Potsdam Institute for Climate Impact Research

Technische Universität Berlin

Land-based climate change mitigation: modeling bioenergy production, afforestation and avoidance of deforestation

PhD defense of

Florian Humpenöder

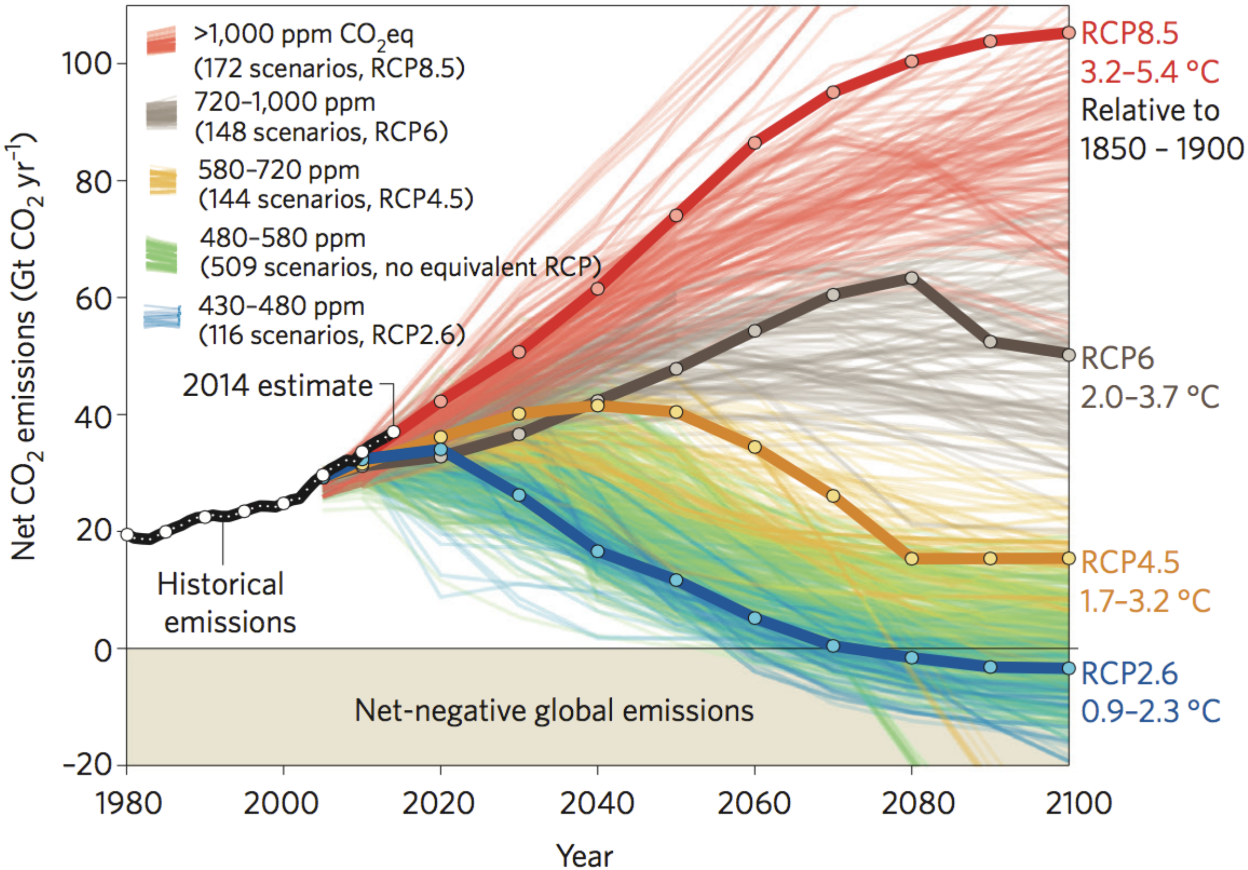
15 October 2015

Outline

- **Motivation**
- **Methodology**
- **Main results**
- **Conclusions**
- **Outlook**

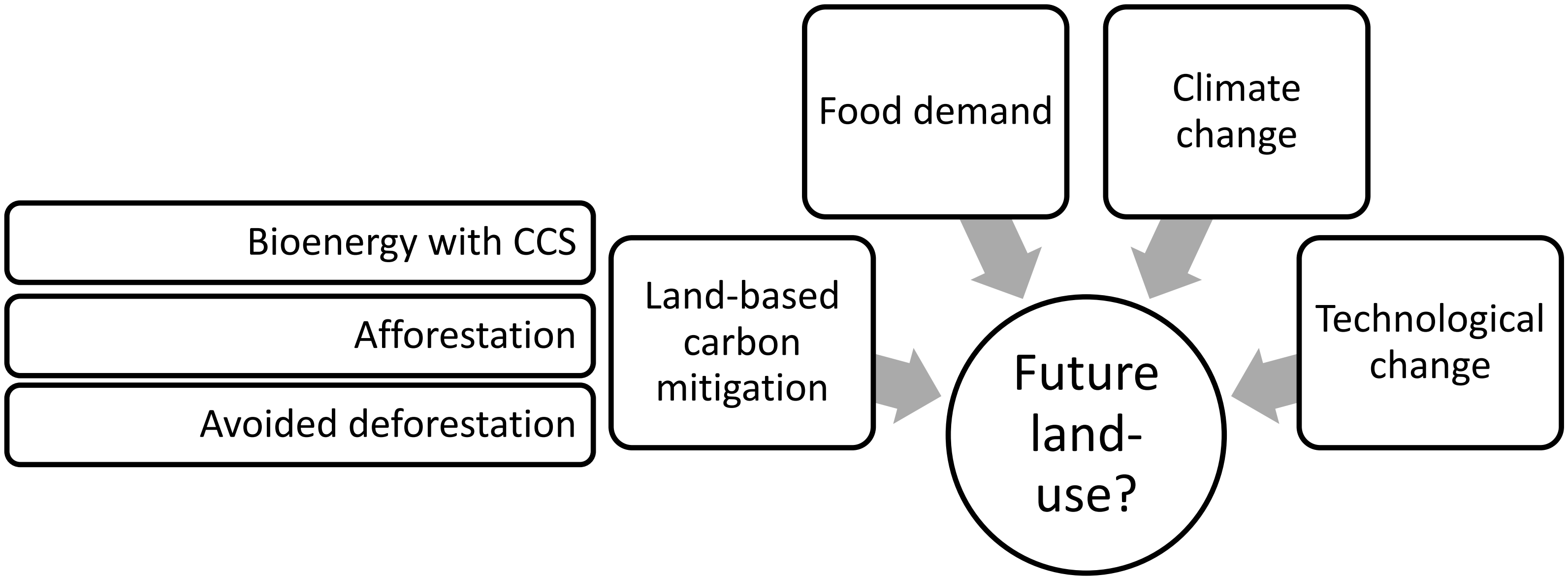
MOTIVATION

Ambitious climate targets require negative emissions from land-based mitigation



Fuss et al. 2014 Betting on negative emissions *Nature Clim. Change* **4** 850–3; Figure 1a
Data sources: IPCC AR5 database, Global Carbon Project and Carbon Dioxide Information Analysis Center

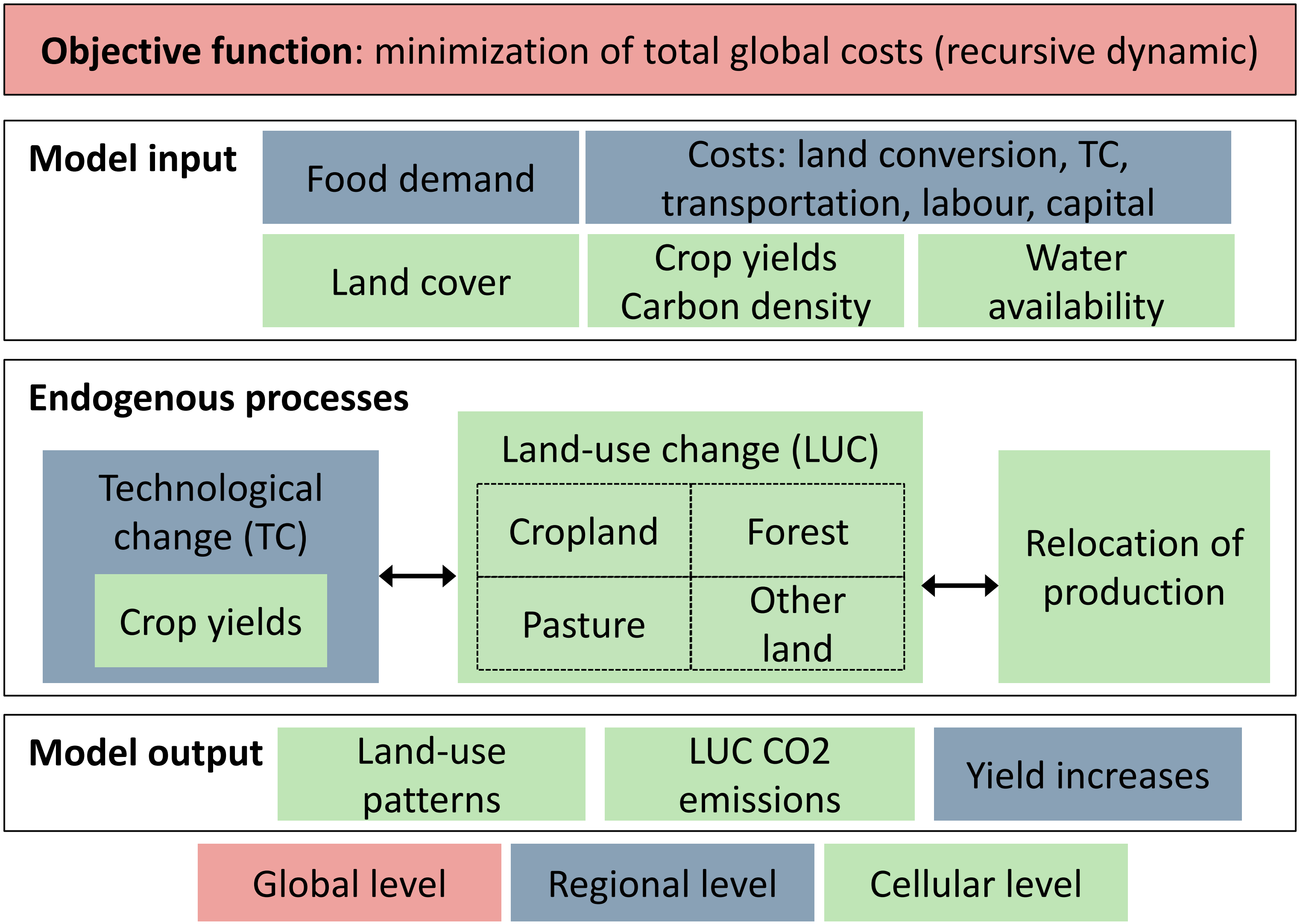
Research questions



- **What is the global potential of land-based carbon mitigation in the 21st century?**
- **What are the associated land requirements?**
- **What are the implications for the agricultural sector?**

METHODOLOGY

MAgPIE: economic land-use optimization model

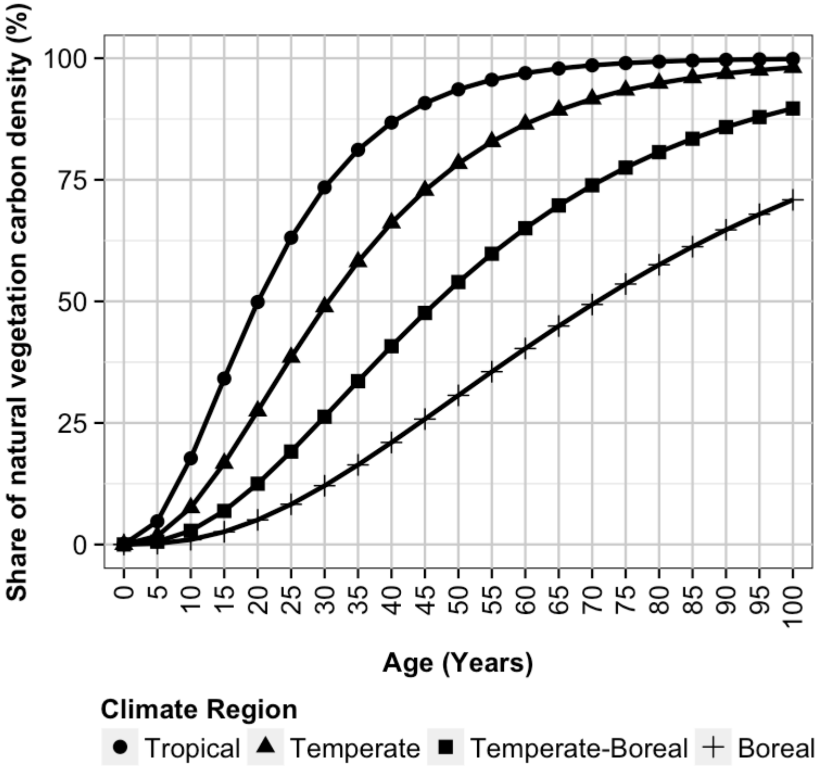


Afforestation / Avoided deforestation

- Global CO_2 price as economic incentive for
  - Avoided deforestation (LUC CO_2 emissions * CO_2 price)
  - Afforestation (neg. CO_2 emissions * CO_2 price = cost reduction)
- Costs for forest established, management and monitoring
  - Indirect costs for investments in TC to free up agricultural land for afforestation
- Afforestation decision is based on a time horizon of 30 years
  - Limited foresight for carbon sequestration
- Afforestation is implemented as managed regrowth of natural vegetation

