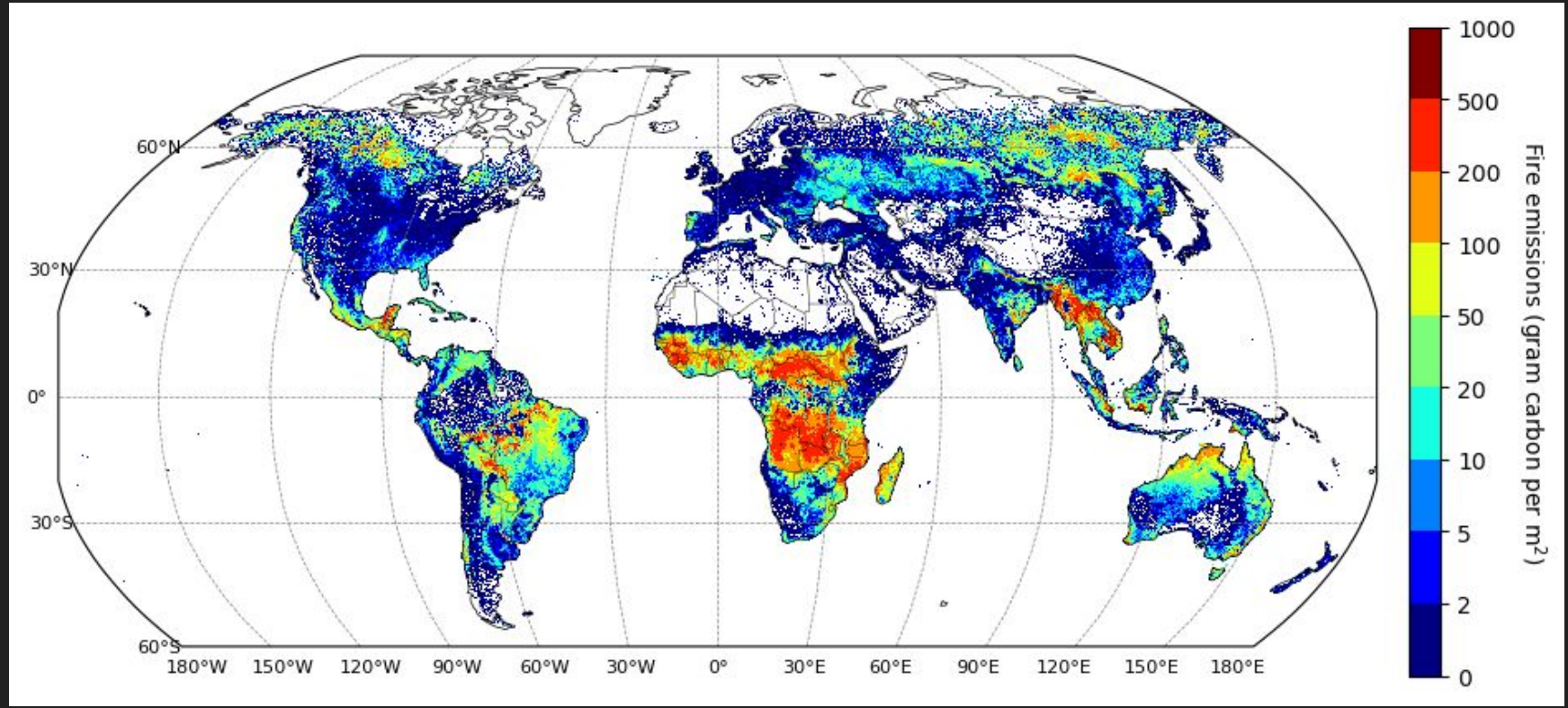


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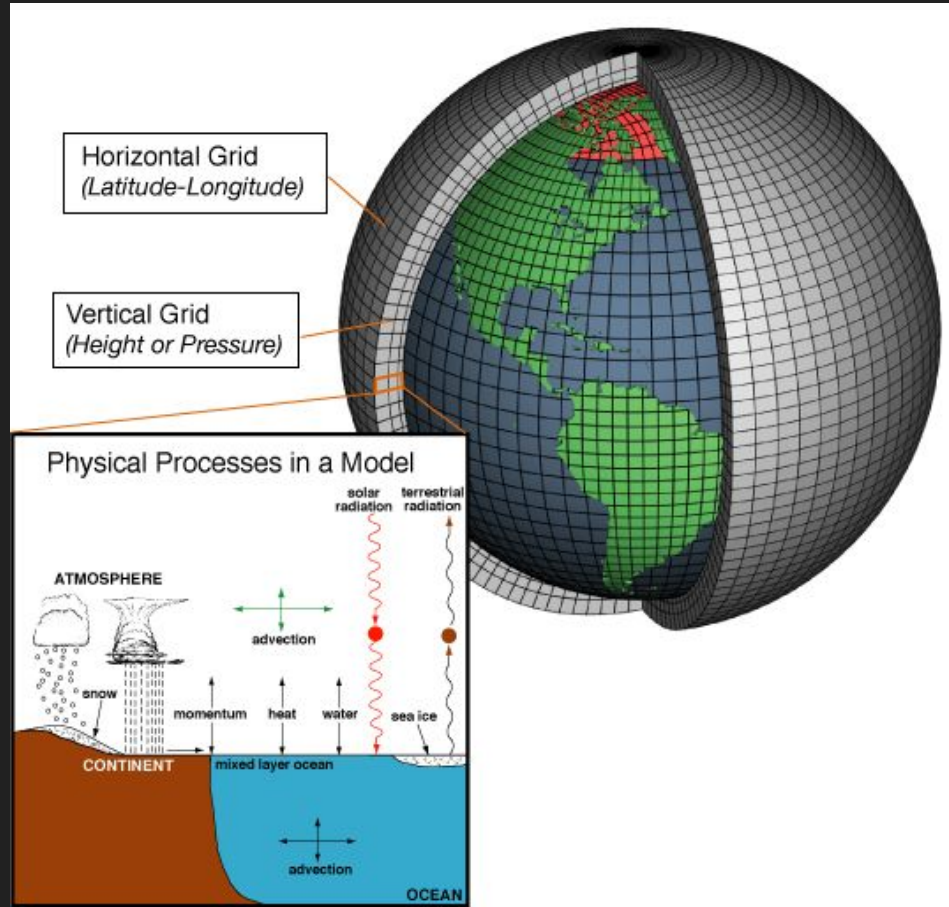
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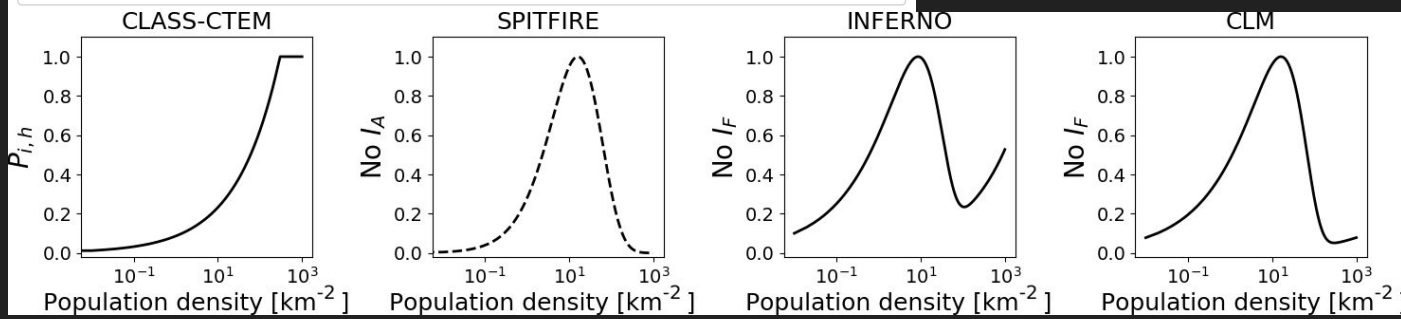
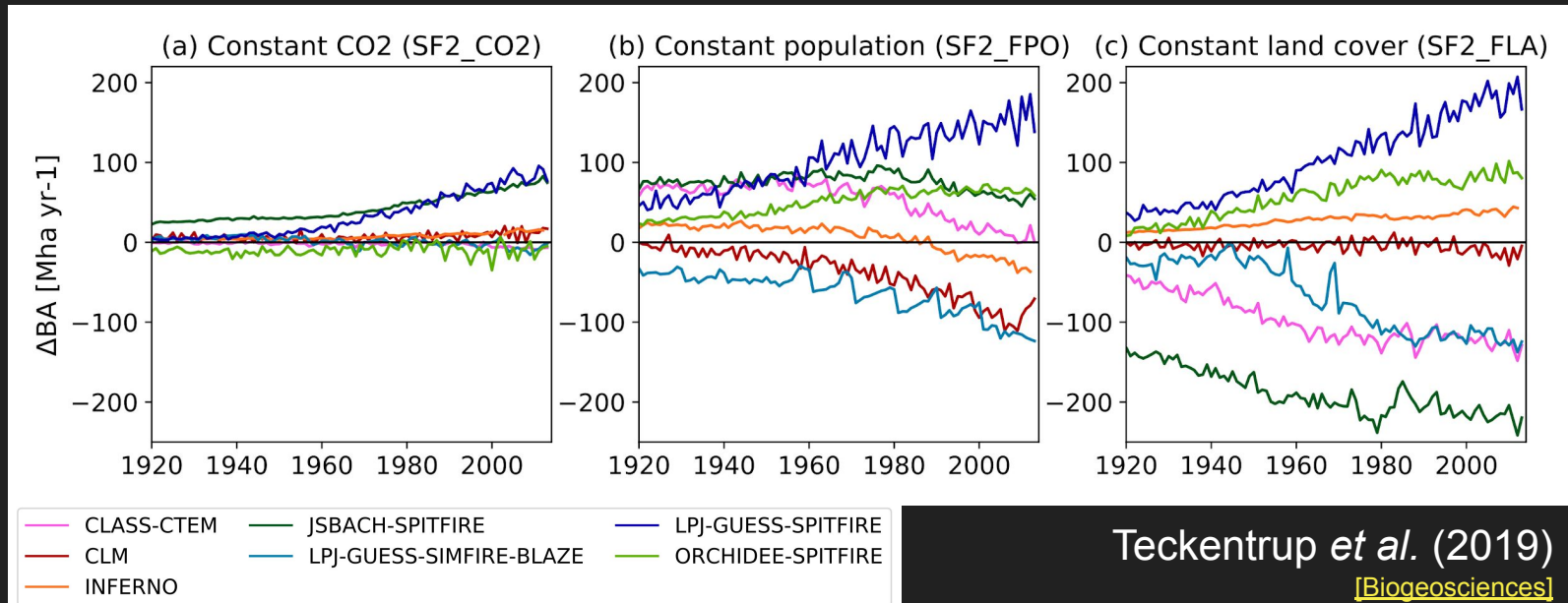
Mean annual *fire* carbon emissions (2002-2025)