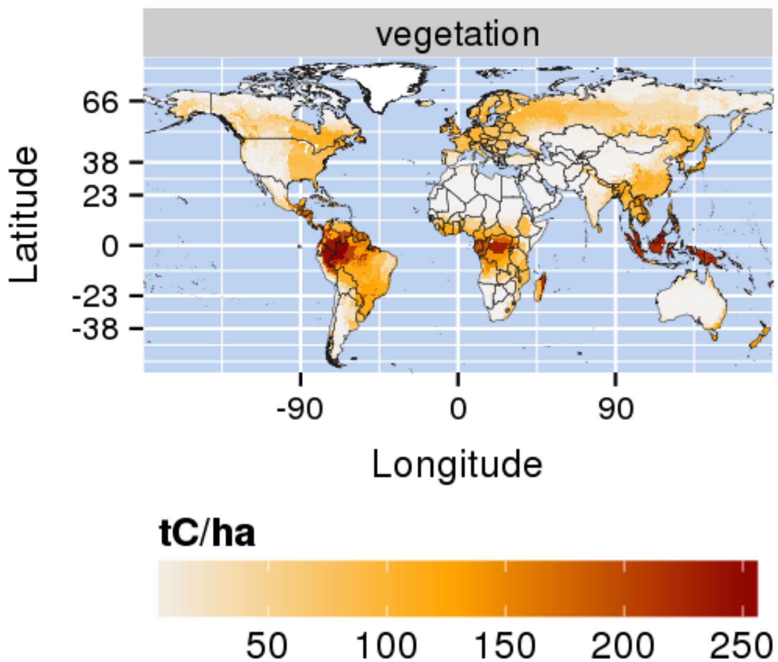
Afforestation / regrowth of natural vegetation

Growth curves for climate regions based on Chapman-Richards volume growth model



Humpenöder et al. (2014), Environ. Research Letters

Spatially explicit carbon density of potential natural vegetation from the biophysical process model LPJmL



Bioenergy in MAgPIE

- **Exogenous**
  - **Bioenergy demand on top of food demand**
- **Endogenous**
  - **CO_2 price as incentive for deployment of bioenergy with CCS**
  - **Capture rate and conversion efficiency determine CDR**
  - **Land-use costs for bioenergy production, and costs for CCS infrastructure and sequestration**

+

MAIN RESULTS

Structure of the thesis

Chap II	**Land use protection for climate change mitigation**
	A. Popp, F. Humpenöder et al. (2014), Nature Climate Change
Chap III	**The global economic long-term potential of modern biomass in a climate-constrained world**
	D. Klein, F. Humpenöder et al. (2014), Environ. Research Letters
Chap IV	**Trade-offs between land and water requirements for large-scale bioenergy production**
	M. Bonsch, F. Humpenöder et al. (2014), GCB Bioenergy
Chap V	**Investigating afforestation and bioenergy CCS as climate change mitigation strategies**
	F. Humpenöder, A. Popp et al. (2014), Environ. Research Letters
Chap VI	**Land-use and carbon cycle responses to moderate climate change: implications for land-based mitigation?**
	F. Humpenöder, A. Popp et al. (2015), Environ. Sci. Technol.

Chapter V

OPEN ACCESS
IOP Publishing

Environmental Research Letters

Environ. Res. Lett. **00** (2014) 000000 (13pp)

Investigating afforestation and bioenergy CCS as climate change mitigation strategies

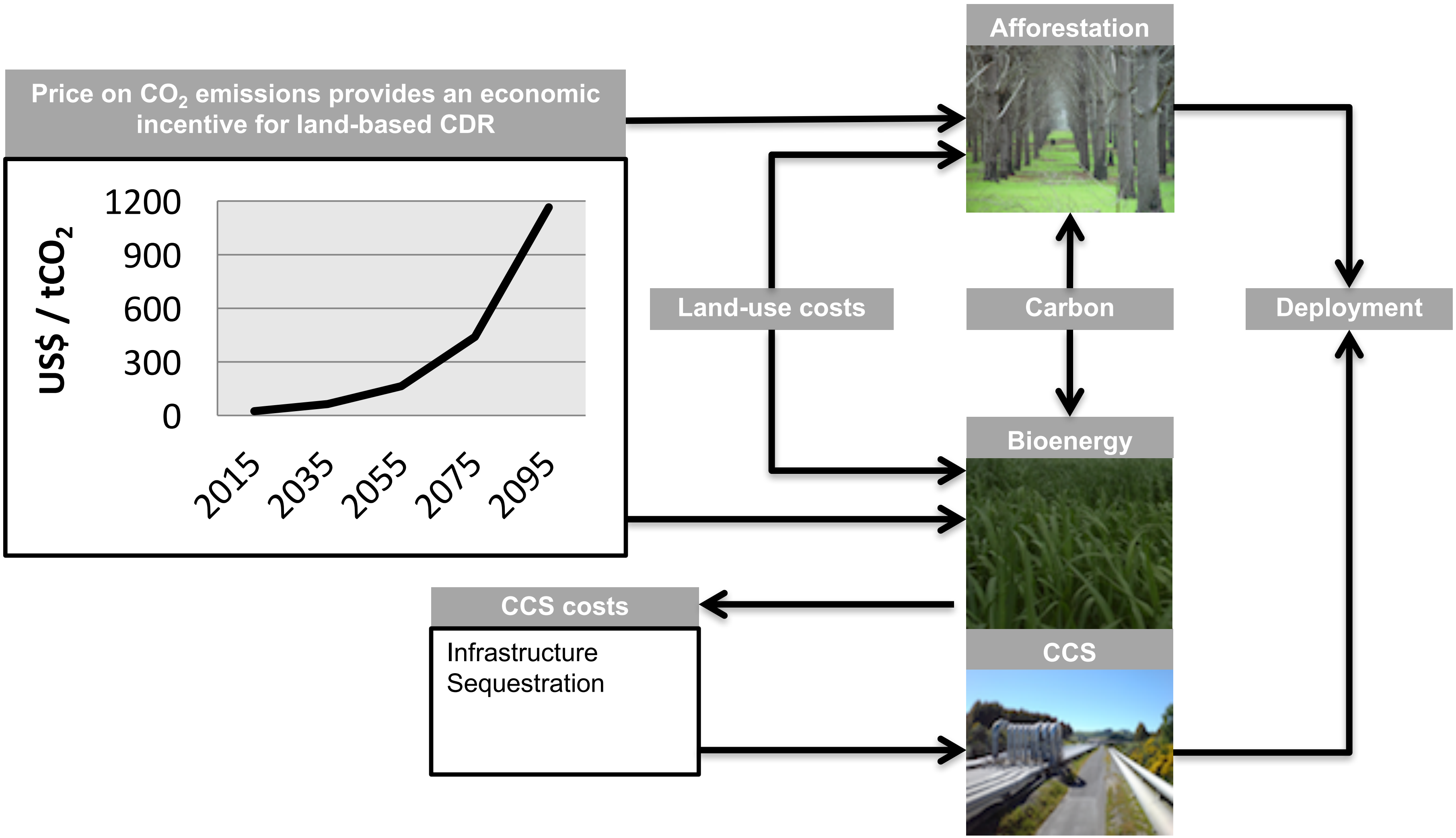
Florian Humpenöder[1,2], Alexander Popp[1], Jan Phillip Dietrich[1], David Klein[1,2], Hermann Lotze-Campen[1], Markus Bonsch[1,2], Benjamin Leon Bodirsky[1,2], Isabelle Weindl[1,3], Miodrag Stevanovic[1,2] and Christoph Müller[1]

[1] Potsdam Institute for Climate Impact Research (PIK), Potsdam, Germany
[2] Technical University of Berlin, Berlin, Germany
[3] Humboldt University of Berlin, Berlin, Germany

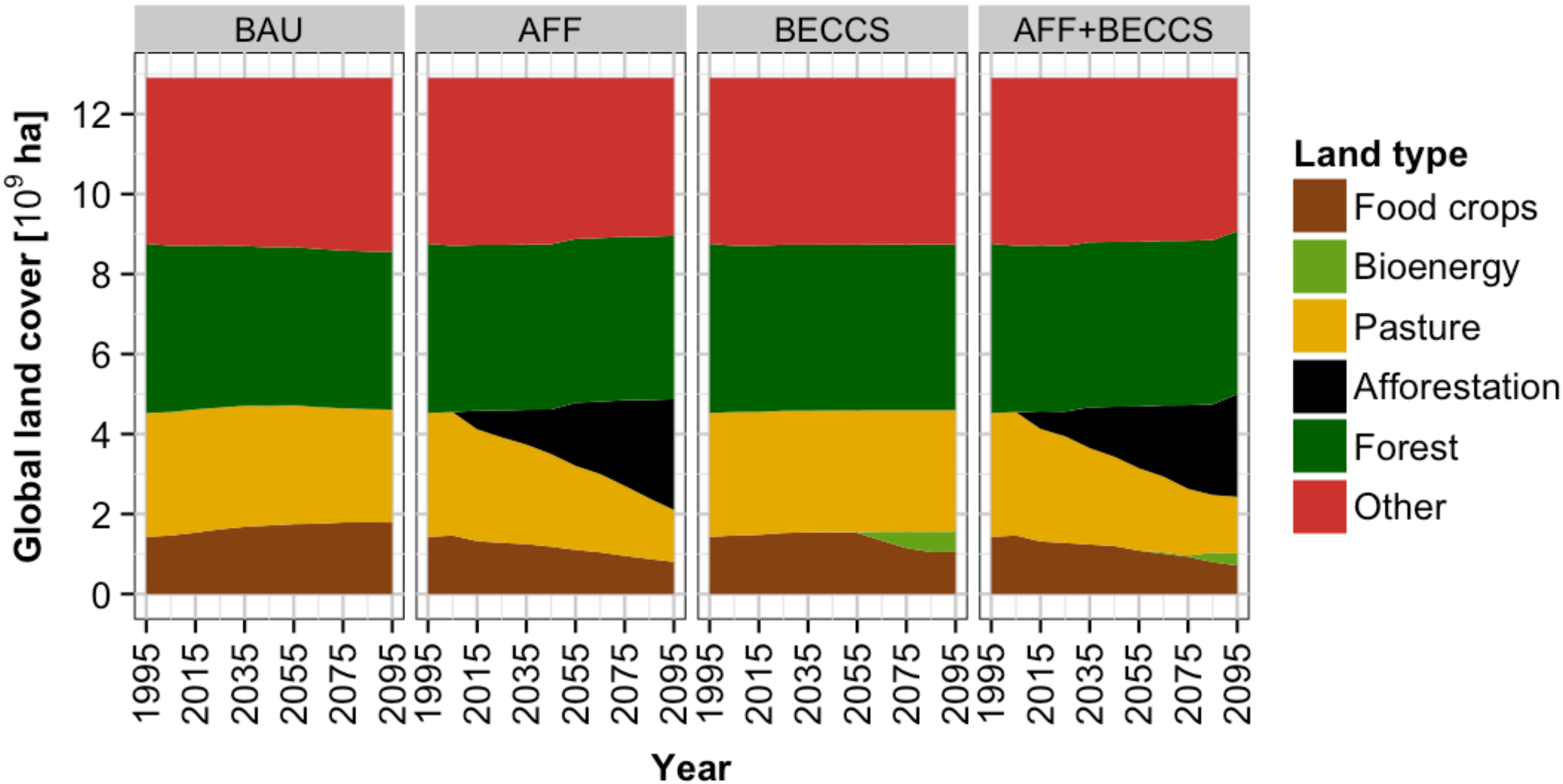
Motivation

- **At what CO_2 price are afforestation and bioenergy with CCS deployed?**
- **How much land do these two options need for how much CDR?**
- **How much intensification would be needed for maintaining food production simultaneously?**

Study design

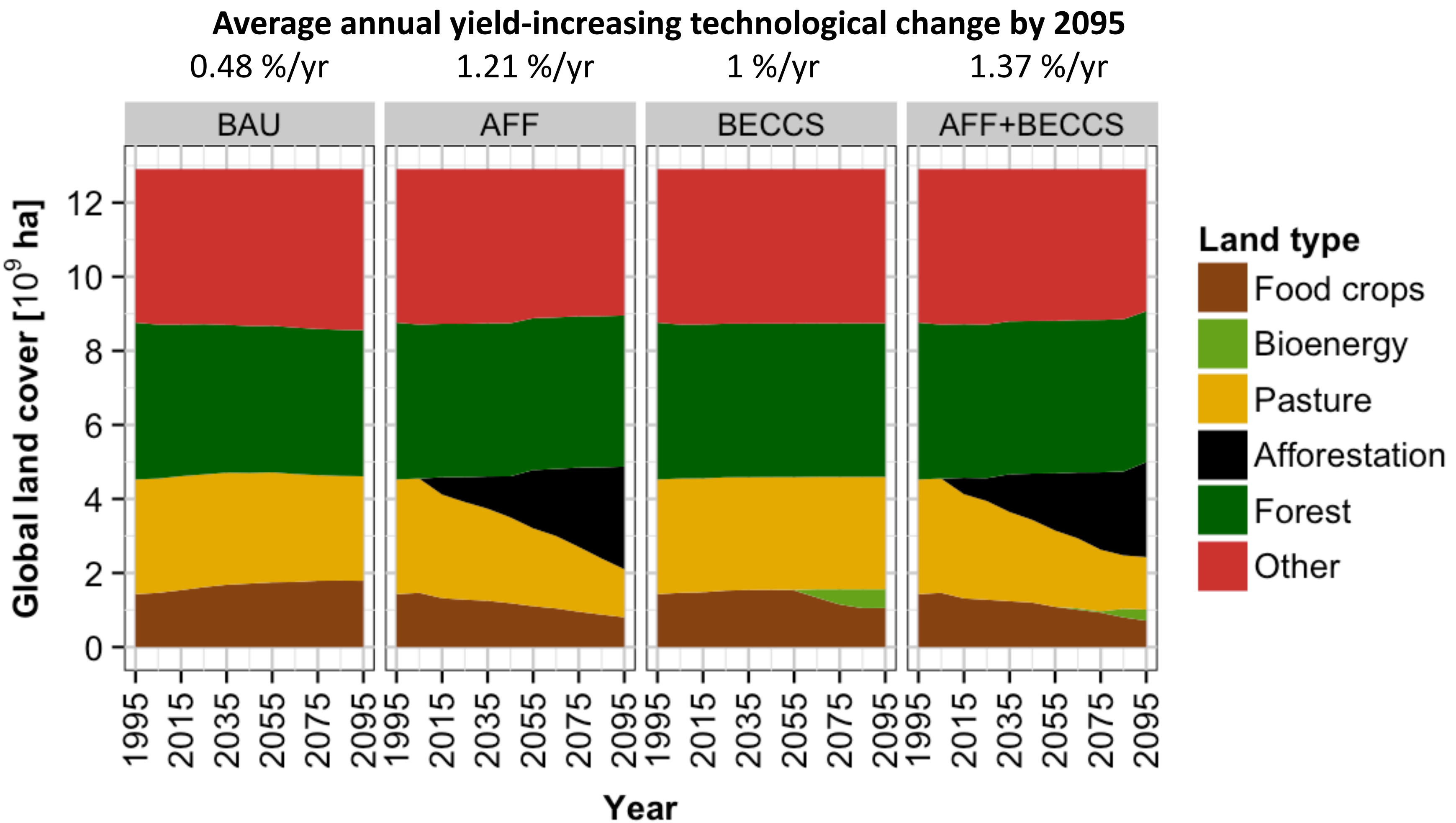


Strong afforestation at low CO_2 prices, bioenergy with CCS only at higher CO_2 prices



Humpenöder et al. (2014), Environ. Research Letters

Large-scale land-based mitigation requires strong intensification of agricultural production

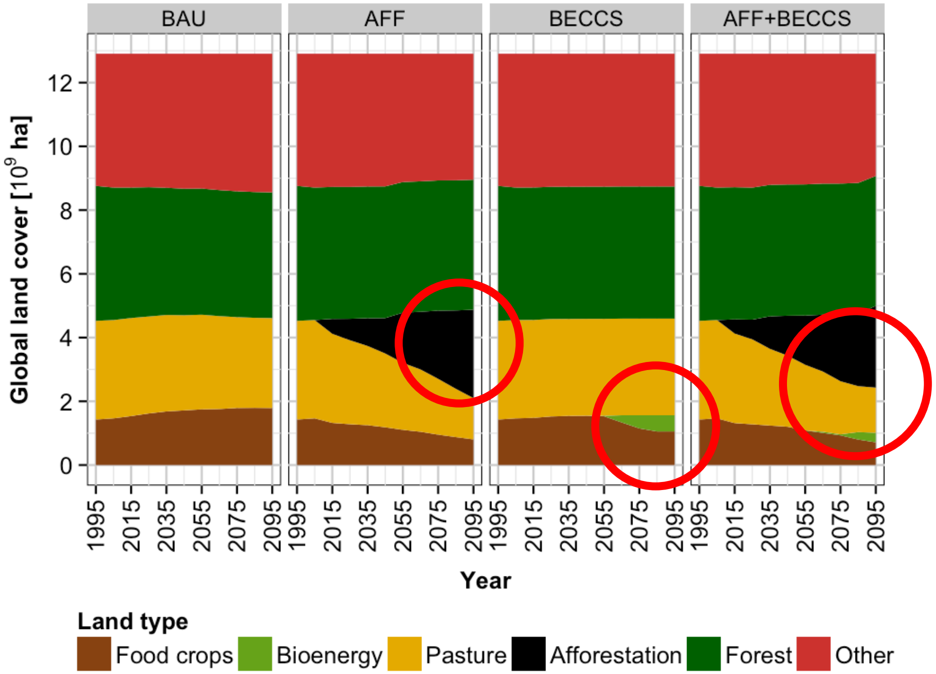


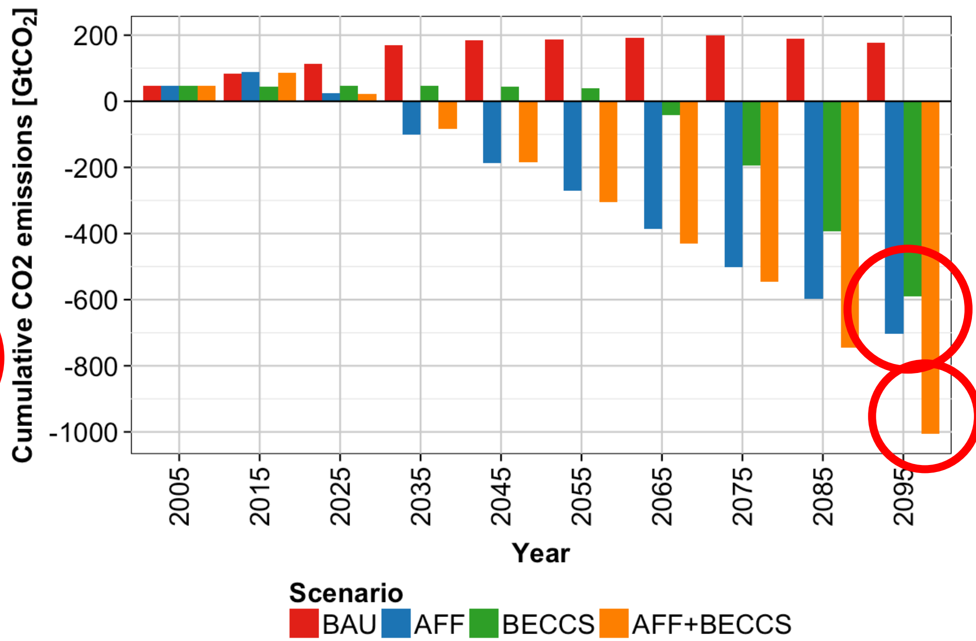
Humpenöder et al. (2014), Environ. Research Letters

Land requirement and CDR

- **Afforestation requires about 5 times as much land as bioenergy with CCS for similar CDR by 2100**
- **Sensitivity of land-based mitigation to CO_2 price, planning horizon (limited foresight), CCS capacity and bioenergy yield**

Humpenöder et al. (2014), Environ. Research Letters





Chapter VI

Environmental Science & Technology

Article

pubs.acs.org/est

Land-Use and Carbon Cycle Responses to Moderate Climate Change: Implications for Land-Based Mitigation?

Florian Humpenöder,[*,†,‡] Alexander Popp,[†] Miodrag Stevanovic,[†,‡] Christoph Müller,[†] Benjamin Leon Bodirsky,[†,§] Markus Bonsch,[†,‡] Jan Philipp Dietrich,[†] Hermann Lotze-Campen,[†,||] Isabelle Weindl,[†,||] Anne Biewald,[†] and Susanne Rolinski[†]

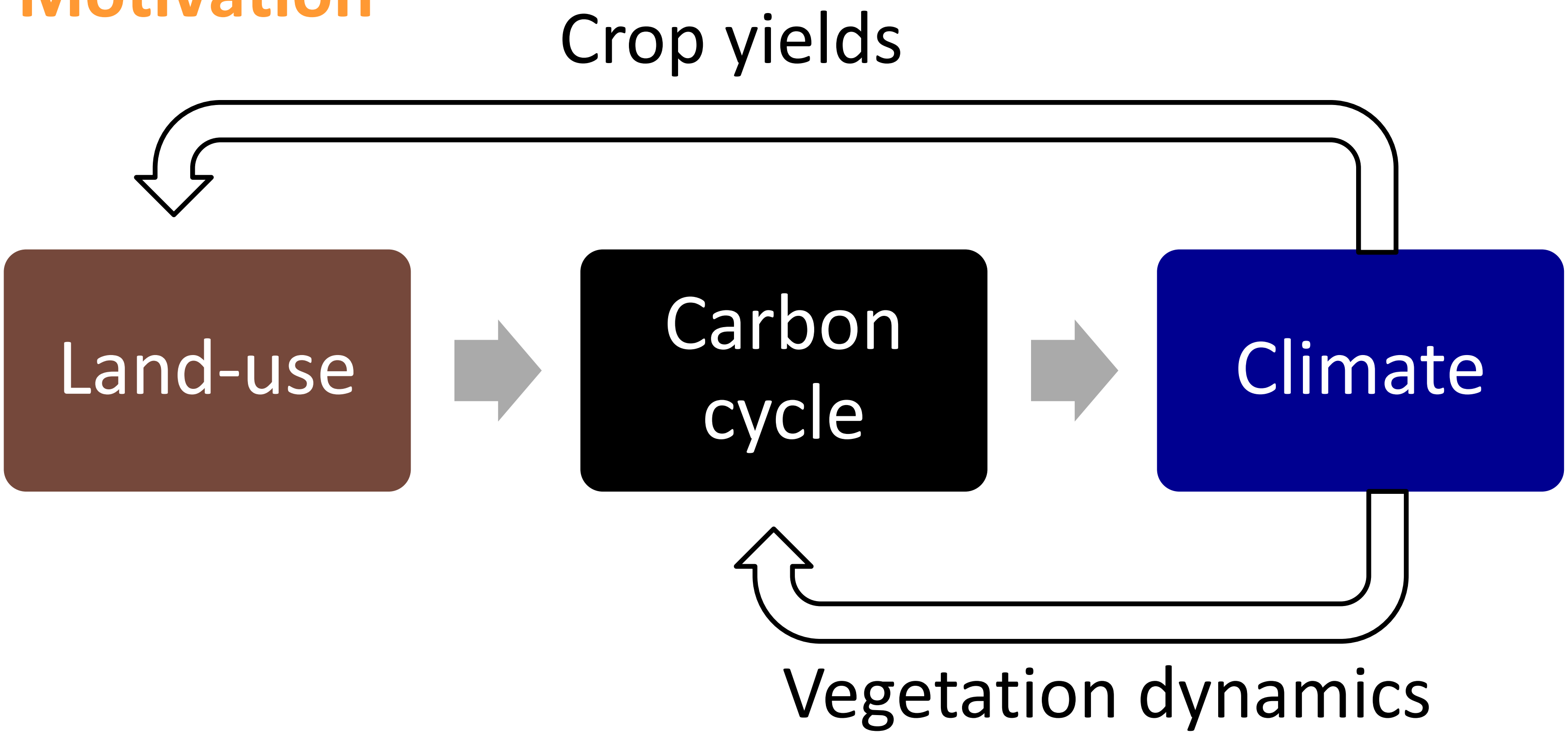
[†]Potsdam Institute for Climate Impact Research (PIK), 14473 Potsdam, Germany

[‡]Economics of Climate Change, Technische Universität Berlin (TU Berlin), 10623 Berlin, Germany

[§]The Commonwealth Scientific and Industrial Research Organisation (CSIRO), Brisbane, Australia