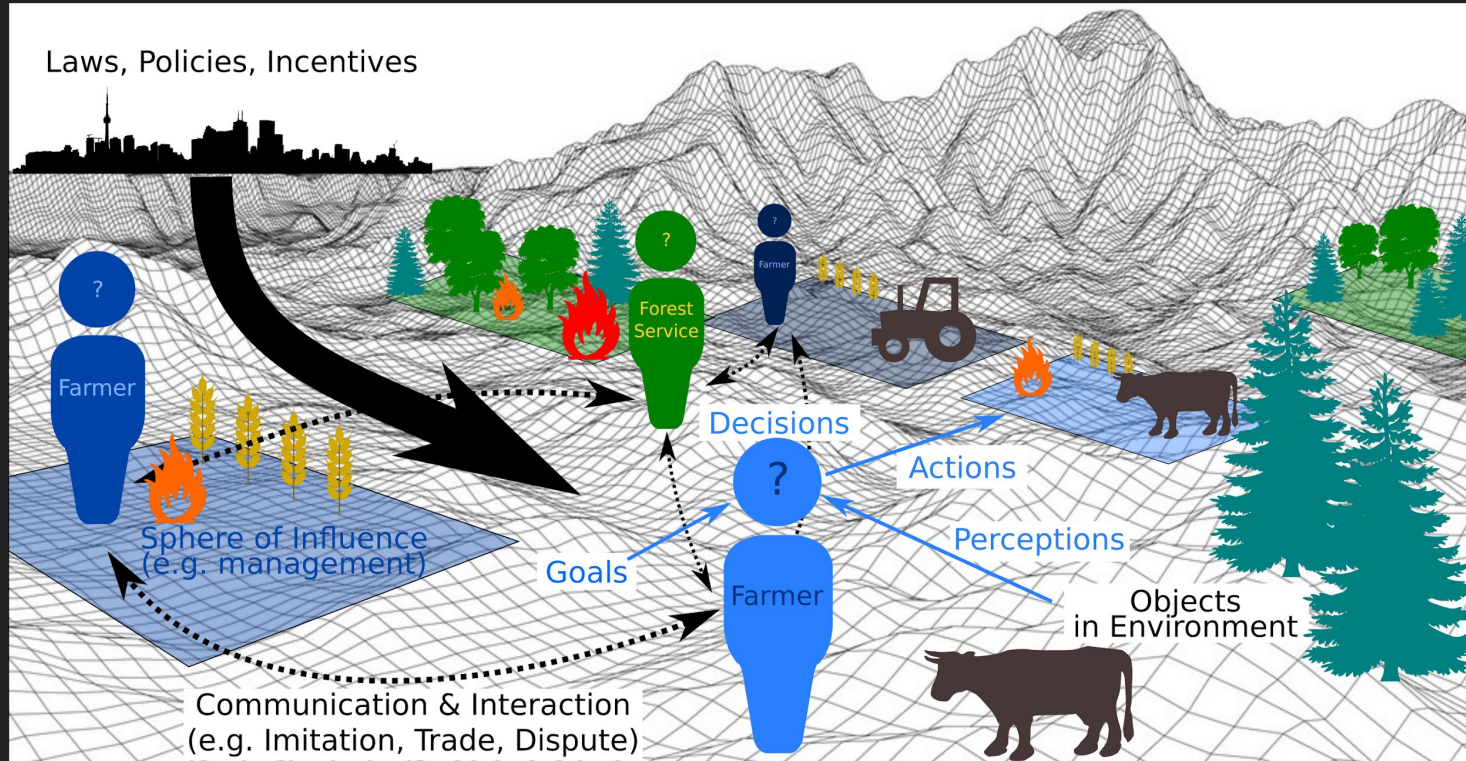
Fire in Earth System Models



Human Activity in Models of Global Fire



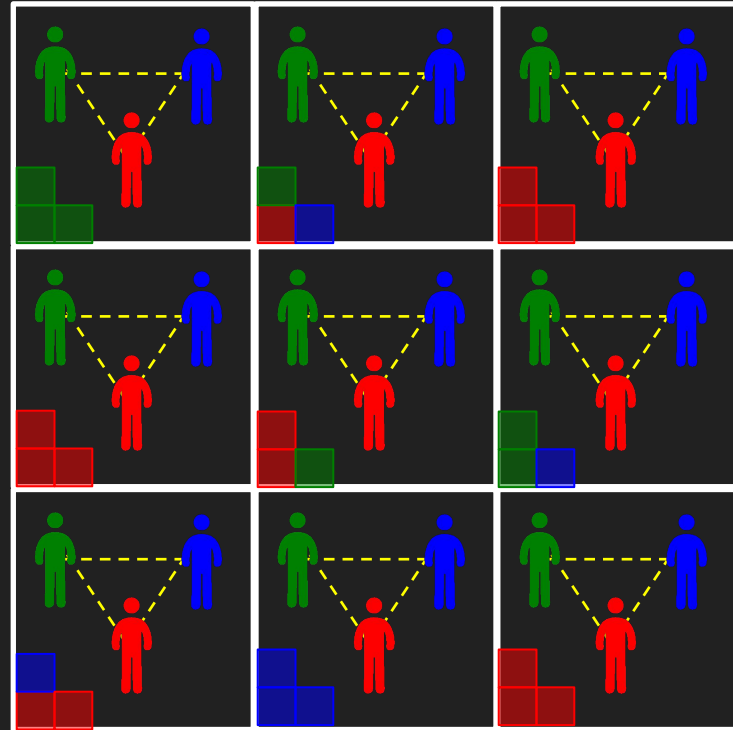
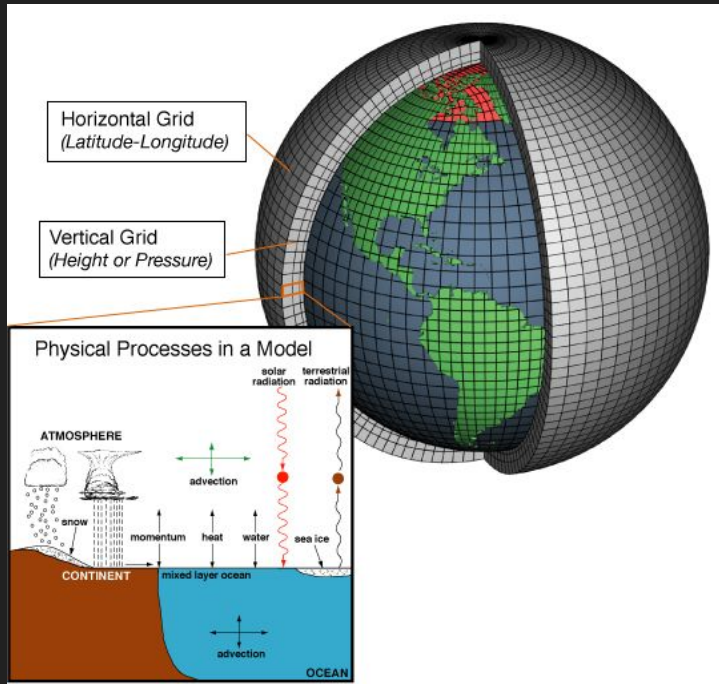
Landscape Agent-Based Modelling



Ford *et al.* (2021)

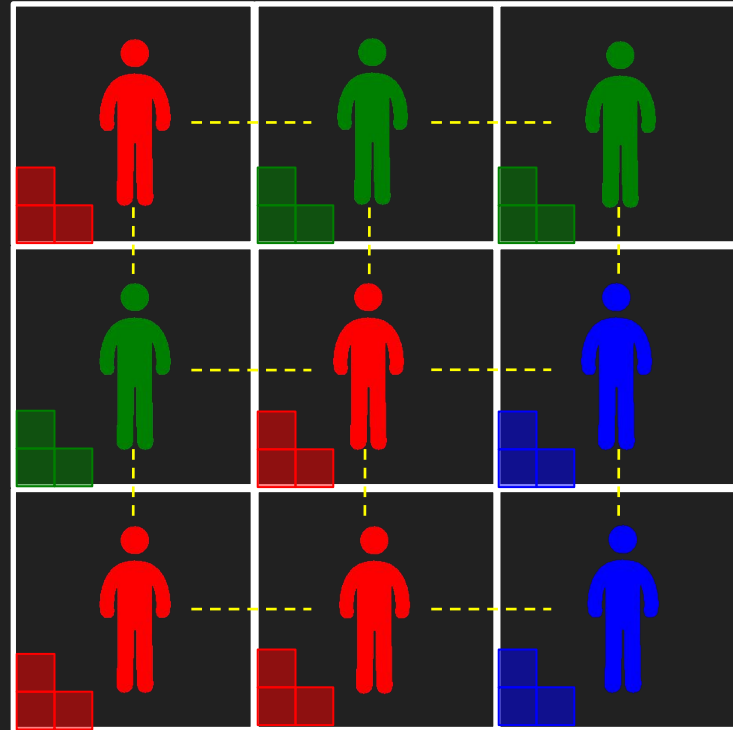
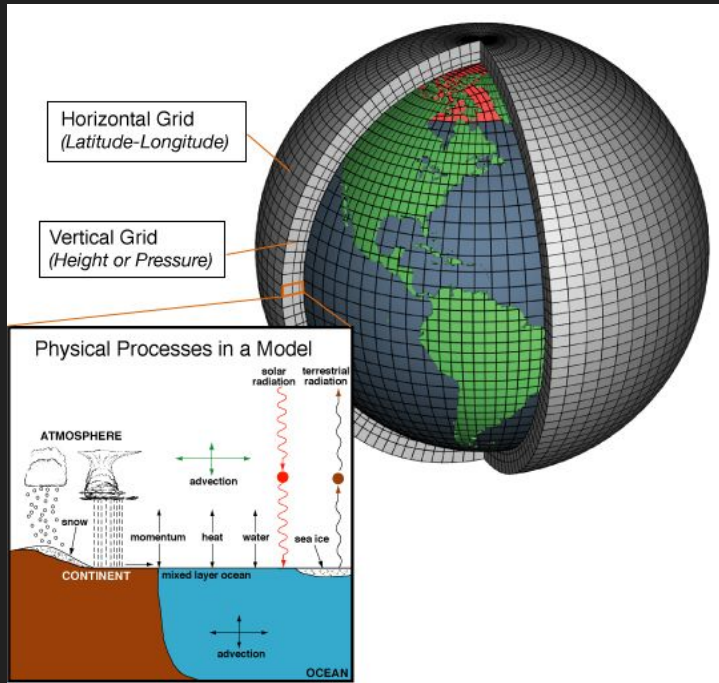
Global Agent-Based Modelling?

Agents on a 0.5° Grid $\longrightarrow$ Multi-agent interactions?



Global Agency-Based Modelling?

Agents on a 0.5° Grid $\longrightarrow$ Single 'agents'?



Fire Agents: Structuring a rational conception

1. Pyne's Fire 'Stages' [\[TED 15 min summary\]](#)

- ~~First Fire~~ — ~~pre-human~~
- Second Fire pre-industrial
- 2.5th Fire transition
- Third Fire industrial
- Pyrocene post-industrial(?)

Stages are attitudes towards fire that imply differing use and management



Fire Agents: Structuring a rational conception

2. Land use drives fire use

Non-Extractive



Forest

Pasture



Cropland

Land-Fire Systems [‘AGENT FUNCTIONAL TYPES’]

From combination of Anthro. Fire Regimes and Land Use Systems

Perkins <i>et al.</i> (2022; 2024)		Land Use System			
		<i>Non-Extractive</i>	<i>Livestock</i>	<i>Crops</i>	<i>Forestry</i>
Anthro. Fire Regime	<i>Pre-Industrial</i>	Unoccupied	Pastoralism (S)	Swidden (S)	Hunt & Gather (S)
	<i>Transition</i>	Unmanaged	Ranching (Extensive, S M)	Small- holding (S M)	Logging (M) (Primary Forest)
	<i>Industrial</i>	Pyro-exclusion (State Manager)	Ranching (Intensive, M)	Farming (Intensive, M)	Managed (M) (Plantation or Second Forest)
	<i>Post-Industrial</i>	Pyro-diverse (Fuel Load Management)	Grazing (Subsidised, Fuel Mgmnt)	Abandoned	Abandoned

Non-Extractive = e.g. parks S = subsistence M = market

Poster: Perkins et al. (2021)
Paper: Millington et al. (2022)
Data: via FigShare

Oliver Perkins^{1,3}, Cathy Smith^{2,3}, James D.A. Millington^{1,3}



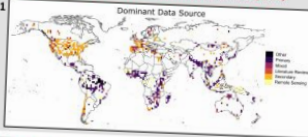
Poster

Order

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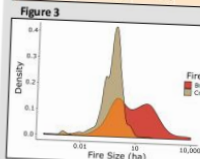
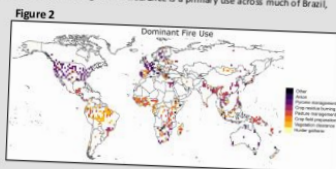
Empirical studies of human use and management of fire in landscapes around the world have been conducted in many different academic fields, including geography, anthropology, land economics and ecology. Studies have varied in approach, from quantitative and broad-scale (e.g., remote sensing) to qualitative and local-scale case studies (e.g., anthropological). No global synthesis of human-fire interactions has yet been attempted that covers the breadth of human fire use and suppression.

We present the most comprehensive meta-analysis of global fire use to date, spanning all key land systems and policy regimes from over 105 countries on all continents (except Antarctica) between 1990–2020. Our study has produced a database comprising data (Table 1) from 523 papers containing 1808 case studies. DAFI was developed in an iterative manner but based on a framework that accounts for fire's stages (after Pety 2019) and land system disciplines and approaches, industrial, transition, industrial & post-industrial while land systems are cropland, pasture, forest & non-forest, and land system. Fire stages are pre-access stage, with a prevalence of secondary studies in Europe and North America versus a dominance of primary studies in Asia and Africa (Figure 1).

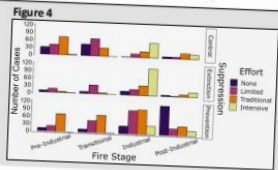
Table 1 Figure 1

Analysis of DAFI reveals that seven fire-use types (listed in Table 2) account for >90% of case studies. The seven fire-use types have distinctive quantitative signatures (Table 2) and spatial distributions (Figure 2). Shifting cultivation field preparation has a similar mean fire size to non-shifting crop residue burning, however, the relatively low fire-return period and high density of fields when combined with the need to shifting cultivation combine to produce a much greater proportional mean burn area. Pyrene management activities dominate in North America and Europe, while vegetation clearance is a primary use across much of Russia and crop residue burning is dominant across parts of Asia.

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Table 2

DAFI enables examination of fire regime characteristics as a function of broader fire use approaches and how fire uses vary between fire stages. For example, cropland fires tend to be smaller than fire broadcast across pasture and forest landscapes (Figure 3). We find distinct differences in fire suppression between fire stages (Figure 4). **Code for analysis of DAFI and plots is available** (Perkins 2021).



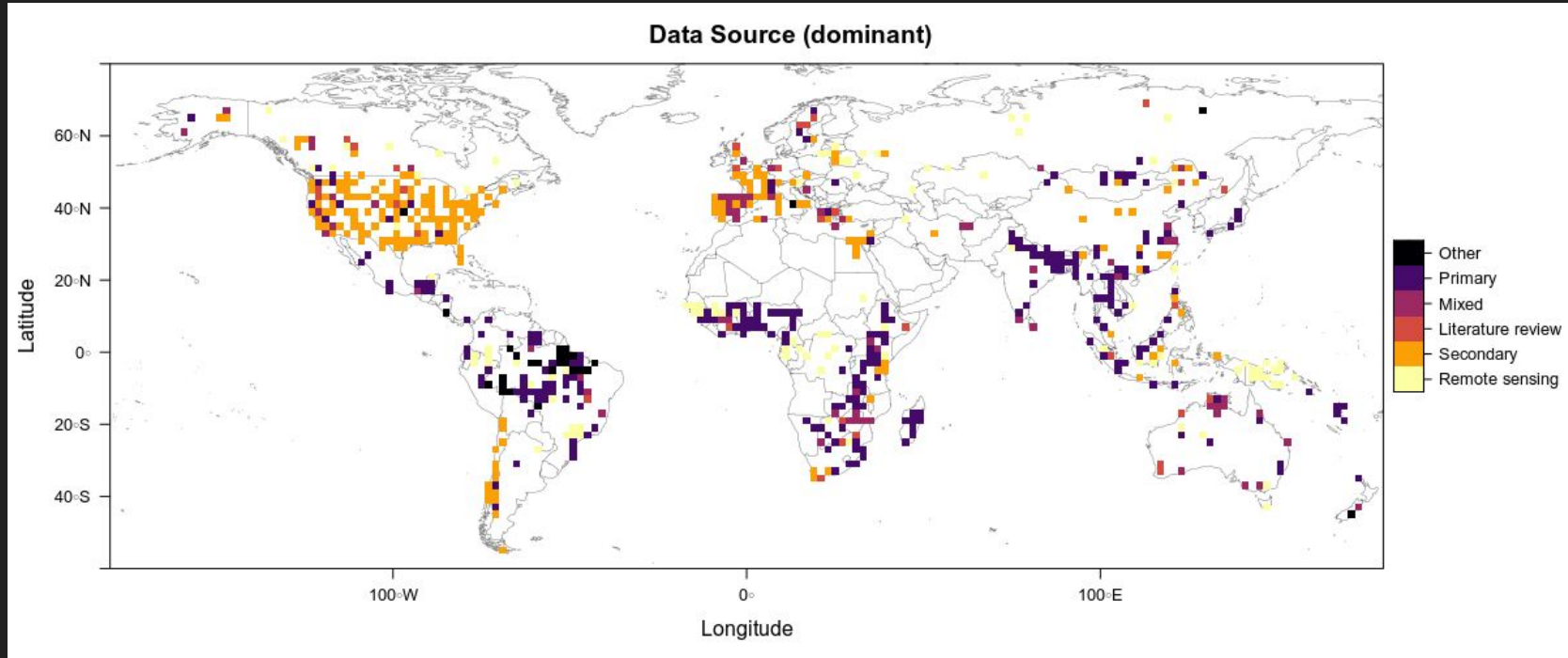
temptoms to ecosystem-human fire interactions have sought to configure human impacts as deviations from underlying 'natural' axes of vegetation (e.g. McWethy *et al.* 2013). Such approaches have not yet developed a coherent overall framework to capture human impacts on wildfire risk, and present a challenge to incorporating anthropogenic fire into Dynamic Global Vegetation Models (DGVMs; Tekkenburg *et al.* 2019). We plan to use DAFl to investigate this empirical basis. **DAFl is freely available (see Perkins and Millington 2020) and will grow.** The present anthropogenic fire in DGVMs still relies on few research-based model approaches to better represent human fire in DGVMs. Representation of human fire using these variables in globally-uniform relationships may be due to the lack of human activity, such as population density and GDP. The poor performance of large-scale models in this context, we will use DAFl to develop 'agent functional types' that characterize anthropogenic fire in the context of different types of underlying land use. Examples may include shifting cultivation farmer, large-scale industrial logging, and conservation and suppression as well as by mapping these types explicitly using ancillary data, we will be able to improve simulation of human fire in DGVMs, including feedbacks with vegetation and climate.

Attempts to systematise human-fire interactions have sought to configure human impacts as deviations from underlying 'natural' axes of vegetation and moisture (e.g. McElroy *et al.* 2013). Such approaches have not yet developed a coherent overall framework to capture human impacts on vegetation and the finding of the Fire Model Intercomparison Project was that the lack of a systematic empirical basis for understanding the role of human impacts on fire presents a challenge to incorporating anthropogenic effects into dynamic models of vegetation (see Perkins and Millington 2021) and continues to grow. We plan to use DAFI to support the development of agent-based models for the future.

DAVID I support the development of agent-based modeling approaches to better understand human life in DGVMs. Representation of anthropogenic climate change relies on few readily-available metrics of human activity, such as population and GDP. The poor performance of these variables in predicting climate change suggests that the relationships may be due to the disregard for how people use and manage land in land systems. To provide this context, we will use DAVID to develop “agent functional types” that characterise anthropogenic fire use and land cover change. The function of underlying land use objectives. Examples may include slash-and-burn cultivation farms, large-scale industrial logger, and conservationist. By mapping these types globally using DAVID data, we will be able to provide simulation model representation of human fire, including feedback that by mapping these types globally using DAVID data, we will be able to provide simulation model representation of human fire, including feedback with vegetation and climate.

DAFI: Database of Anthropogenic Fire Impacts

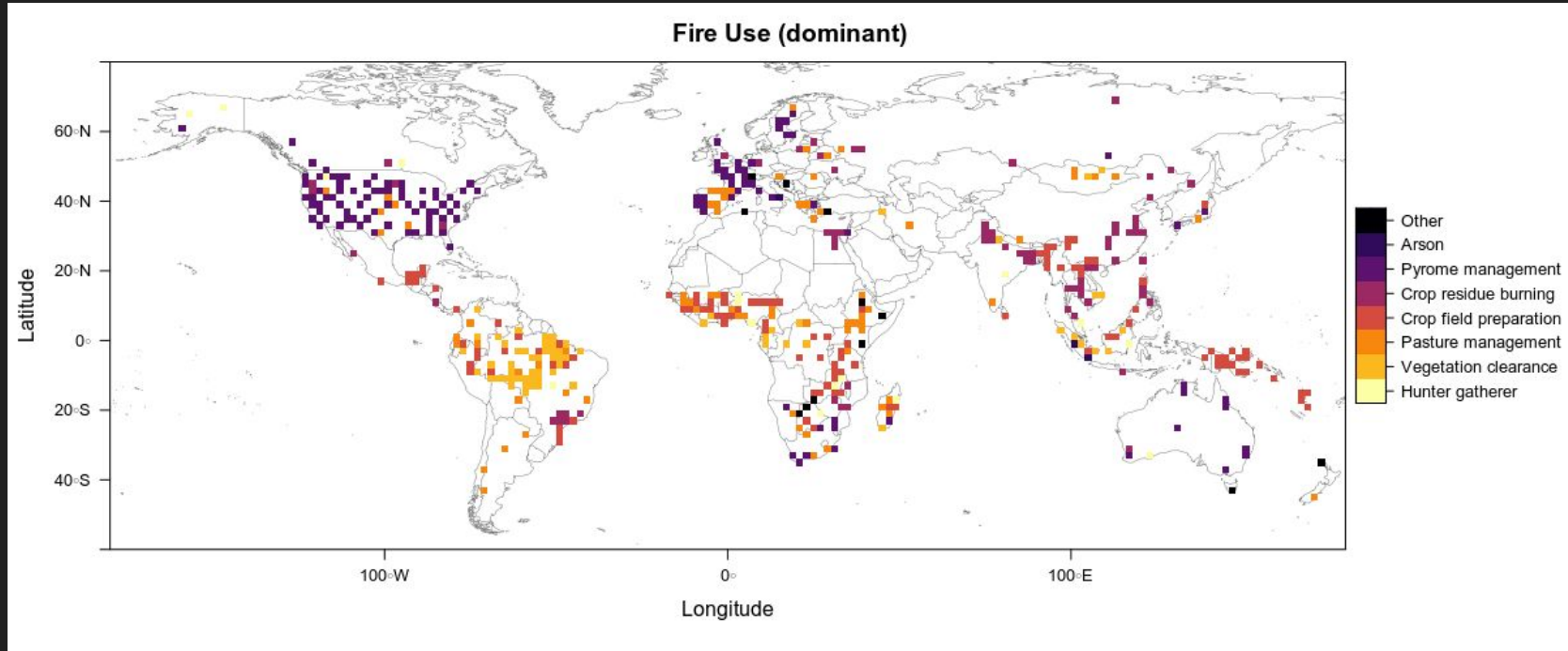
Data on fire use, suppression and policies



Millington *et al.* (2022)
[[Data](#), [Code](#)]

DAFI Analysis

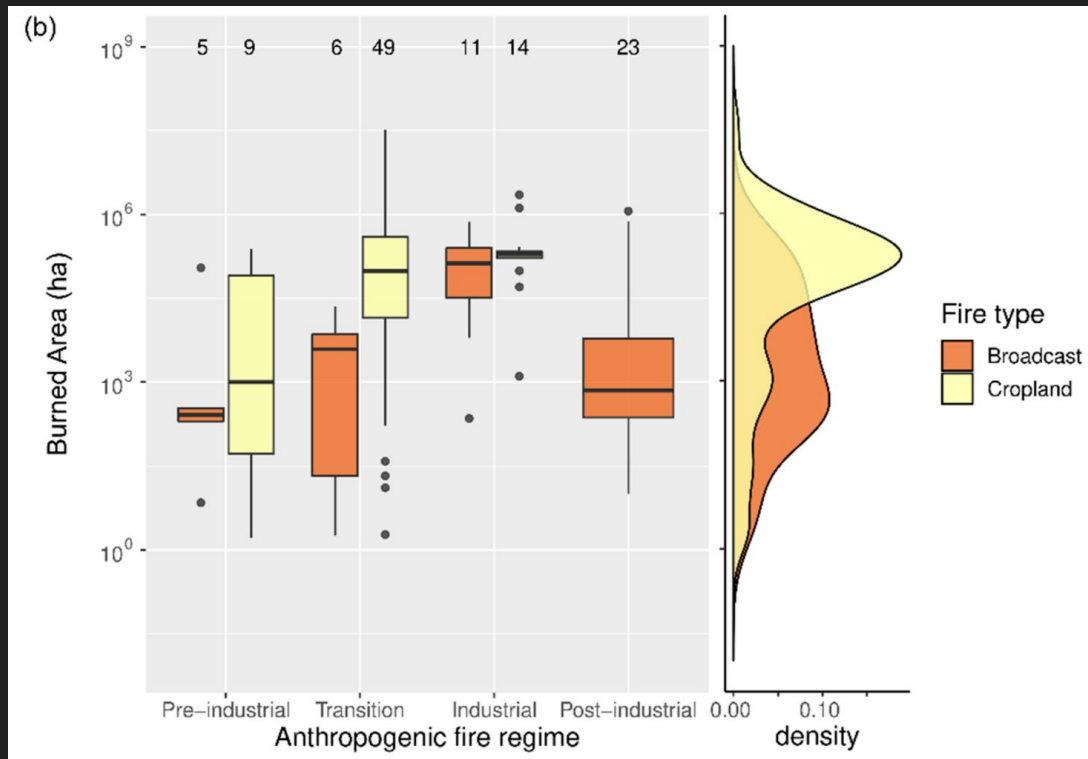
Seven fire use types describe 90% of the records



Millington *et al.* (2022)
[[Data](#), [Code](#)]