[||]Humboldt-Universität zu Berlin, 10099 Berlin, Germany

Motivation



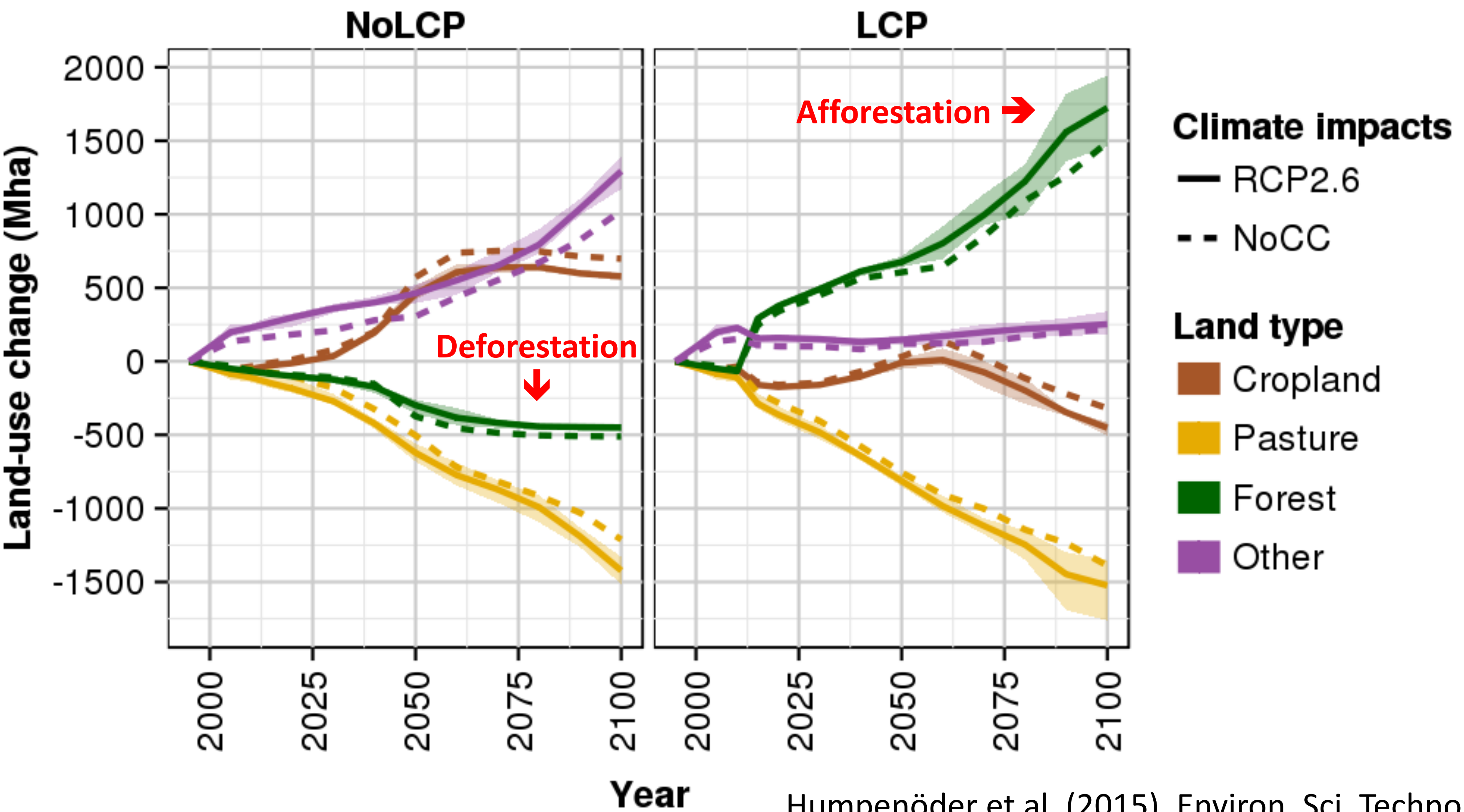
- **What are the direct and indirect effects of moderate climate change (RCP2.6) on terrestrial carbon stocks?**
- **What are the implications for land-based mitigation?**

Study design

Two dimensions

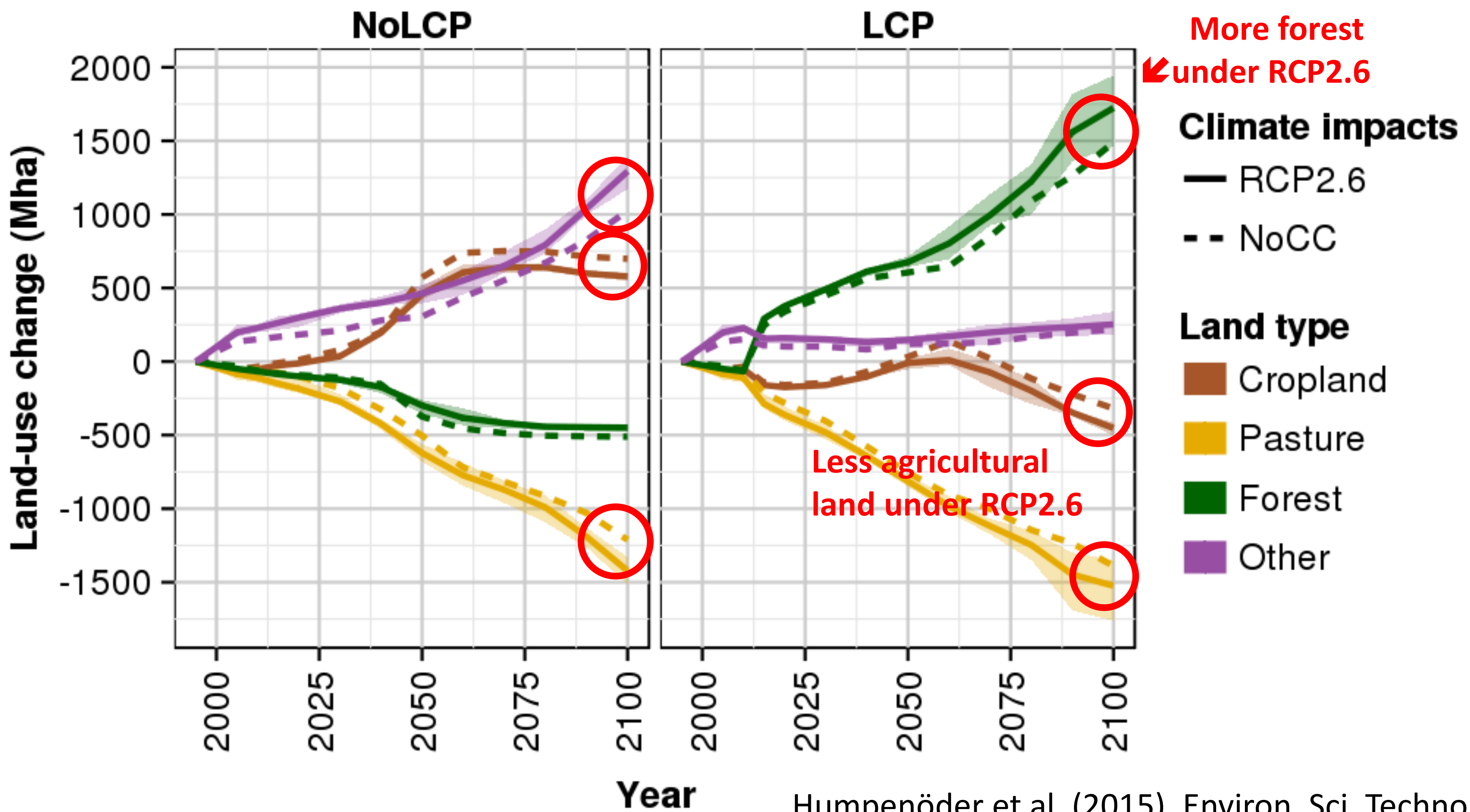
- **Land-based climate policy**
  - **LCP:** CO_2 price as incentive for afforestation / avoided deforestation
  - **NoLCP:** No CO_2 price
- **Climate impacts on the land system**
  - **RCP2.6:** Crop yields and carbon densities derived by LPJmL for RCP2.6 (incl. CO_2 fertilization) based on five different GCMs
  - **NoCC:** Crop yields and carbon densities are static at 1995 levels

Land-based climate policy (LCP) has strong effects on land-use dynamics



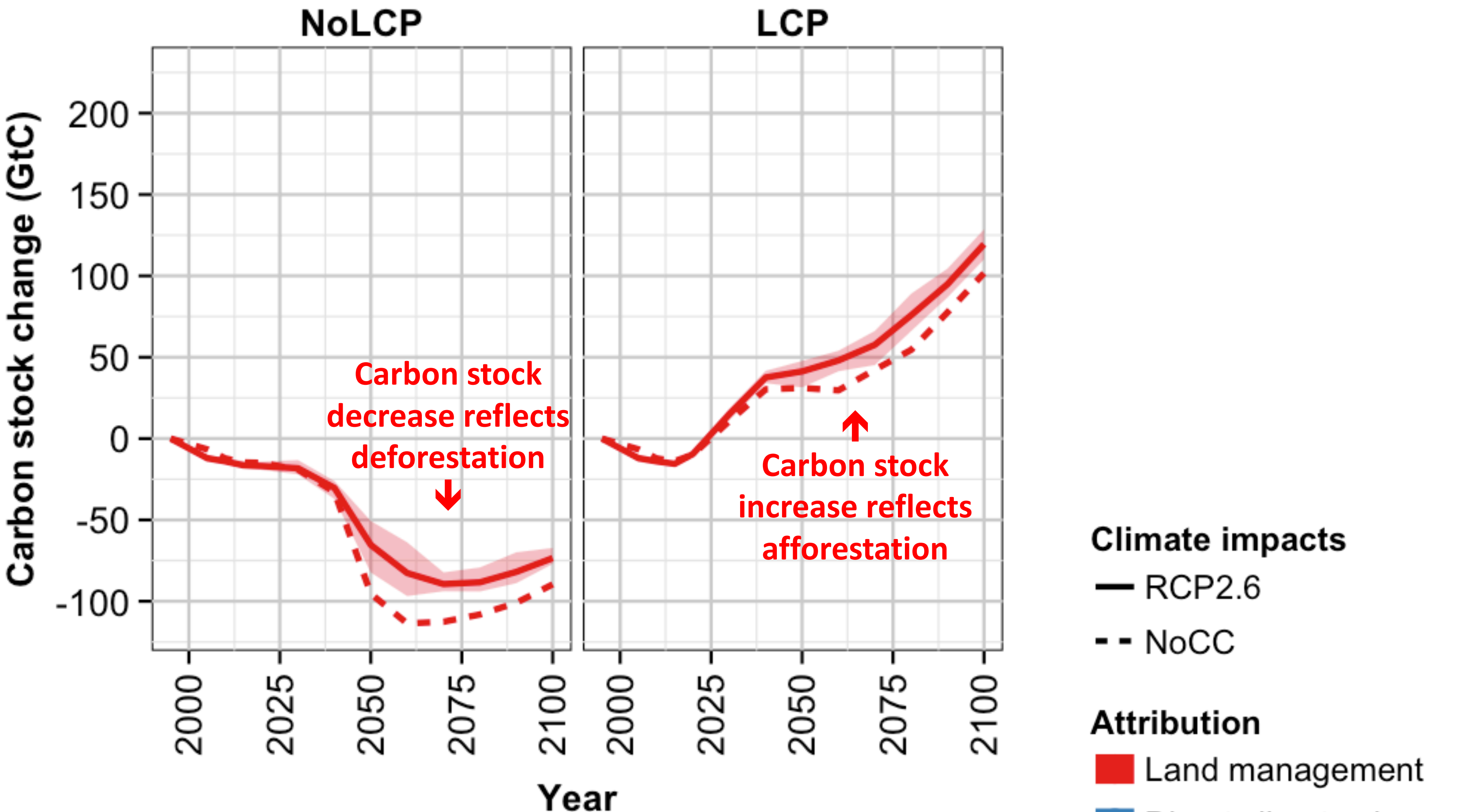
Humpenöder et al. (2015), Environ. Sci. Technol.