DAFI Analysis: Fire Size

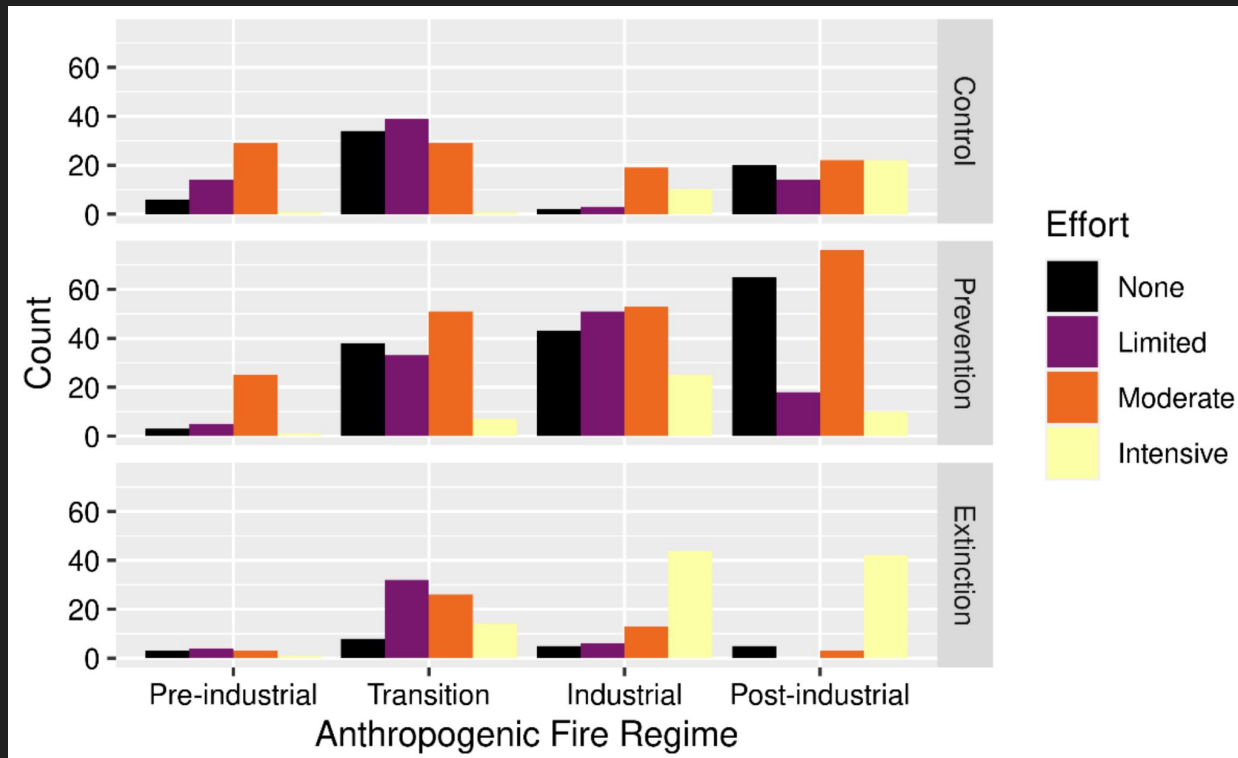
Crop fires much smaller than other landscape fires



Millington *et al.* (2022)
[[Data](#), [Code](#)]

DAFI Analysis: Suppression

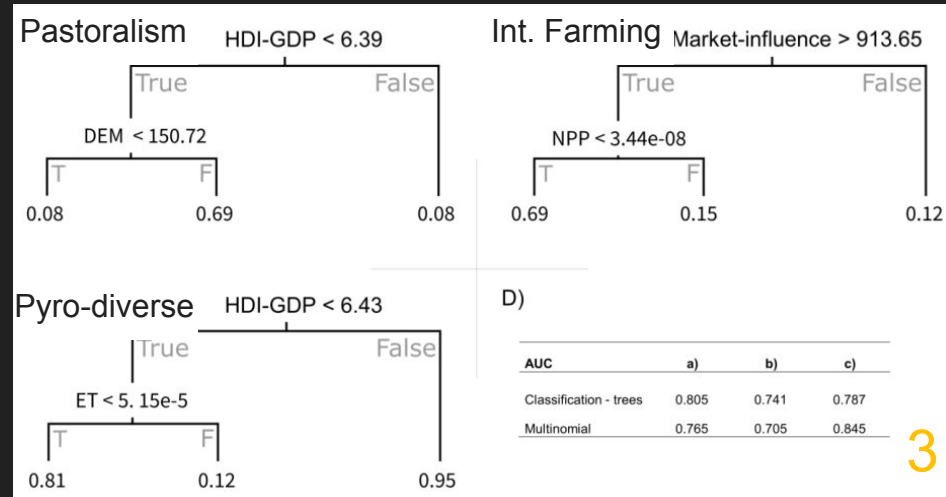
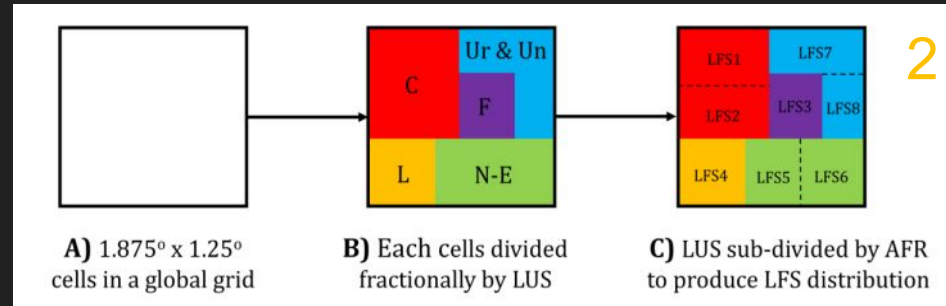
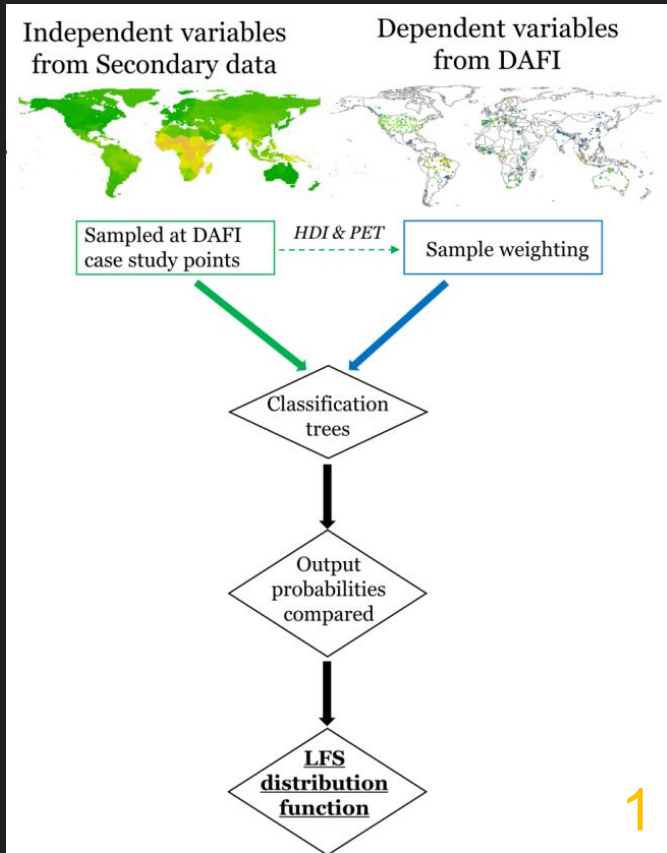
Differences in suppression by anthropogenic fire regime



Millington *et al.* (2022)

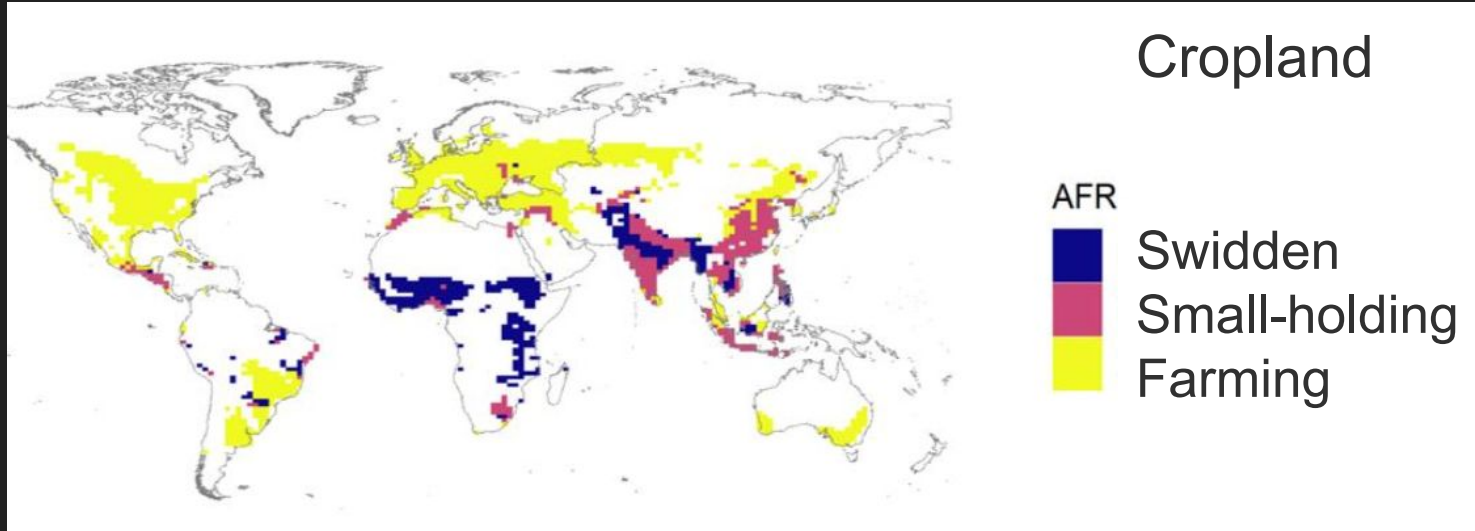
[[Data](#), [Code](#)]

Spatial Distribution of Land-Fire Systems



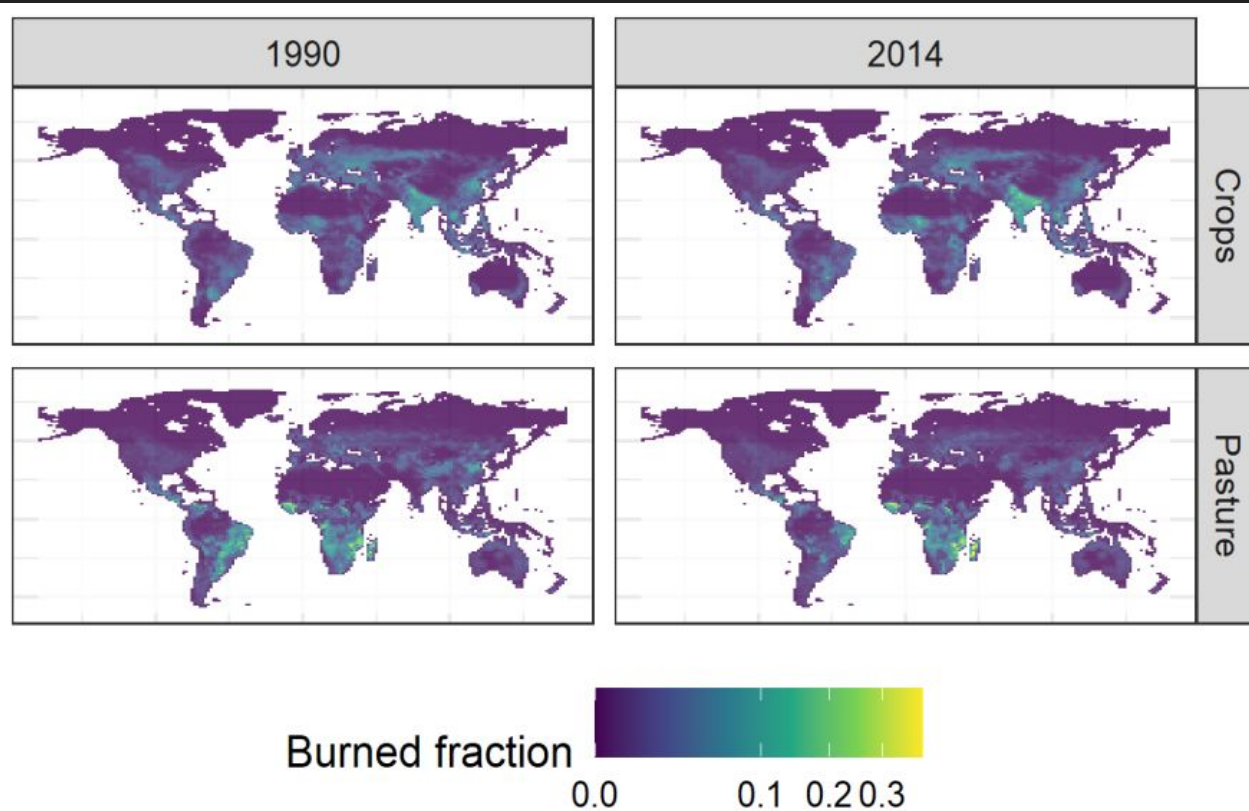
Figs from Perkins *et al.* (2022)

Modelled Spatial Distribution of LFS



Combine density of *LFS* with *data from DAFI* to estimate *human Burned Area*

Modelled Agriculture Burned Area



Paper:
Perkins *et al.* (2024)

Structure of WHAM!