Climate impacts under RCP2.6 reduce cropland requirements (positive effect on crop yields)



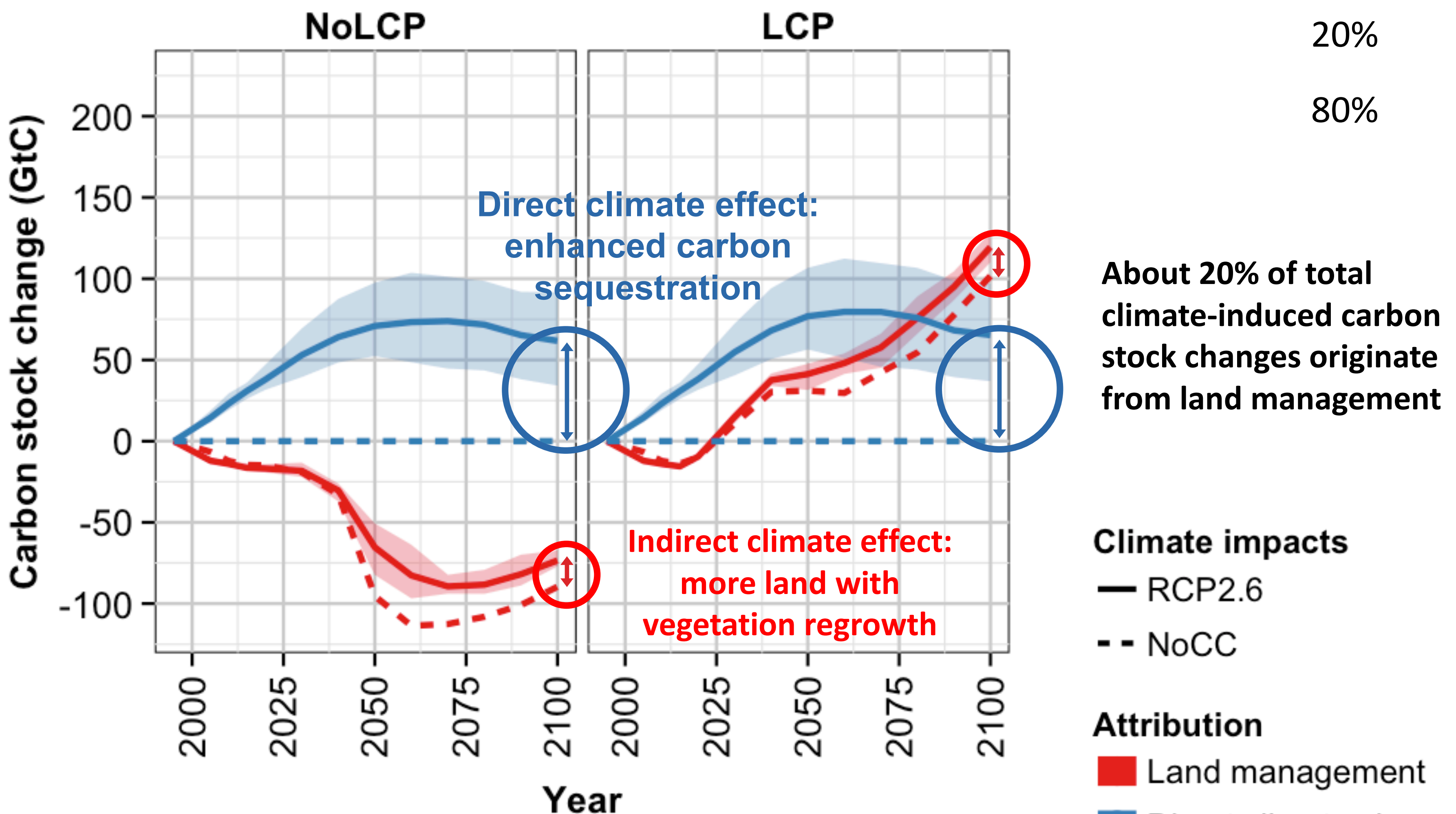
Humpenöder et al. (2015), Environ. Sci. Technol.

Land-based climate policy (LCP) has strong effects on carbon stock dynamics



Humpenöder et al. (2015), Environ. Sci. Technol.

Climate change (RCP2.6) has beneficial effects on global terrestrial carbon stocks



20%

80%

About 20% of total climate-induced carbon stock changes originate from land management

Humpenöder et al. (2015), Environ. Sci. Technol.

CONCLUSIONS

Conclusions

- **Afforestation and bioenergy with CCS could remove considerable amounts of carbon from the atmosphere but have substantially different land requirements**
- **Large-scale land-based mitigation and maintaining food production at the same time would require strong continuous intensification of agricultural production**
- **A moderate increase of the atmospheric CO_2 concentration (RCP2.6) has beneficial effects on global terrestrial carbon stocks, but does not further increase the potential of land-based mitigation**
- **Future analysis of mitigation pathways in IAMs should consider land-use and associated carbon cycle responses to climate change**

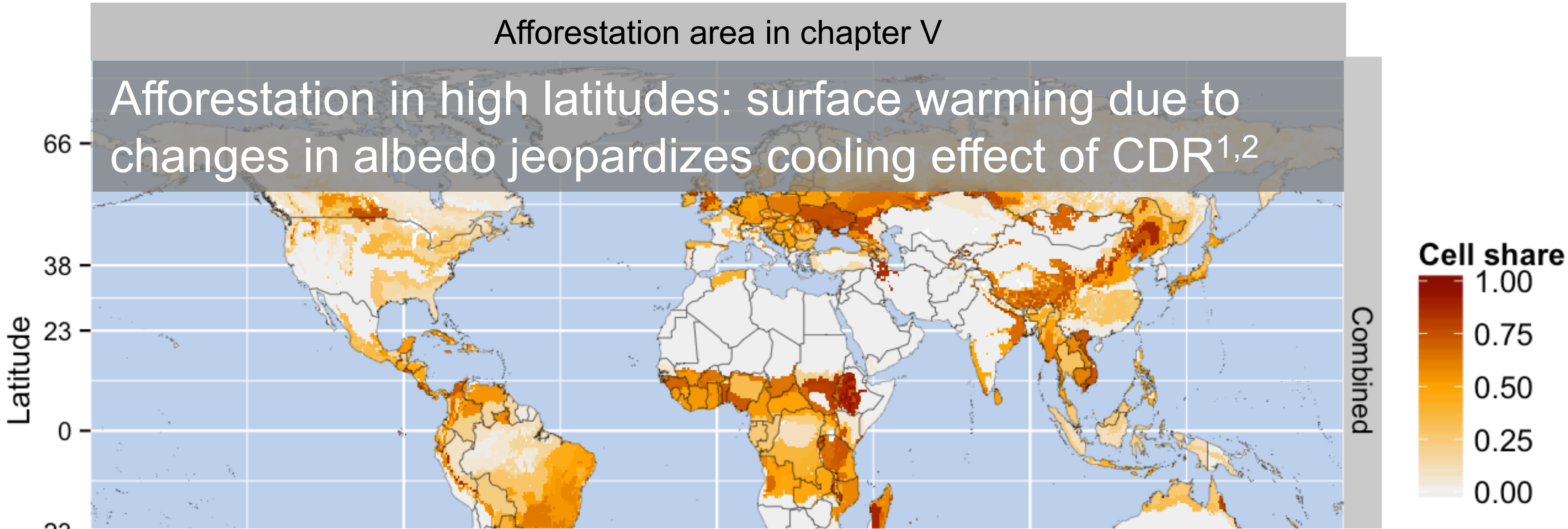
OUTLOOK

Outlook

- **Accounting for surface albedo effects of afforestation**

Afforestation and surface albedo effects

Afforestation in high latitudes: surface warming due to changes in albedo jeopardizes cooling effect of CDR[1,2]



	Chapter V (no restriction)	Chapter VI (boreal excluded)	Difference
Afforestation area	2566 Mha	1489 Mha	42%
CDR	409 $GtCO_2$	370 $GtCO_2$	10%

[1]Schaeffer M, Eickhout B, Hoogwijk M, Strengers B, van Vuuren D, Leemans R and Opsteegh T 2006 CO2 and albedo climate impacts of extratropical carbon and biomass plantations, Global Biogeochemical Cycles
[2]Bala G, Caldeira K, Wickett M, Phillips T J, Lobell D B, Delire C and Mirin A 2007 Combined climate and carbon-cycle effects of large-scale deforestation *PNAS* **104** 6550–5

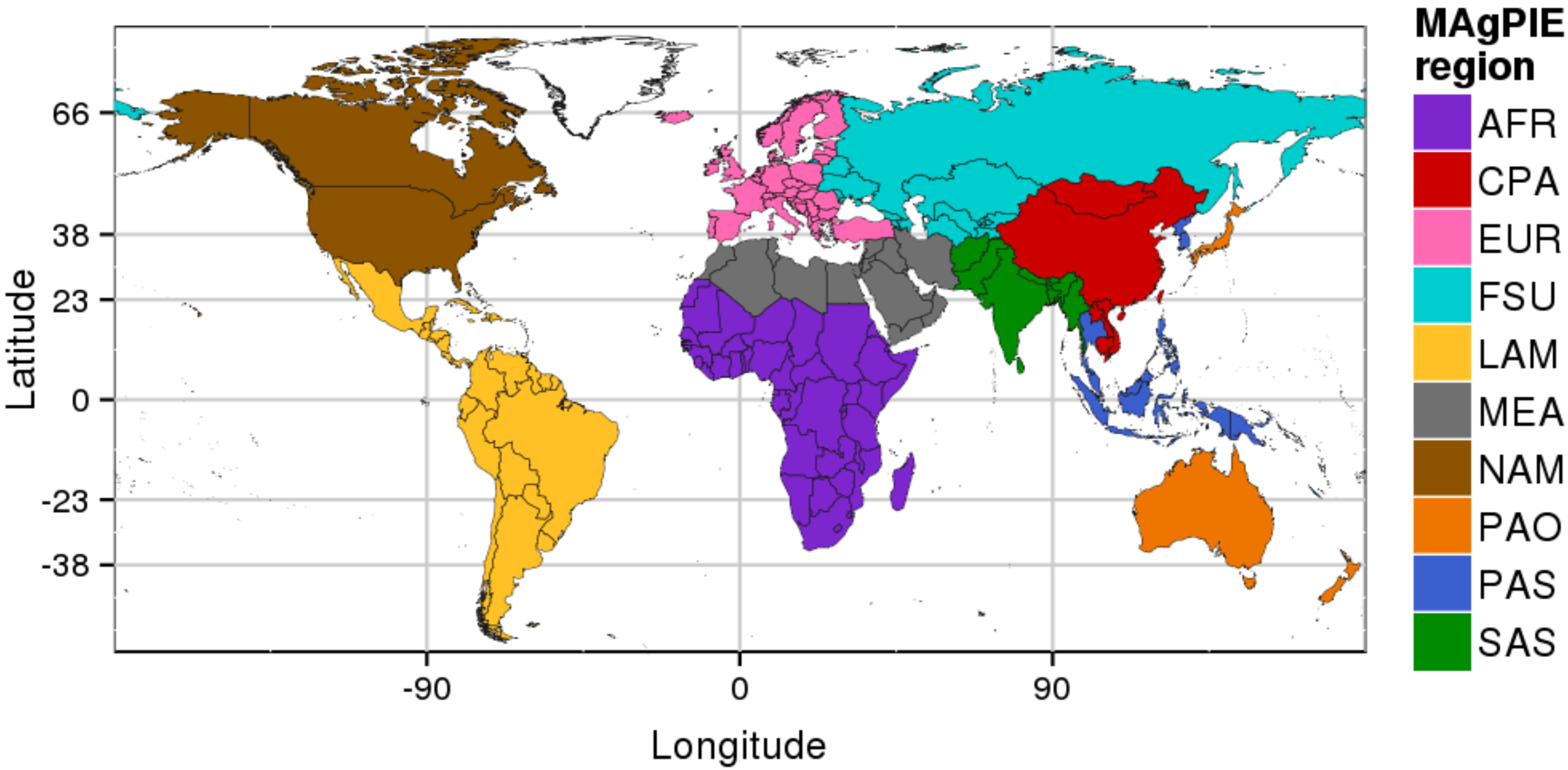
Outlook

- **Accounting for surface albedo effects of afforestation**
- **Permanence of terrestrial carbon sinks**
- **Exploring interactions of land-based mitigation with options in other sectors**
- **Food security issues of large-scale land-based mitigation**

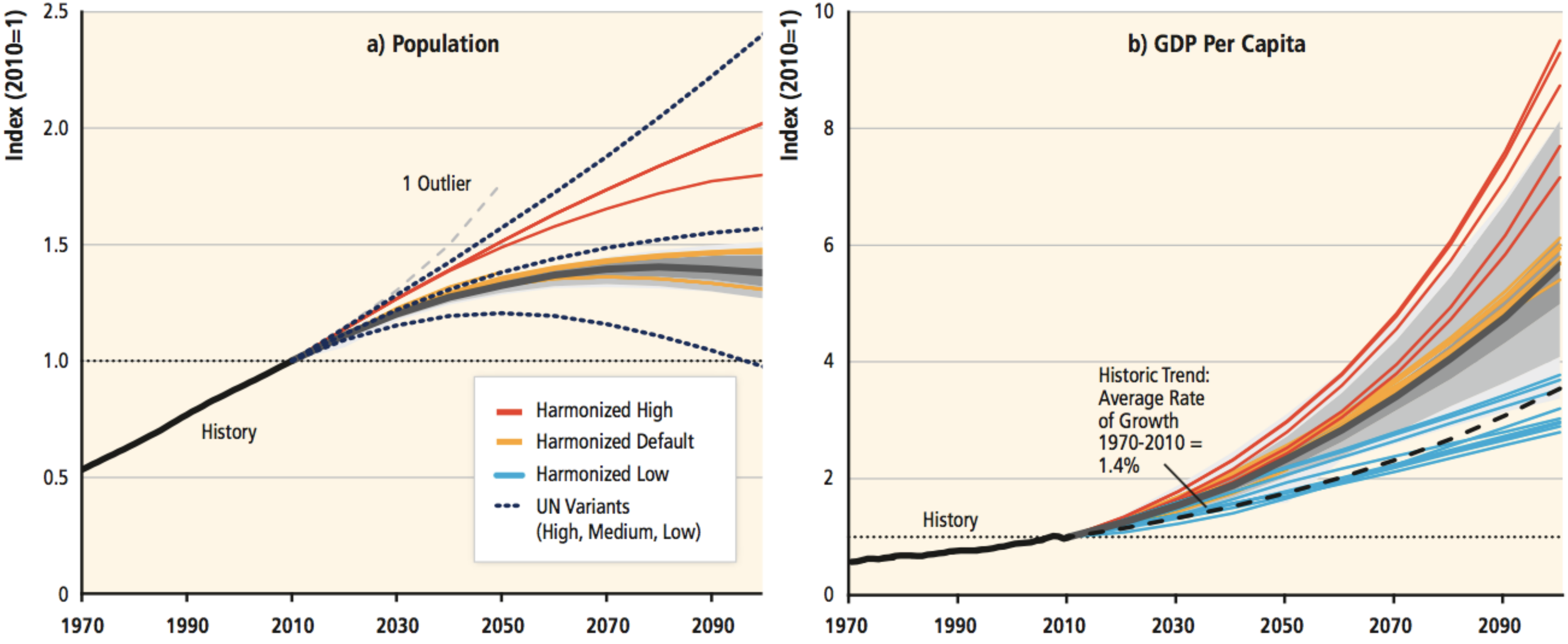
THANK YOU FOR YOUR ATTENTION

BACKUP SLIDES

MAgPIE world regions

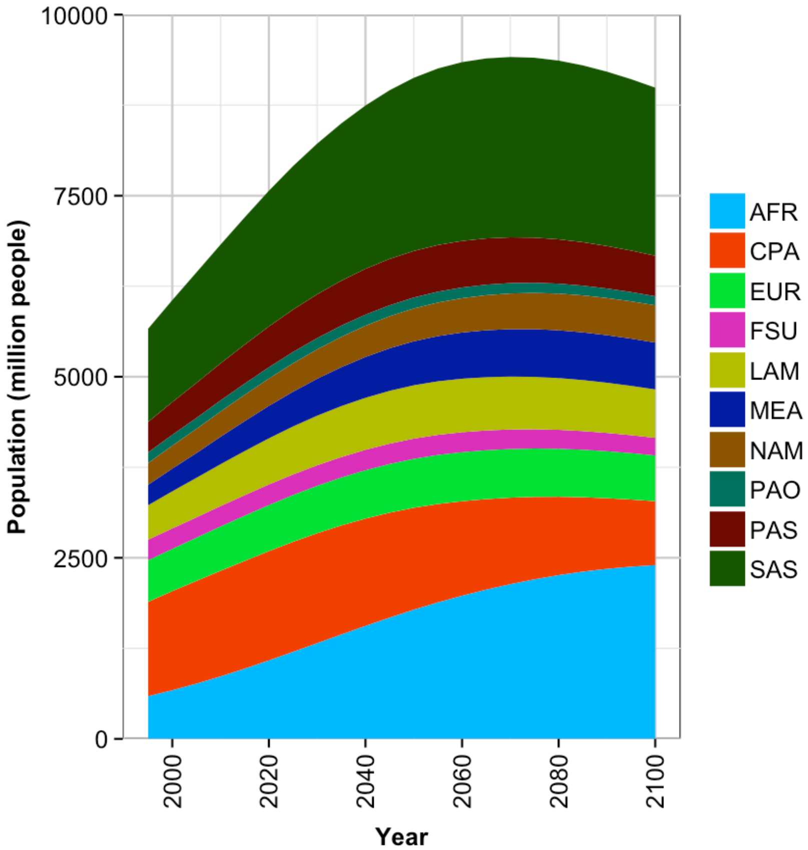


Population and GDP projections

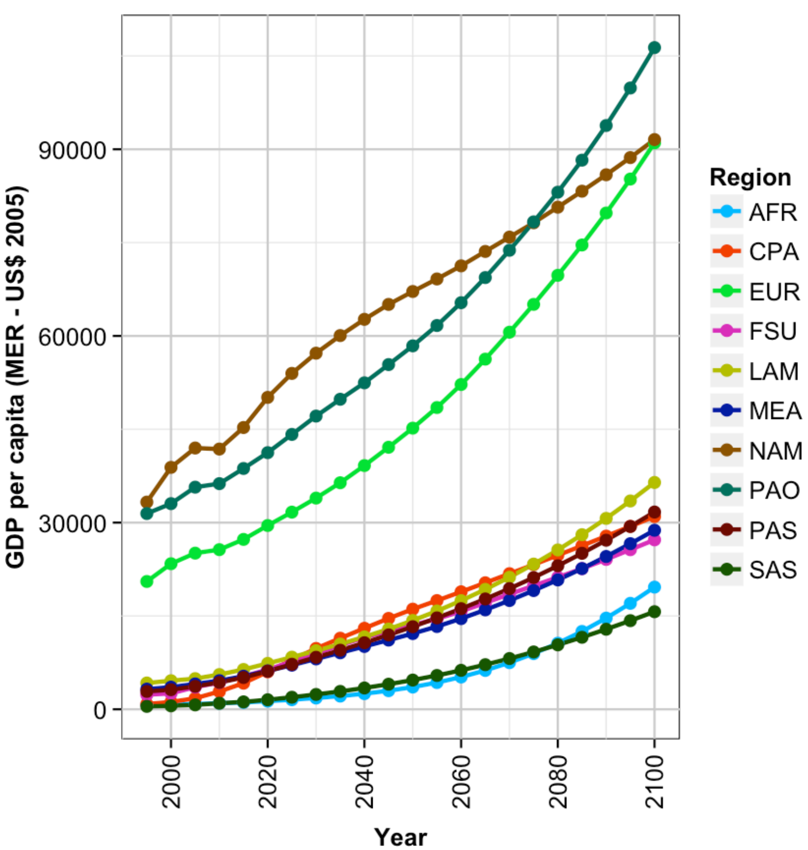


IPCC AR5 WG III, based on Fig. TS.7

Population (SSP2)

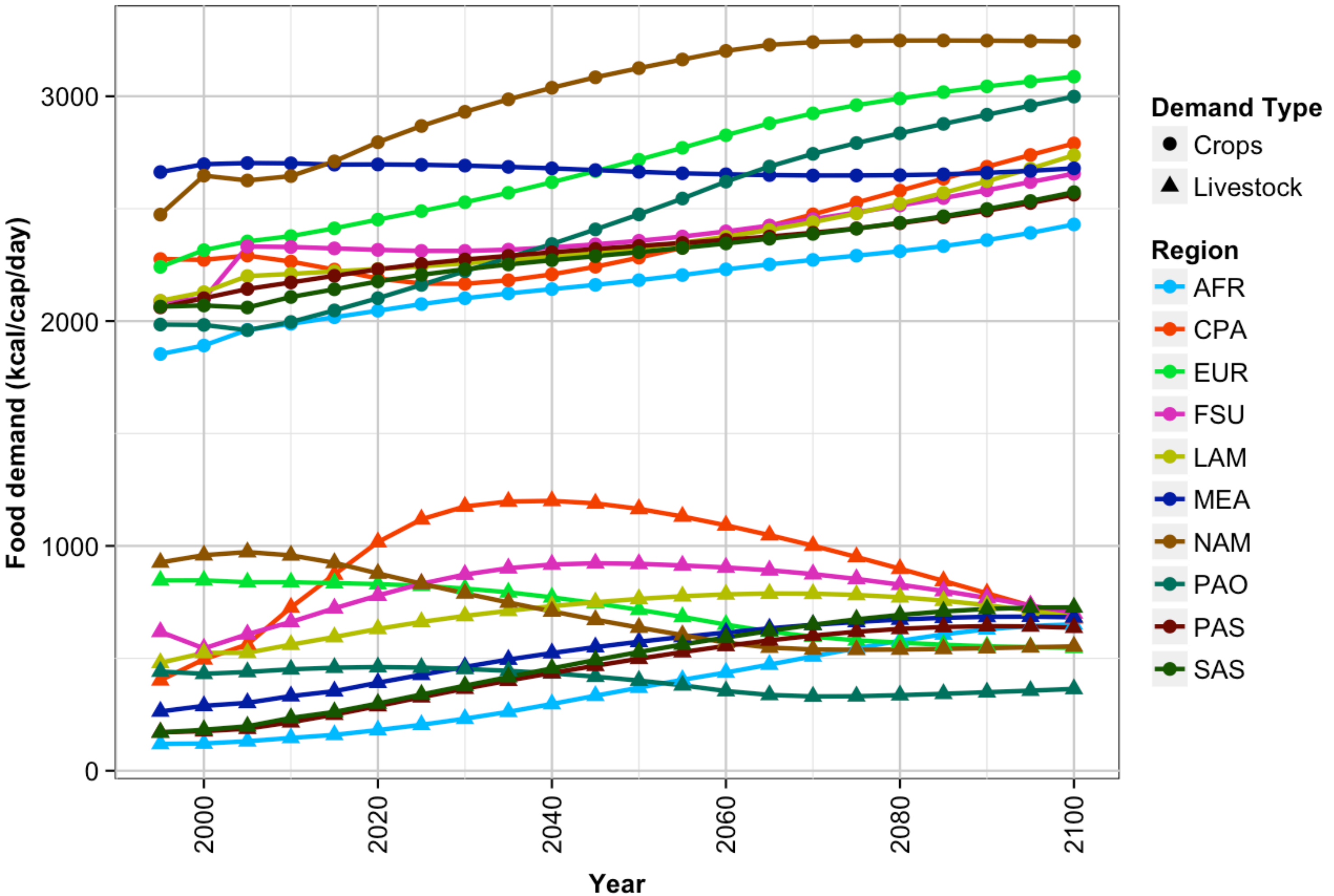


GDP per capita (SSP2)

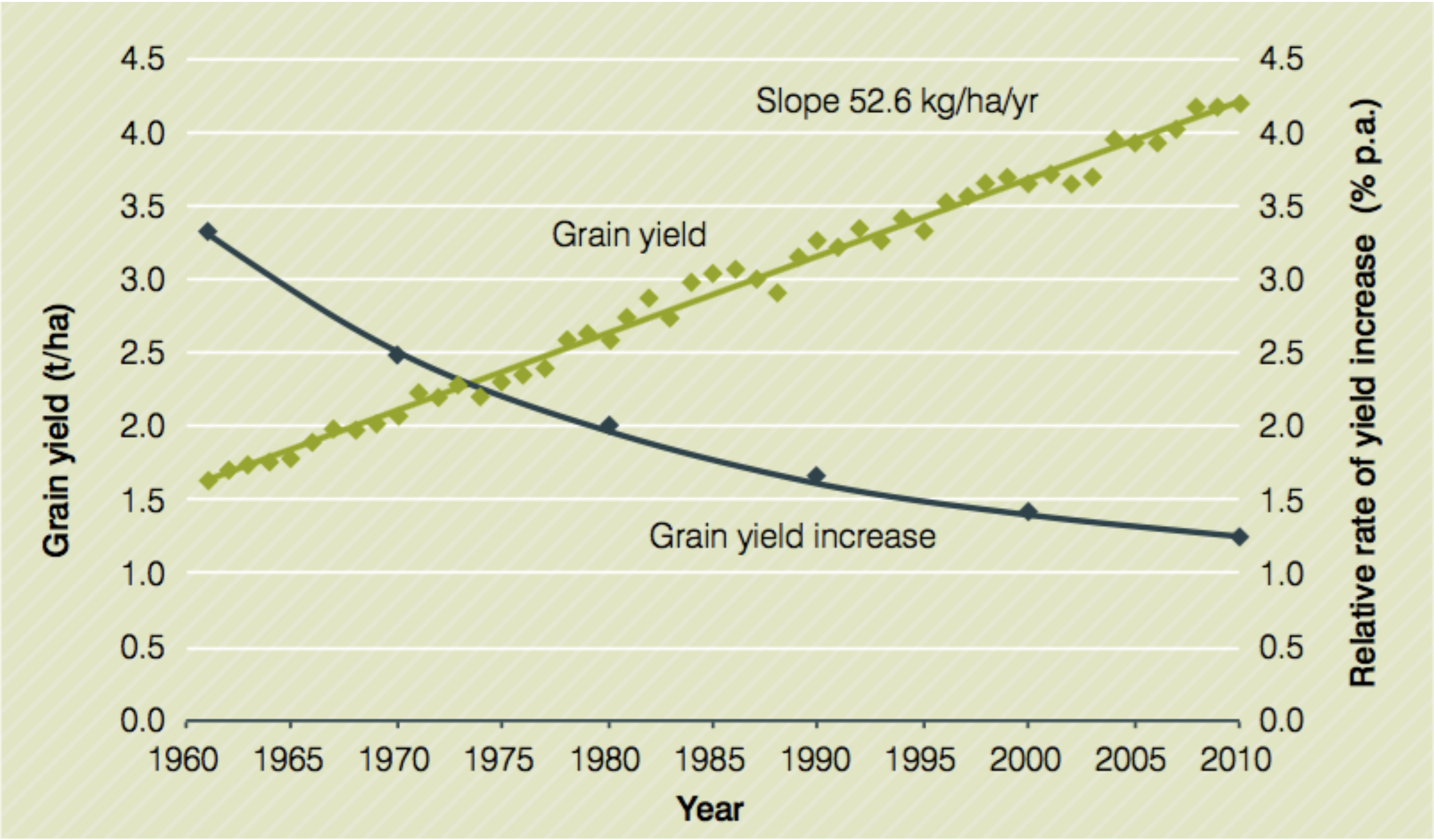


Based on Humpenöder et al. (2014), Environ. Research Letters

Food demand per capita (SSP2)