- Represents Agent Functional Types (e.g. 'Pastoralist', 'State forester')
- AFTs have characteristic effects on fire:
 - Burned Area, Frequency
 - Prob. fires escape management (wildfires)
 - Suppression and Firefighting
- Projects AFTs spatially 0.25-1.85° over decades
- Uses classification trees driven by environmental and socioeconomic variables

Paper:
Perkins *et al.* (2024)

Model: WHAM!

1. What did you find most challenging in your modelling?
 - Data gathering (i.e. DAFI)
 - Convincing non-modeller social scientists that our agent types are appropriate (naming is an issue?)
 - Ongoing integration with climate modelling requires buy-in (expertise)

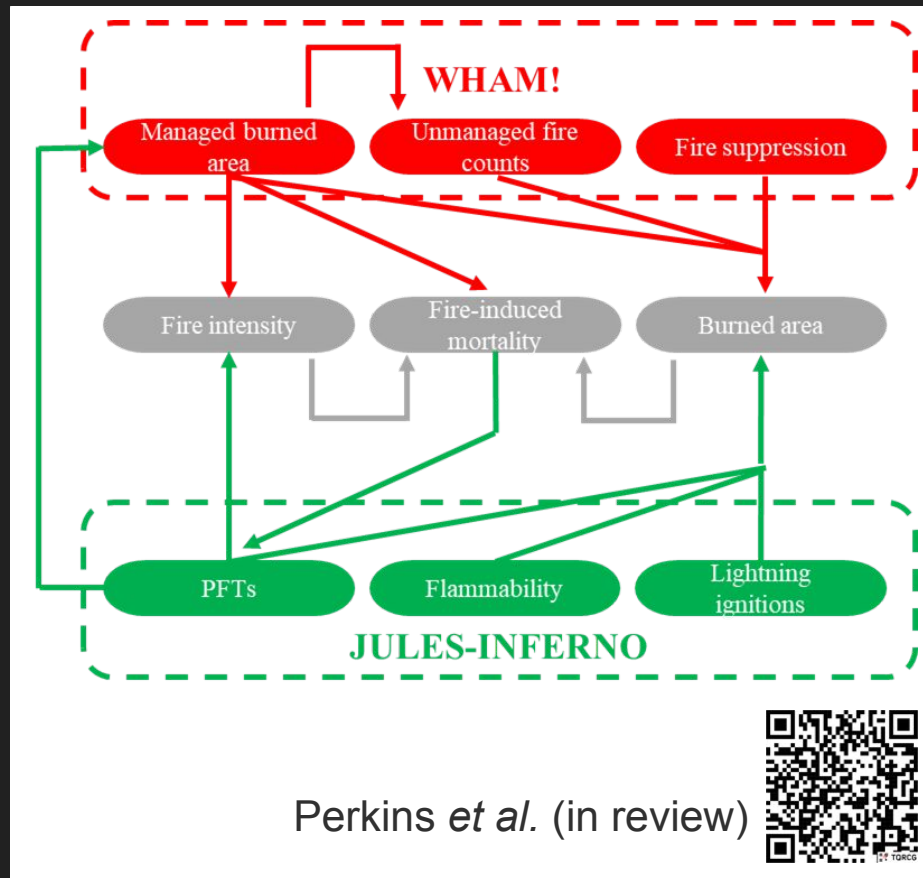
2. Which community effort would help you most?
 - Harmonising data inputs (e.g., for SSP scenarios)
 - Model intercomparison, integrating with ISIMIP

WHAM-JULES-INFERNO

JULES-INFERNO is a fire-enabled dynamic global vegetation model

[[UKESM](#), [JULES](#)]

Coupling with WHAM!
enables representation of socio-economic drivers of fire alongside biophysical (and their interaction)



Integrated Fire Management (IFM)

The integration of economic, sociocultural and environmental factors for ecologically and socially appropriate fire management

➤ Recognises

- benefits of indigenous and local community fire practices
- limitations of suppression-oriented management approaches
- why and how a fire is burning matters, not only where and when

➤ Emphasises

- living with fire rather than excluding it
- human-fire interactions and systemic, holistic understanding
- **pro-active fuel management rather than reactive fire-fighting**

Experiments - future scenarios

Management

Management scenario	Social attitude to human fire use (all purposes)	Controlled burning for fire regime management	Fire suppression
Baseline	Default	Medium	Medium
Suppression-max	Opposed	Low	High
IFM-max	Supportive	High	Medium

Socio-economics

SSPs	SSP1.26	SSP3.70
Carbon Emissions	Low	High
Economic Dev. in Global South	Strong	Weak
Barriers to Adaptation	Low	High

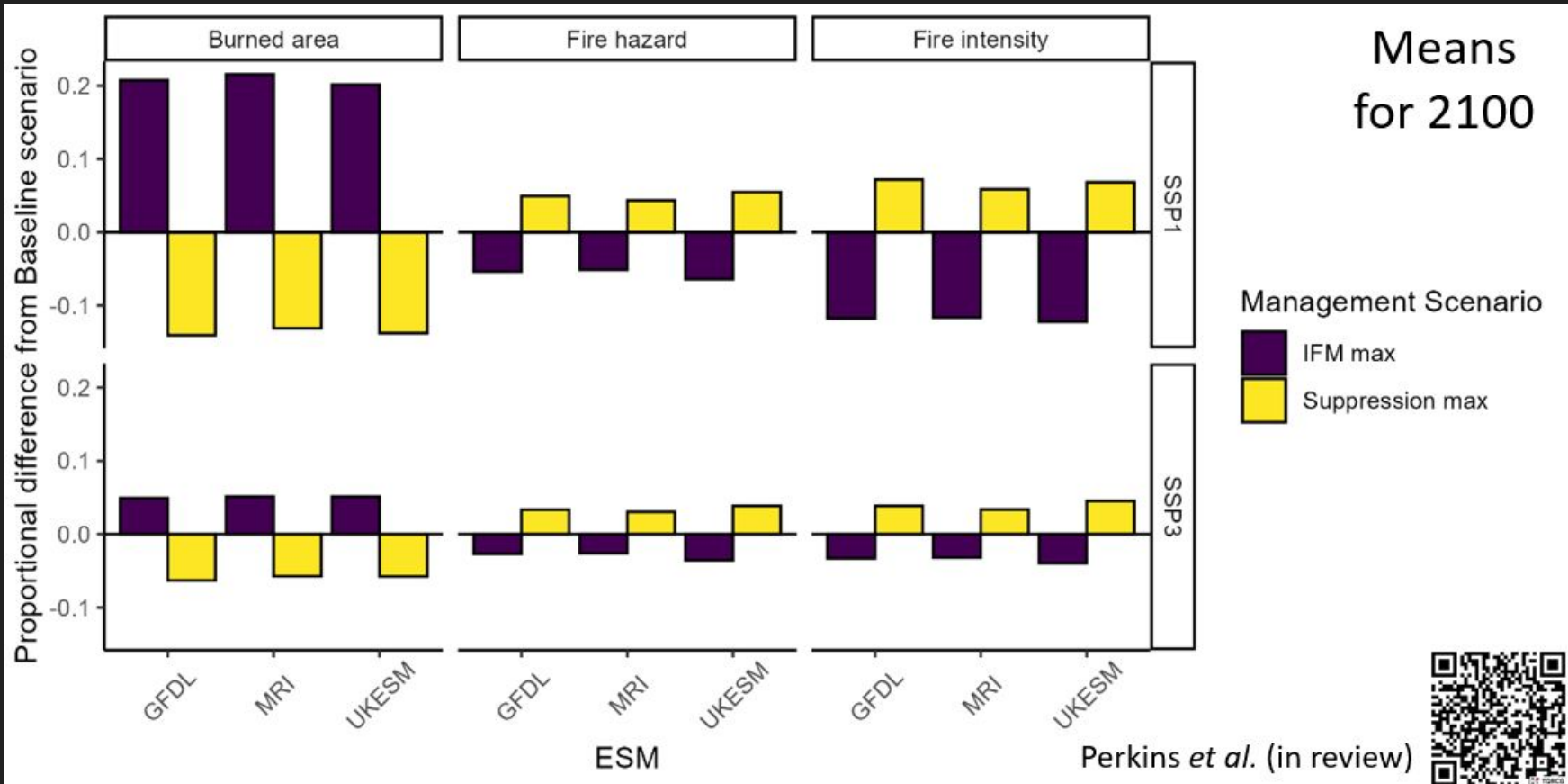
Gridded socio-economic capitals for SSPs

Global projections decadal to 2100 with spatial resolution of 0.25°

<i>Capital</i>	<i>Input Data (Baseline)</i>	<i>Input Data (Projection)</i>	<i>Rescaling Method</i>	<i>Output units</i>
<i>Health</i>	HDI health index - (Kummu et al., 2018).	Life Expectancy - (UNDESA, 2022); Country-level Gini - (Rao et al., 2019).	Rasterisation of sub-national polygons	0-1 index
<i>Education</i>	HDI education index - (Kummu et al., 2018).	Participation proportion - (KC & Lutz 2017); Participation years - ((Potančoková et al., 2014); Country-level Gini - (Rao et al., 2019).	Rasterisation of sub-national polygons	0-1 index
<i>Working age population</i>	Working Age Population - (KC & Lutz 2017); Total Population - (CIESIN NASA, 2018).	Working Age Population - (KC & Lutz 2017); Total Population - (Jones & O'Neill 2016).	Rasterisation of national data using population	Count (persons) per pixel
<i>Gini</i>	Country-level Gini - (Rao et al., 2019); 'Light Gini' index - (Mirza et al., 2021).	Country-level Gini - (Rao et al., 2019).	Rasterisation of national data using 'light Gini'	0-1 index
<i>Total energy consumption</i>	Energy use per capita - (EIA 2024, EI 2024).	Energy supply - (Riahi et al., 2017, Bauer et al., 2017); Total Population (Jones & O'Neill 2016).	Rasterisation of national data using population	kWh
<i>Market access</i>	Urban Fraction - (Hurt et al., 2020); Population Density - (CIESIN, 2017); Road Density - (Meijer et al., 2018); GDP per capita - (Kummu et al., 2018).	Urban Fraction - (Hurt et al., 2020); Total Population - (Jones & O'Neill, 2016); Road Density - (Meijer et al., 2018); GDP per capita - (Murakami et al., 2021).	None	0-1 index

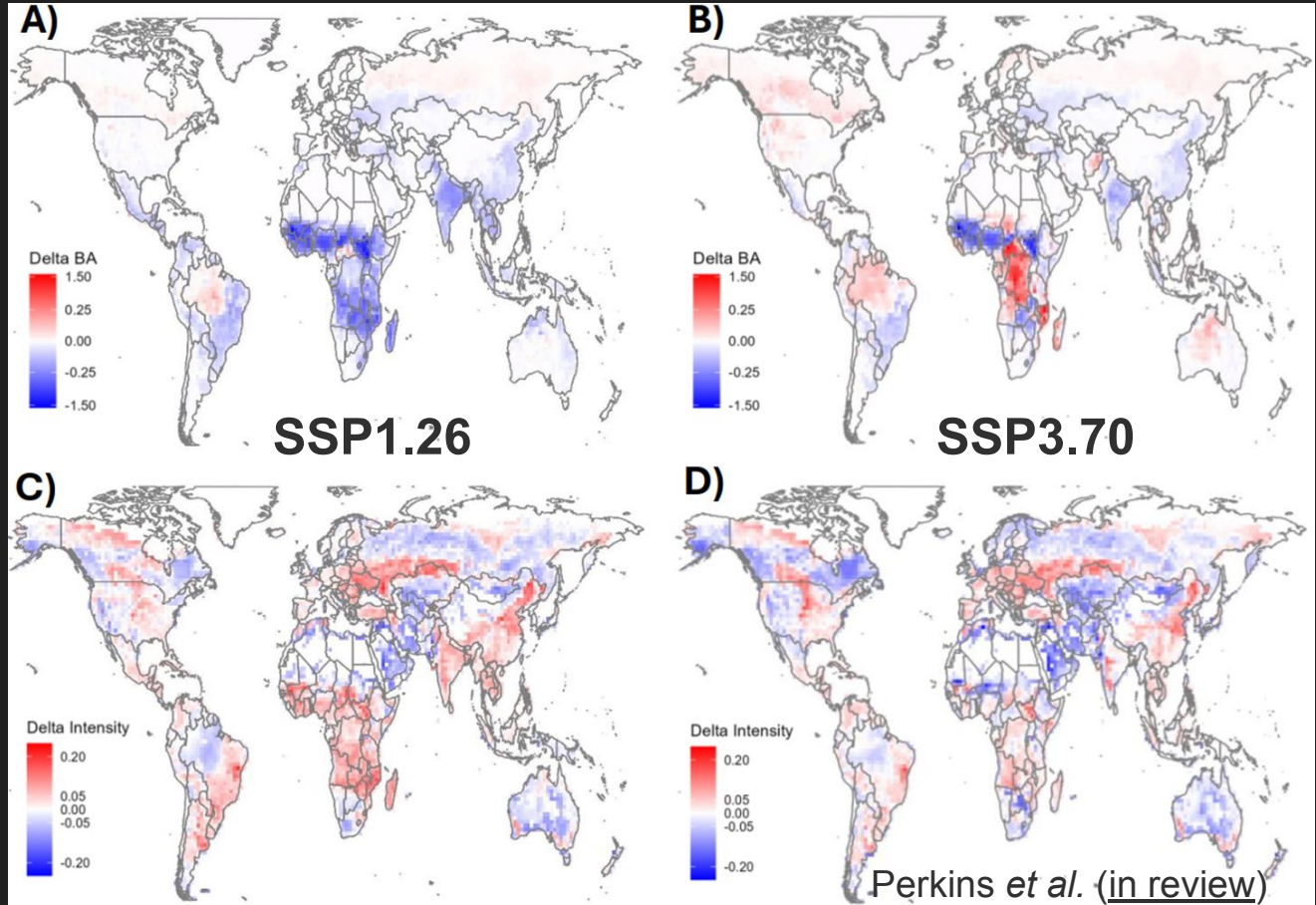
Data available at
Perkins *et al.* (2025)