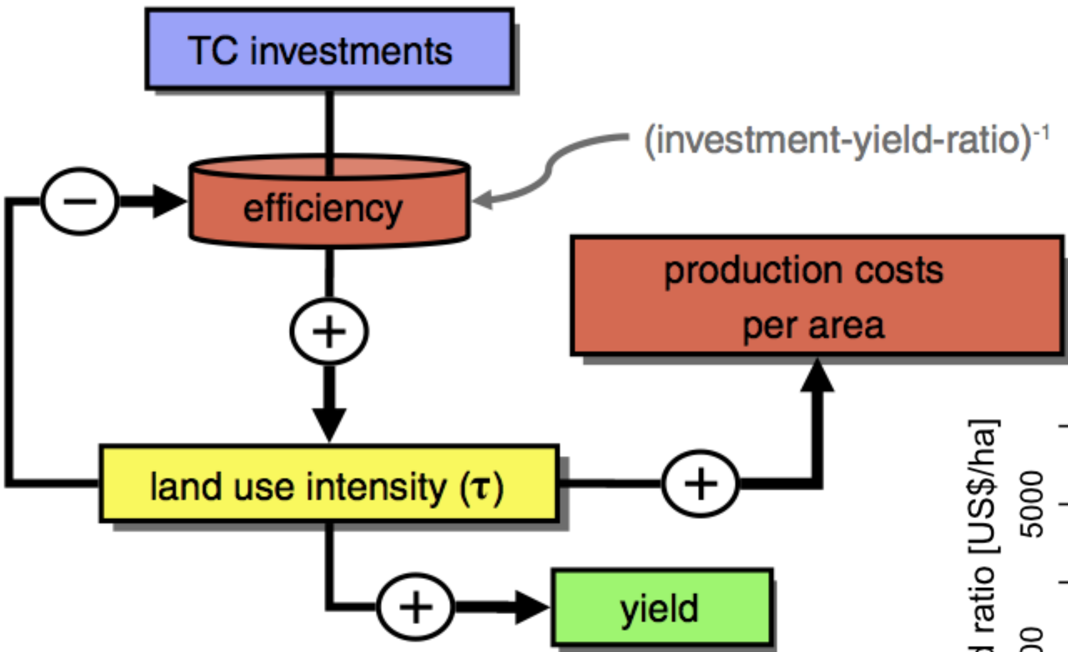


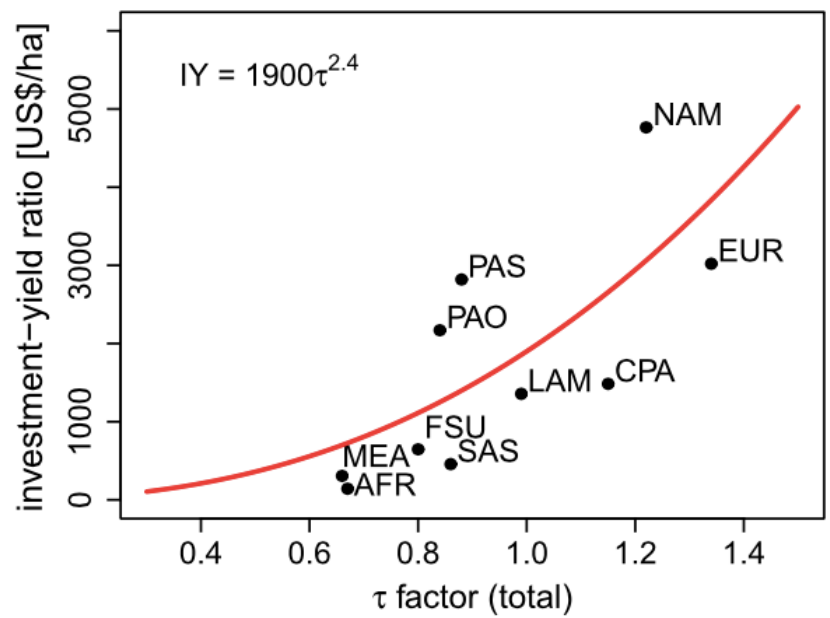
Historical development of grain yields



Fischer T, Byerlee D and Edmeades G 2014 Crop yields and global food security: Will yield increase continue to feed the world? ACIAR Monograph 2014; 158. Australian Centre for International Agricultural Research; Data based on FAOSTAT (2013)

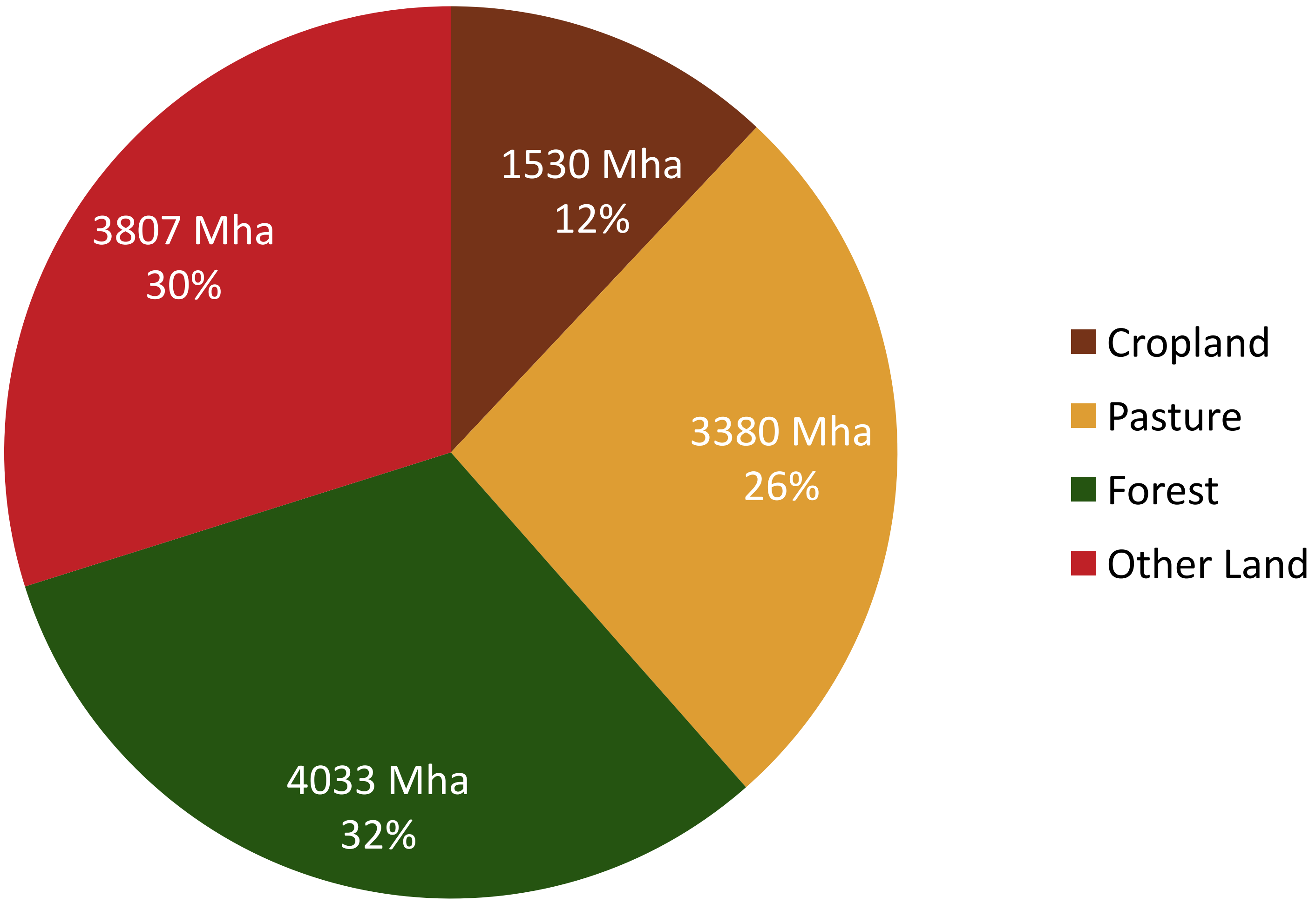
TC in MAgPIE





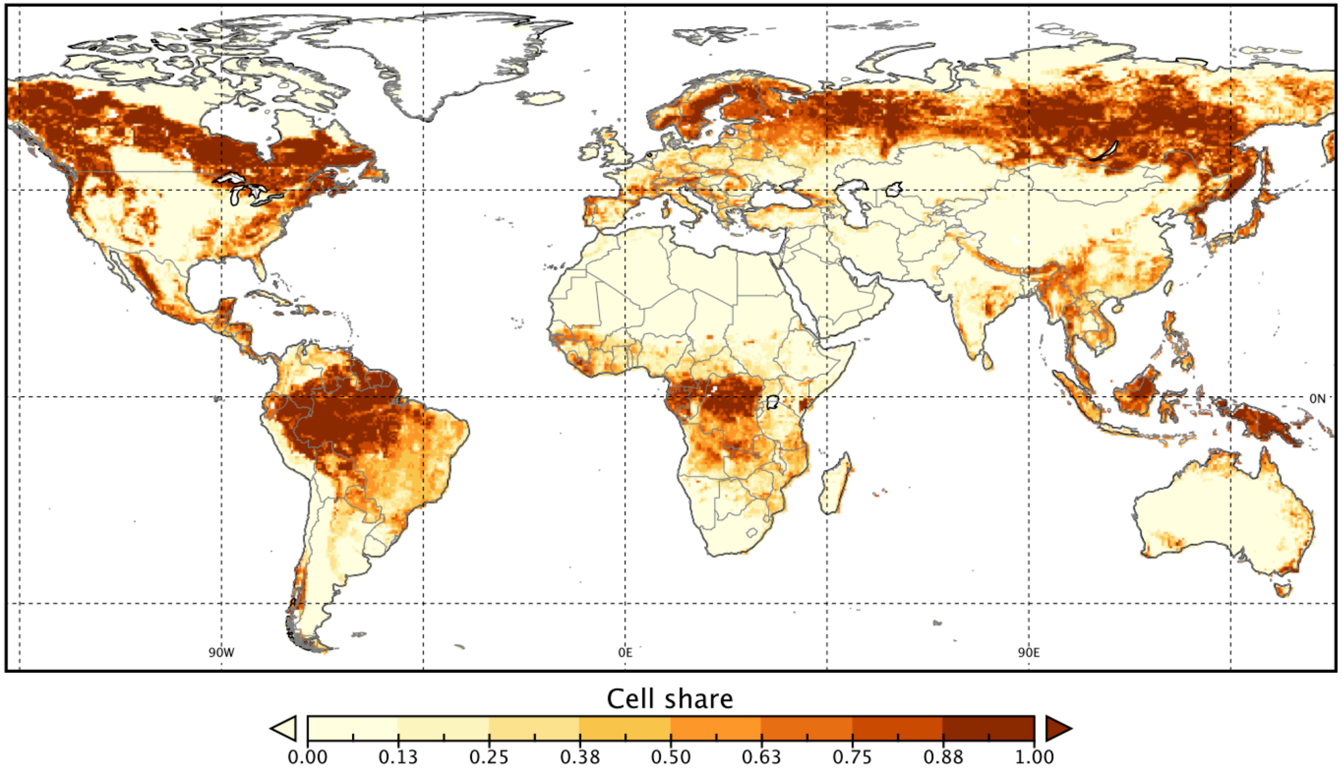
Dietrich J P, Schmitz C, Lotze-Campen H, Popp A and Müller C 2014 Forecasting technologica
change in agriculture—An endogenous implementation in a global land use model
Technological Forecasting and Social Change 81 236–49