Results: Management



Results: SSPs

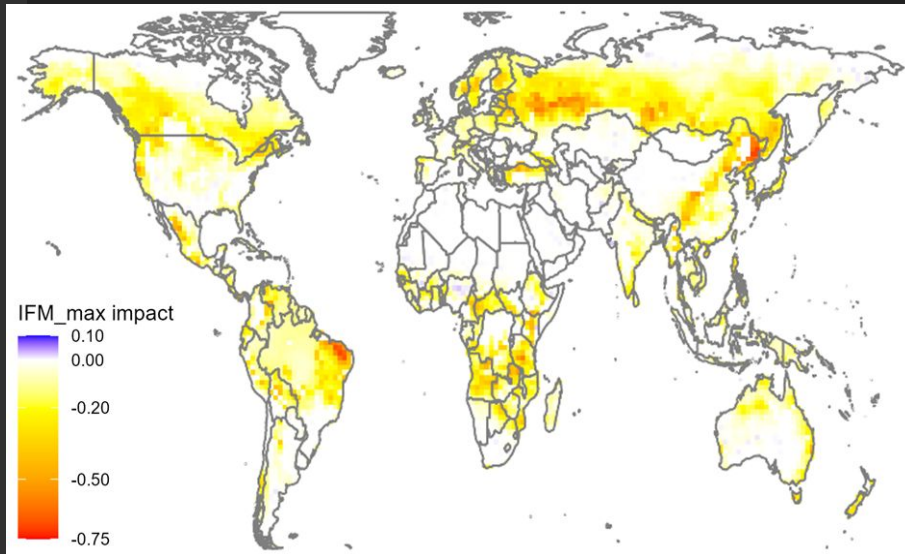
Burned Area



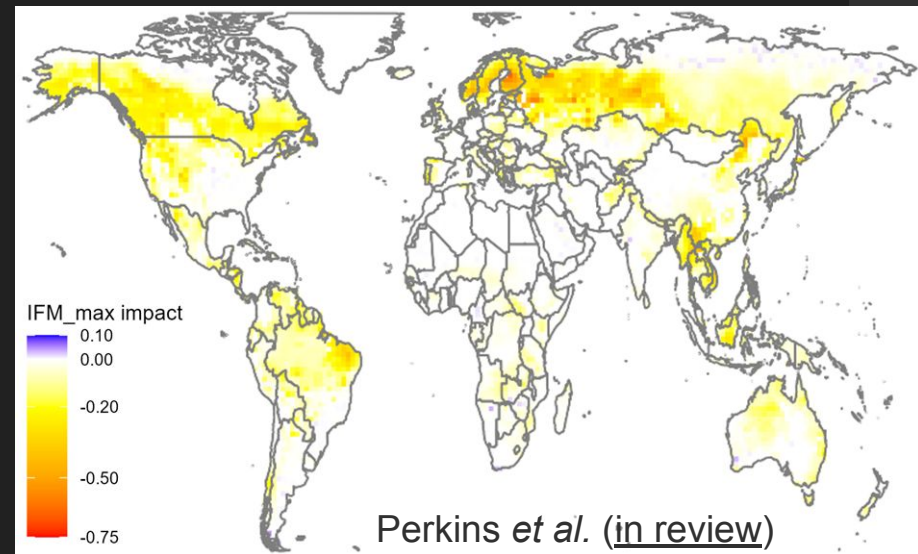
Results: Management vs SSPs

Integrated Fire Management *does* reduce intensity
(but is not as important as socio-economic conditions)

SSP1



SSP3



Perkins *et al.* (in review)

Red is greater reduction in intensity 2015-2100

WHAM!

The Wildfire Human Agency Model

Ol Perkins, James Millington, *et al.*



Project Homepage



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MEFCAP

Market-based Environmental Fuzzy Cognitive
Agents and Producers Model

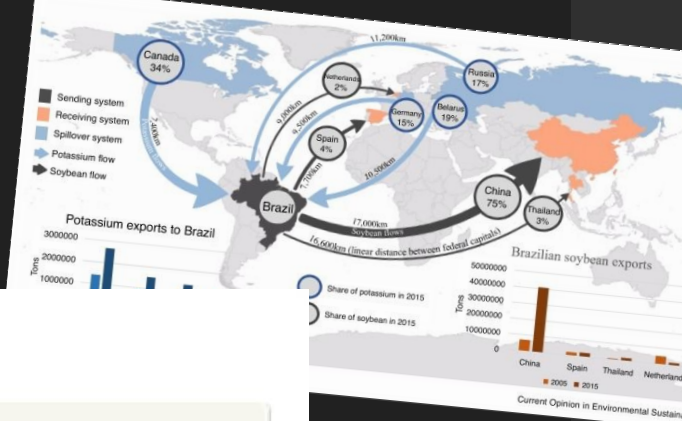
Viera Ukropcova, James Millington



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Supply Chains in Telecoupling



GLOBAL VALUE CHAIN (Soy)



Note: Net - offset ecosystem loss, Zero-gross def. - no loss of forest, Sustainability - incl. primary forests Deforestation - only includes forest, Conversion - includes all other natural ecosystems

Source: Supply Chain & Forest 500

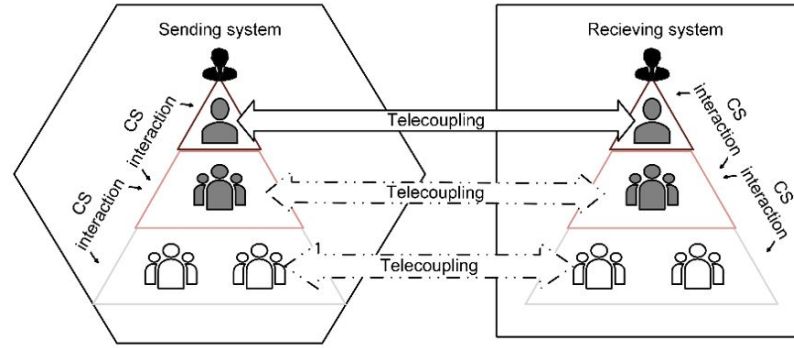
Certification

Liu et al. (2018)

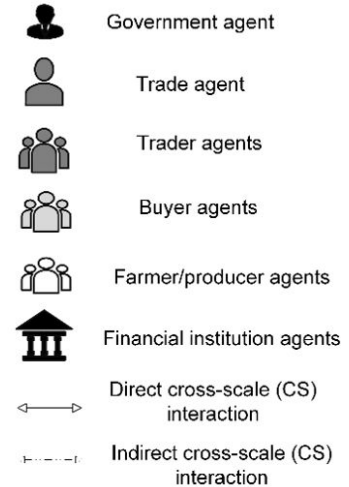
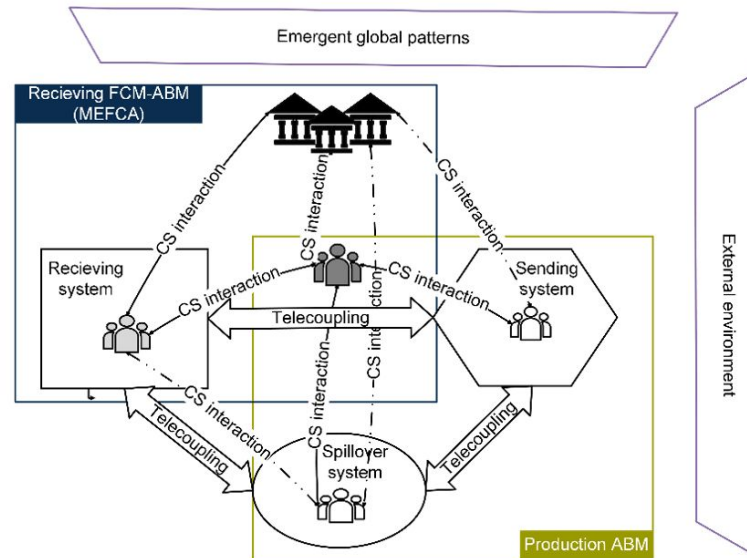
WWF & BCG
(2021)

TeleABM

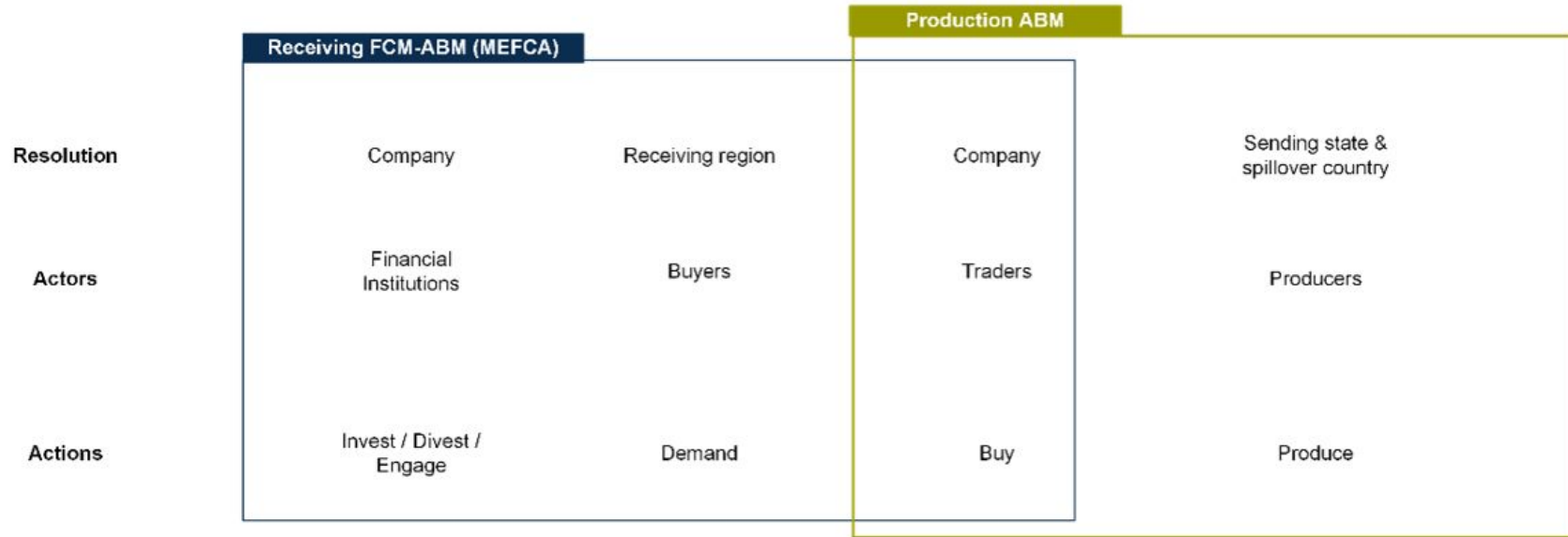
Dou et al. (2019, 2020)



MEFCAP



MEFCAP: Telecoupled Agents



Fuzzy Cognitive Mapping

Fuzzy: decisions based on imprecise, non-numerical information

Cognitive Map: understanding of interactions btw. components

Subjects here are:

- financial institutions (FIs)
- traders/buyers (companies)

Constructed here through survey of experts representing:

- Companies (11)
- Financial institutions (13)
- NGOs (3)

Survey design from modeller hypotheses, literature review

Social Fuzzy Cognitive Map

Feedbacks between concepts drive:

- Strategies
- Investment
- Divestment



FCM: Complex Feedbacks

Strategy change (C) influenced by:

- market demand, regulation, **divestment** (via cost of capital), environmental risk

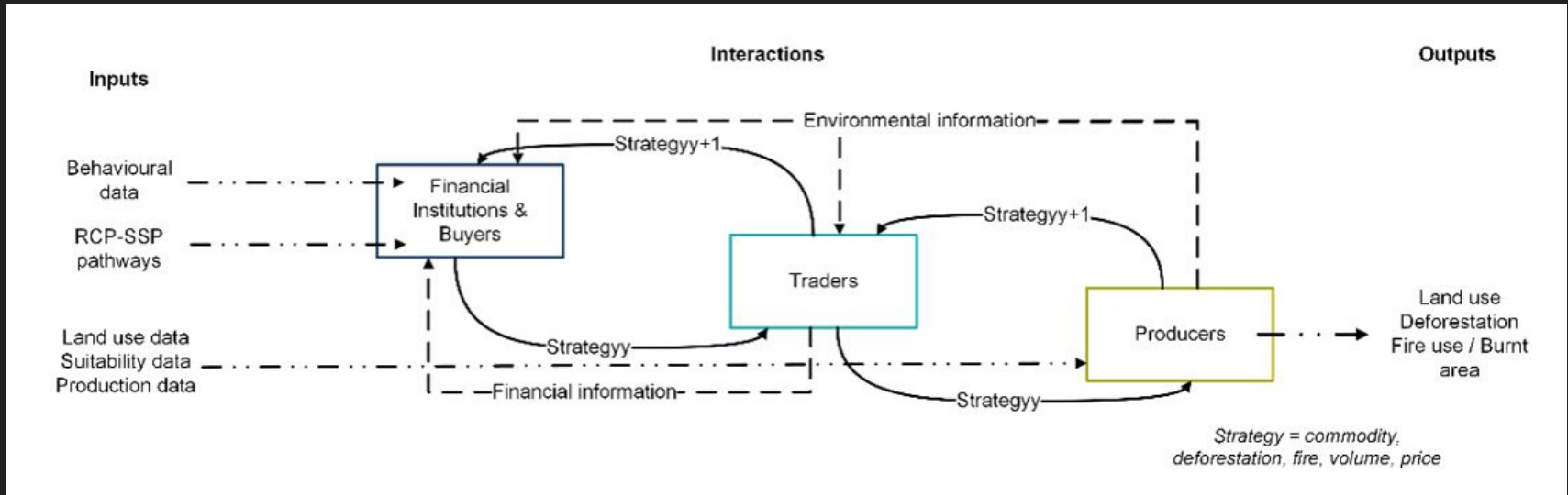
Divestment (FI) is influenced by:

- *strategy change* (C), environmental performance, financial performance, reputation, institutional risk

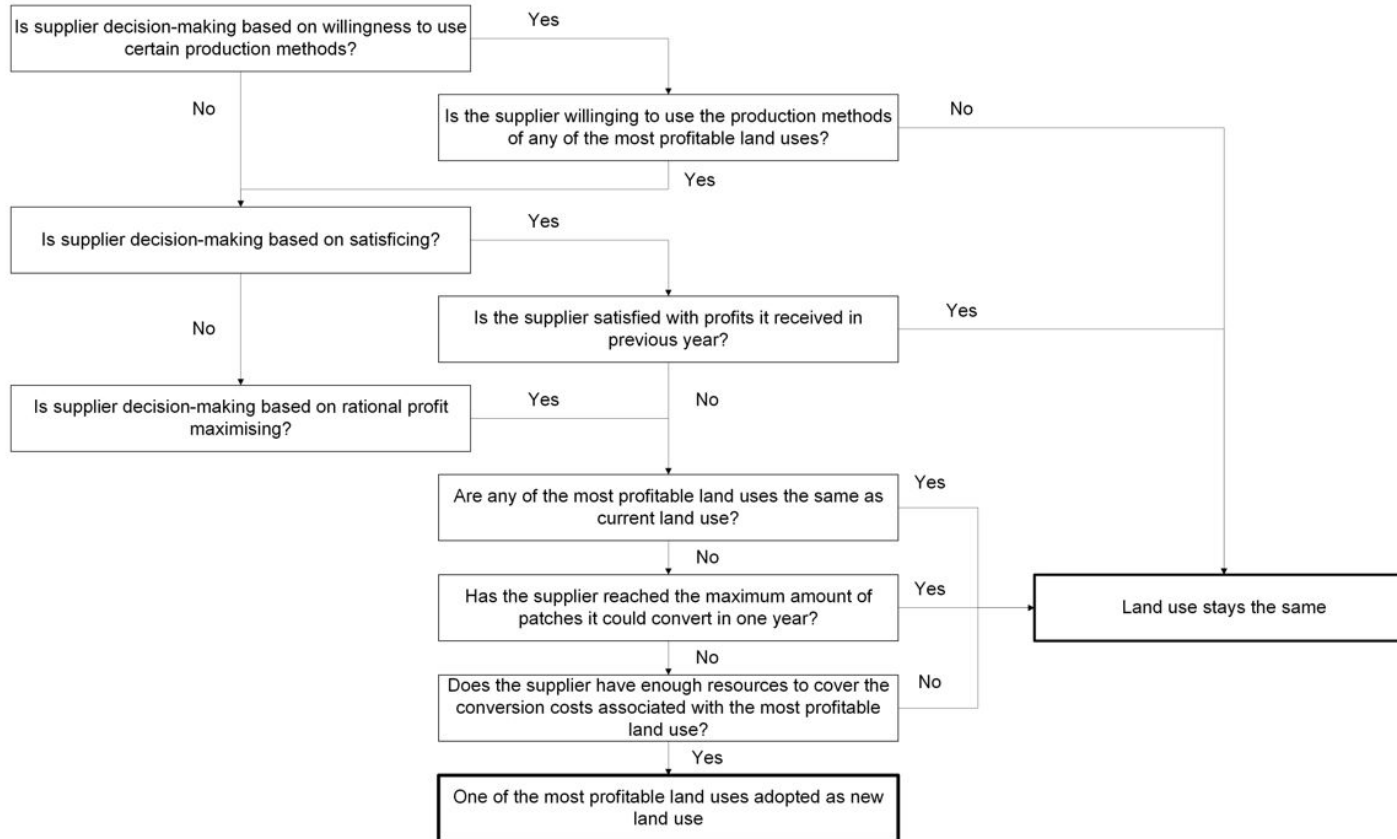
Institutional risk (FI) influenced by:

- *strategy change* (C), other FI's **divestment**, environmental risk, regulation, financial performance

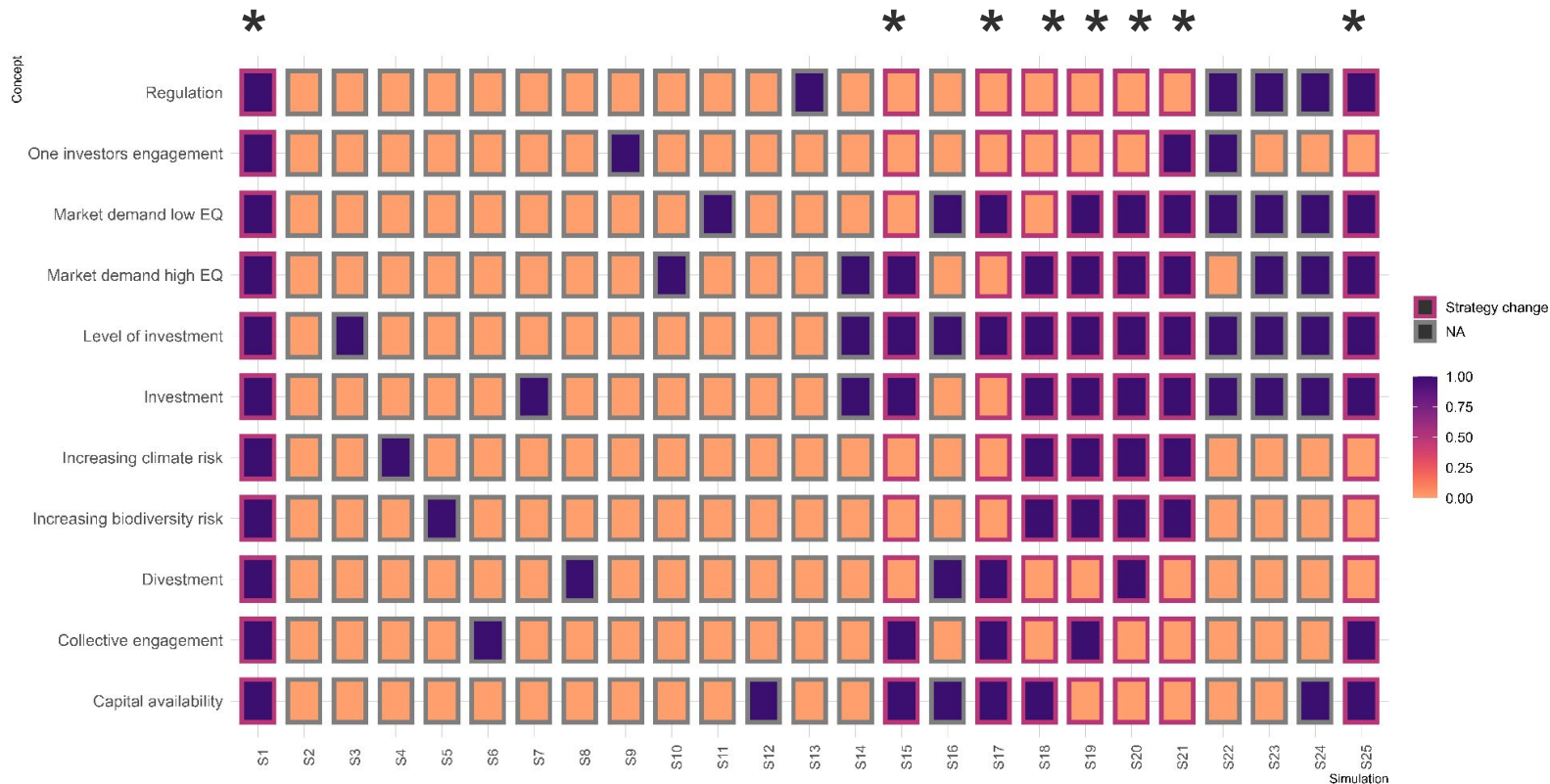
Strategy Change



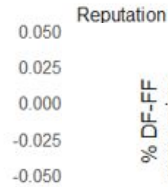
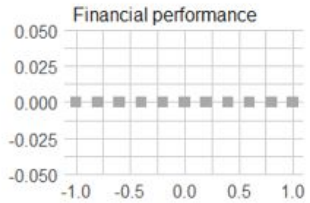
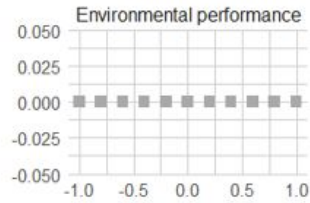
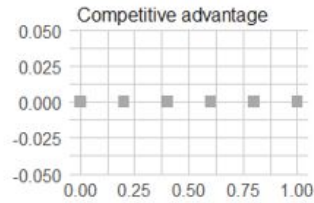
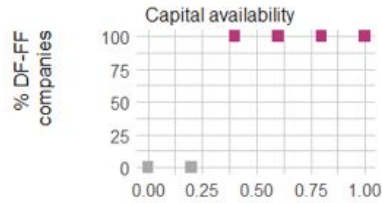
Producer Decision-Making Tree



Multiple levers needed for strategy change

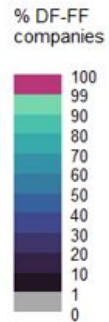
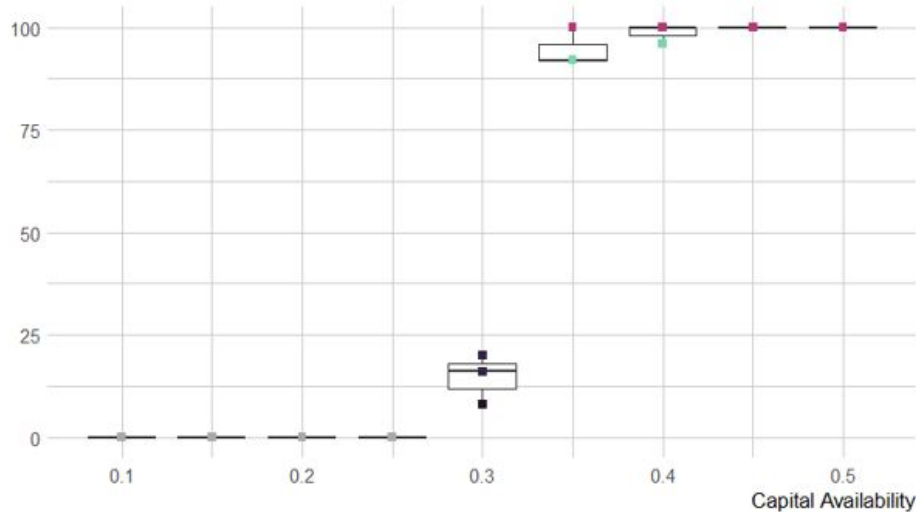


Sensitivity Analysis: Threshold Behaviour

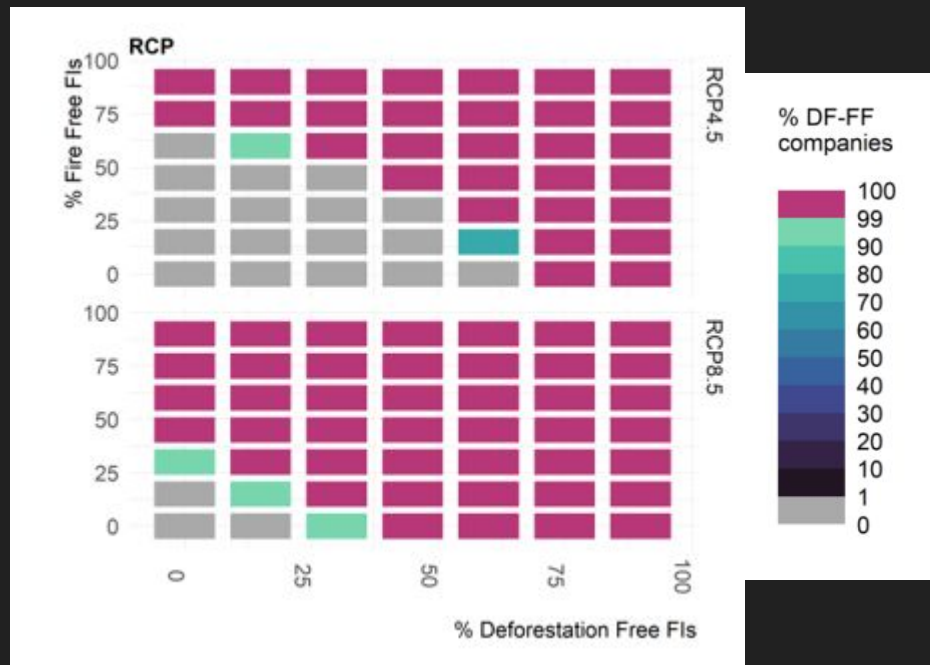


Return

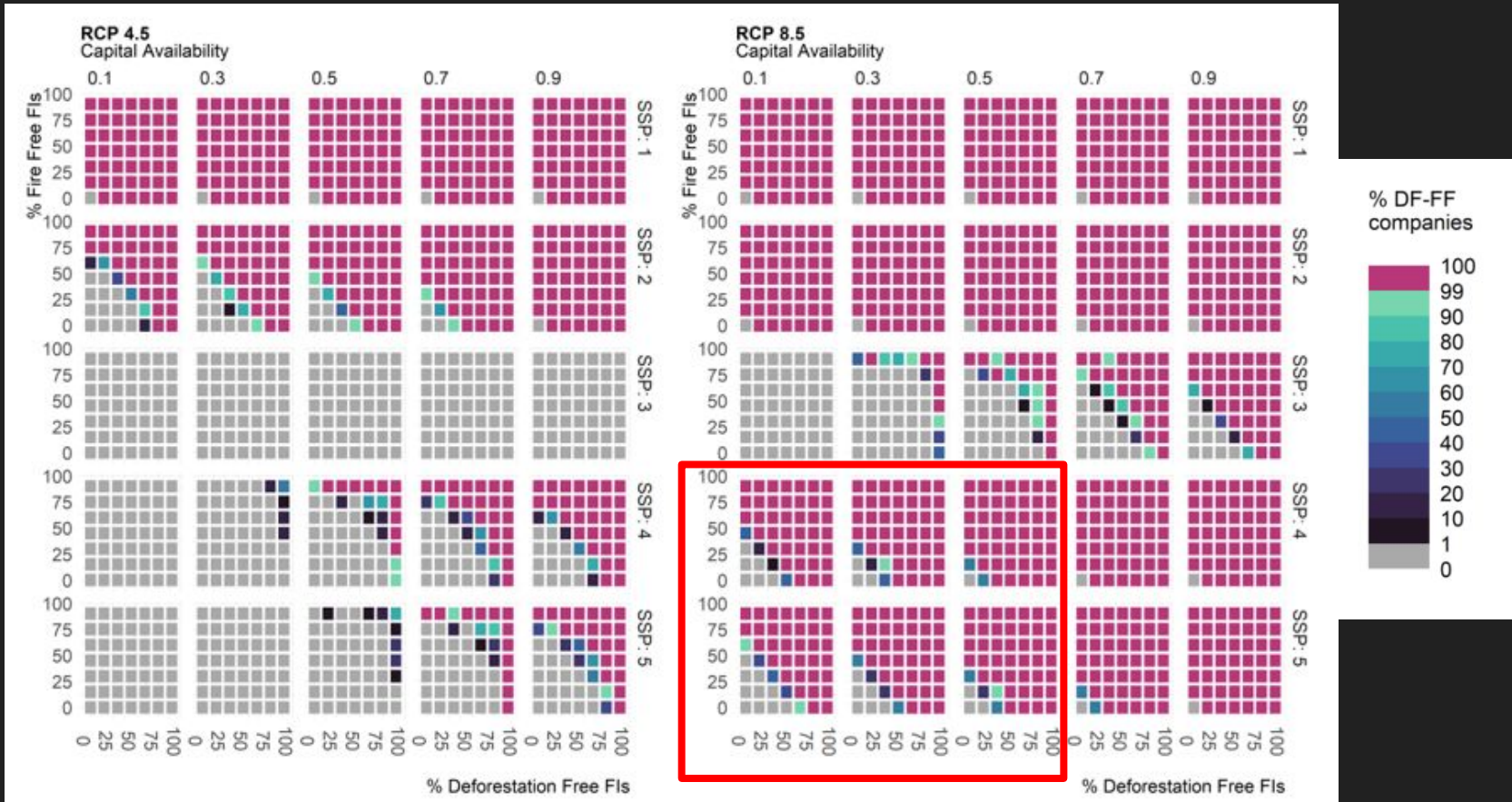
% DF-FF companies



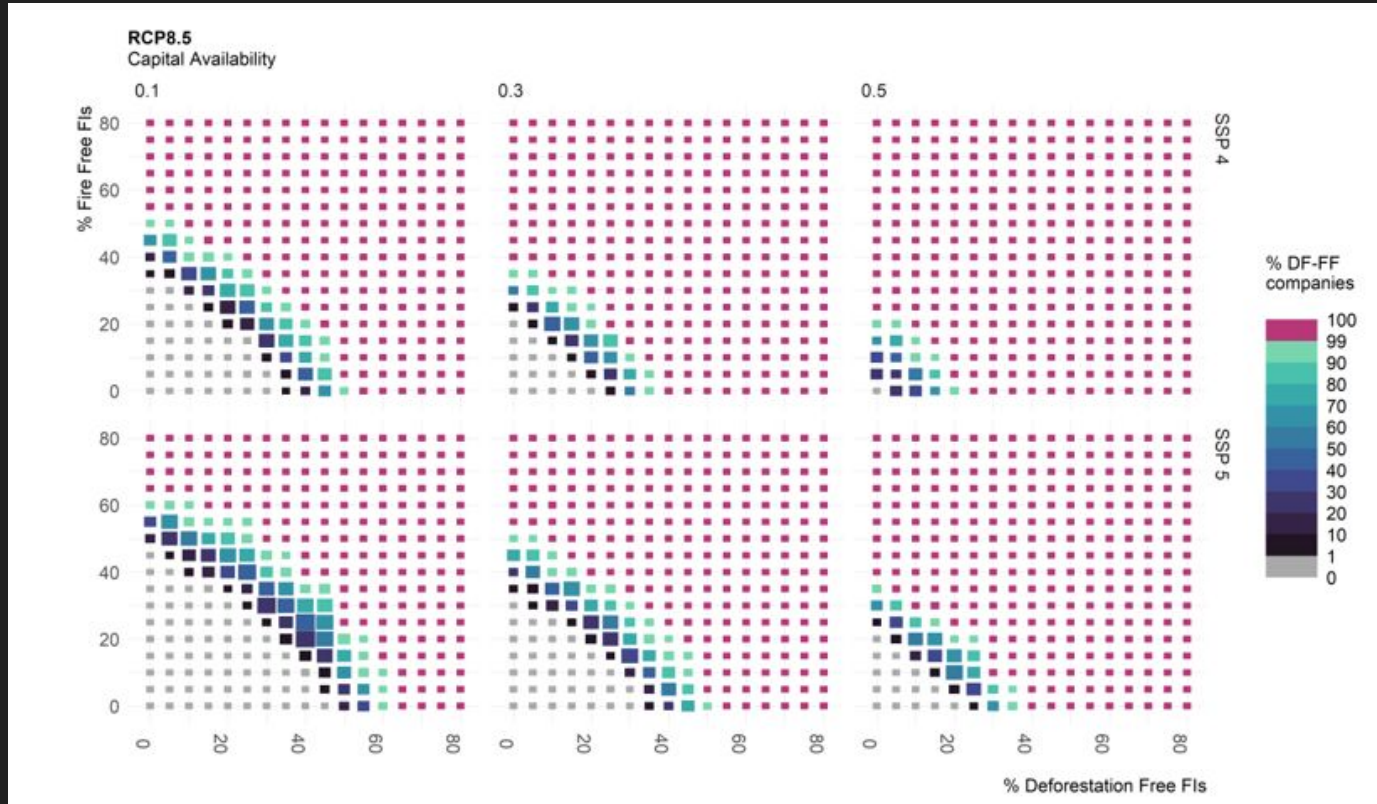
Financial institutions matter for company behaviour



But the effect varies... (e.g. capital availability)

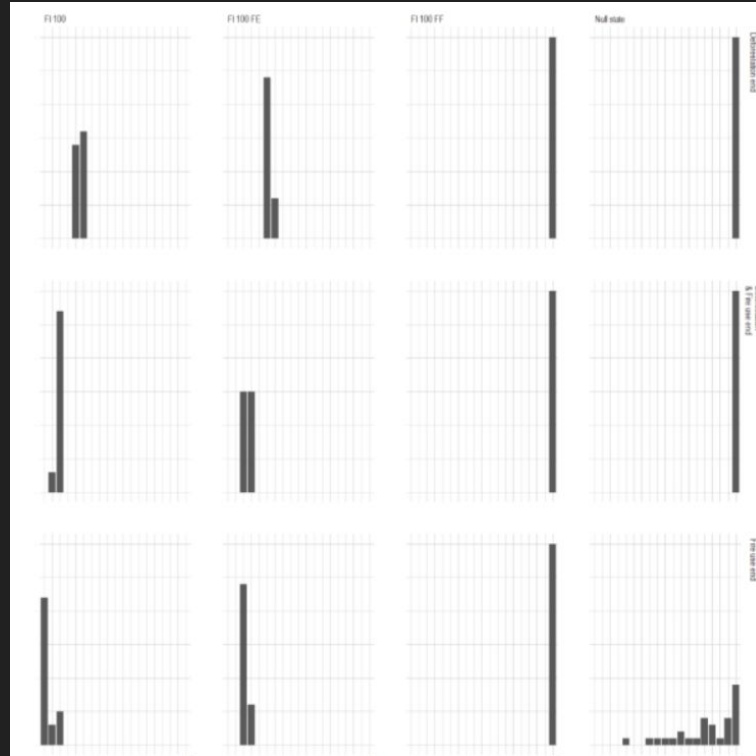


But the effect varies... (e.g. capital availability)



Producer Behaviour Change

Number of producers ending behaviour



Deforestation

Deforestation & Fire use

Fire use

Take Home Messages

Data on human behaviour is vital for understanding sustainability challenges... but it is expensive

- **Case Study Data** are out there, but for large extents are likely sparse, non-uniform, varied and incomplete
- **Fuzzy Cognitive Maps** useful for summarising understanding of feedbacks (but private institutions often means low sample size)

A clear theoretical framing is needed to specify the categorisations, quantifications and decisions made when constructing models from these data

Rational Abstractions & 'Chaotic Conceptions'

“Abstractions can be made in various ways ...

A rational abstraction is one which isolates a significant element of the world which has some unity and autonomous force, such as a structure.

A bad abstraction [‘chaotic conception’] arbitrarily divides the indivisible and/or lumps together the unrelated and the inessential, thereby ‘carving up’ the object of study with little or no regard for its structure and form.”

Sayer (2010, p.93)

Method in Social Science

Global Land Programme: BeModelS WG

GLOBAL LAND PROGRAMME

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Oliver Perkins in BeModelS: Behavioural Models of Land Systems Working Group

...

About

The Behavioural Models of Land Systems Working Group is a joint venture between the **AIMES** project and the Global Land Programme. In linking two Global Research Projects of the **Future Earth** network, the group aims to support and build interdisciplinary collaboration across scientific disciplines. The group welcomes a wide range of perspectives and members with interests in any aspects of human behaviour (e.g. individual, collective,