Current global land-use



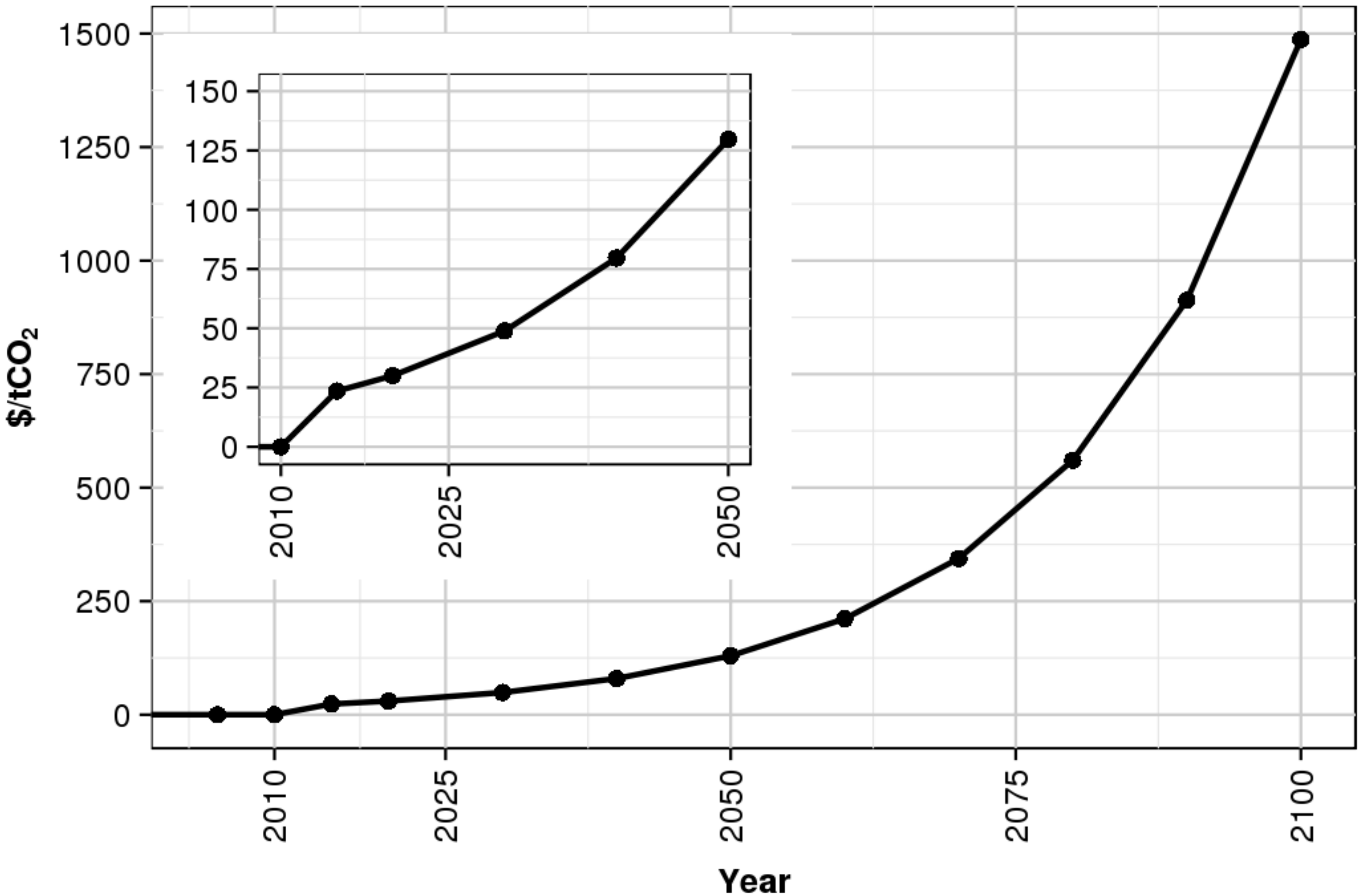
Own illustration based on Foley et al (2011), Ramankutty et al (2008) and FAO (2010)

Global forest cover in the year 2000

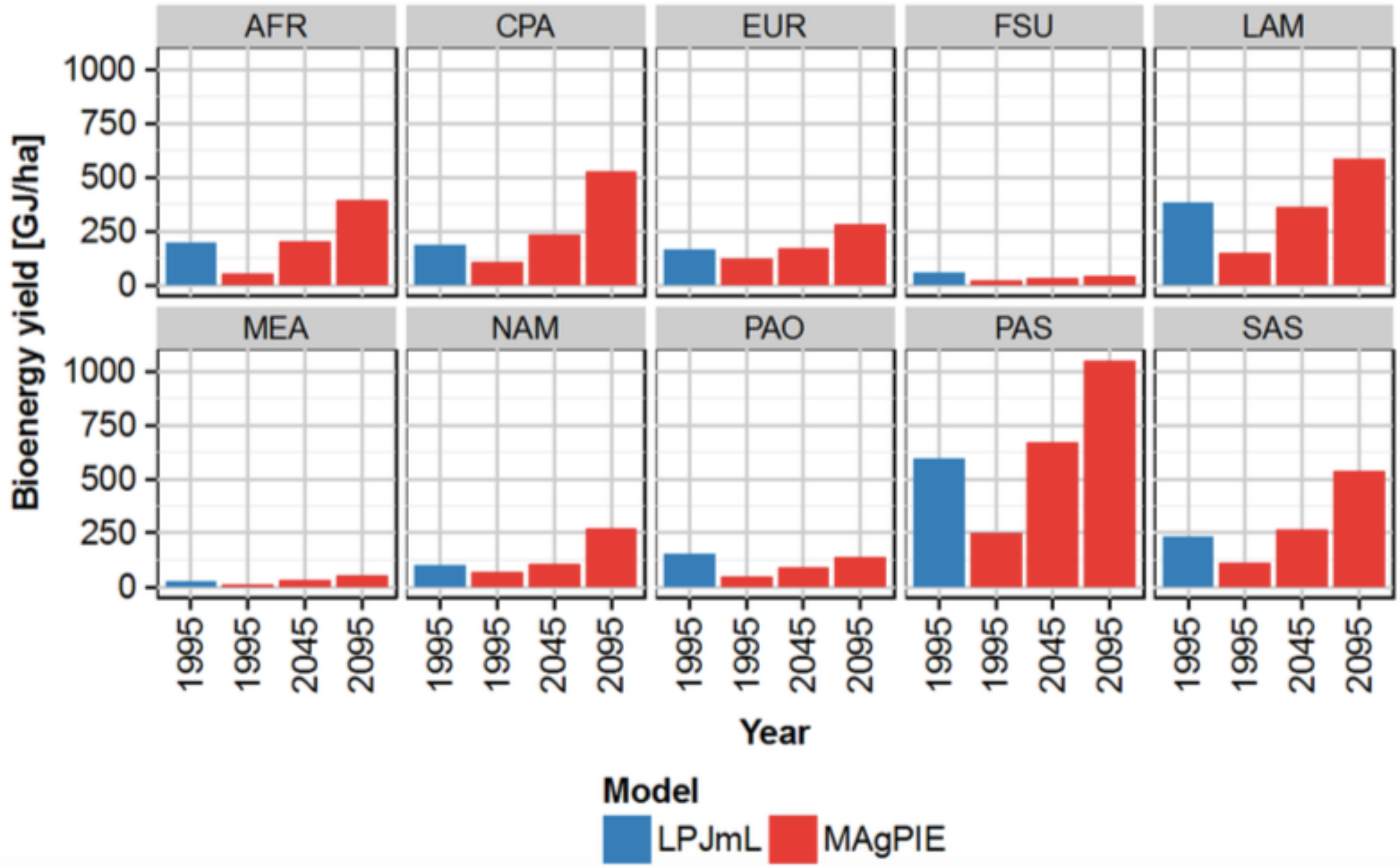


Based on Erb K-H, Gaube V, Krausmann F, Plutzar C, Bondeau A and Haberl H 2007 A comprehensive global 5 min resolution land-use data set for the year 2000 consistent with national census data *Journal of Land Use Science* **2** 191–224

CO2 price trajectory



Herbaceous bioenergy yields (AFF+BECCS)



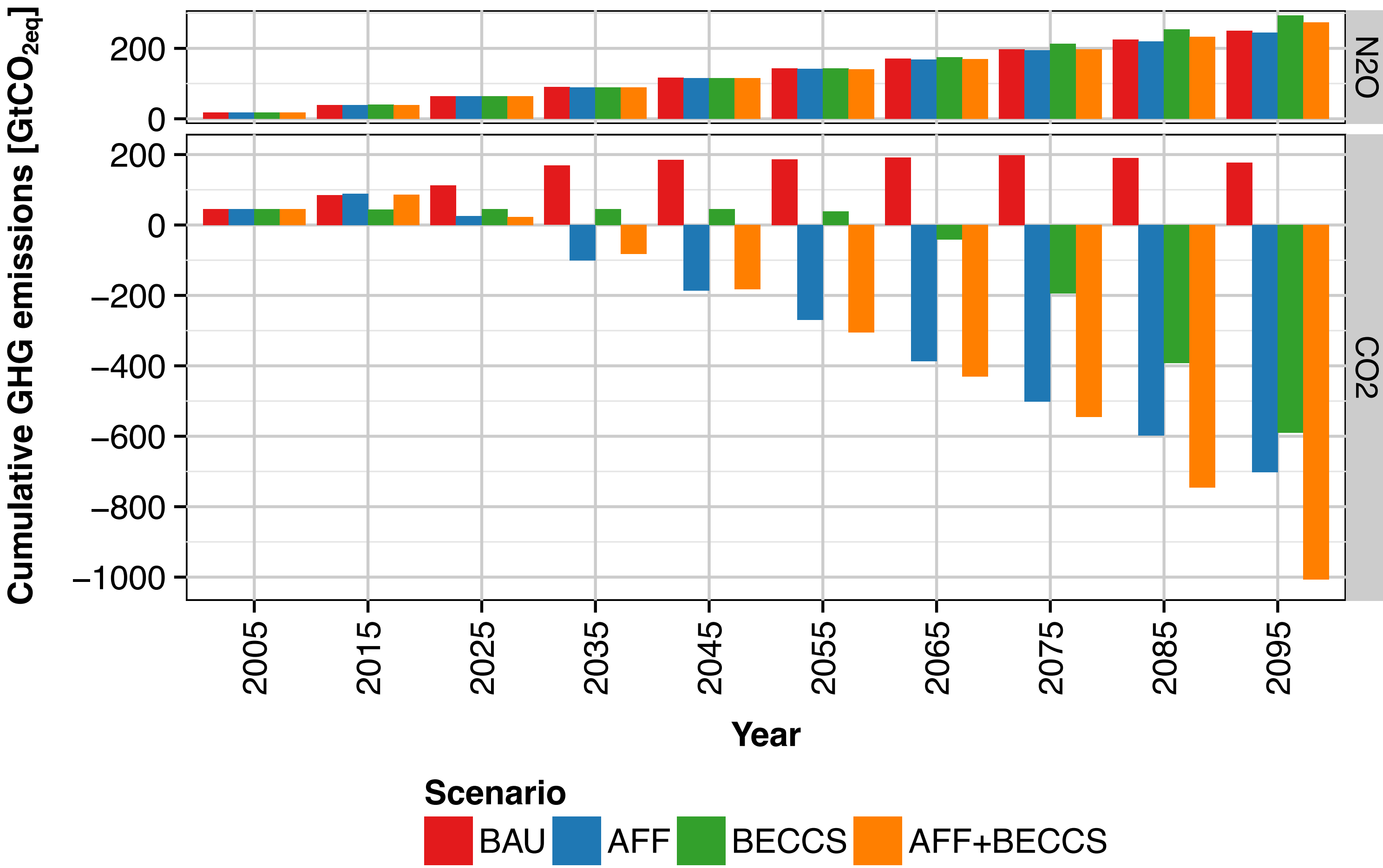
Humpenöder et al. (2014), Environ. Research Letters

Biomass conversion routes with CCS in MAgPIE

- **Biomass to Hydrogen (B2H2)**
  - **capture rate 90%, conversion efficiency 55%**
- **Biomass Integrated Gasification Combined Cycle (BIGCC)**
  - **capture rate 80%, conversion efficiency 31%**
- **Biomass to Liquid (B2L)**
  - **capture rate 48%, conversion efficiency 41%**

Humpenöder et al. (2014), Environ. Research Letters

GHG emissions



Sensitivity analysis of land-use and CDR

CCS capacity

- Low: 198 $GtCO_2$
- Default: 3960 $GtCO_2$
- High: 79200 $GtCO_2$

GHG tax (growth rate 5%)

- Low: 5 $/$tCO_2$
- Default: 30 $/$tCO_2$
- High: 50 $/$tCO_2$

Discount rate

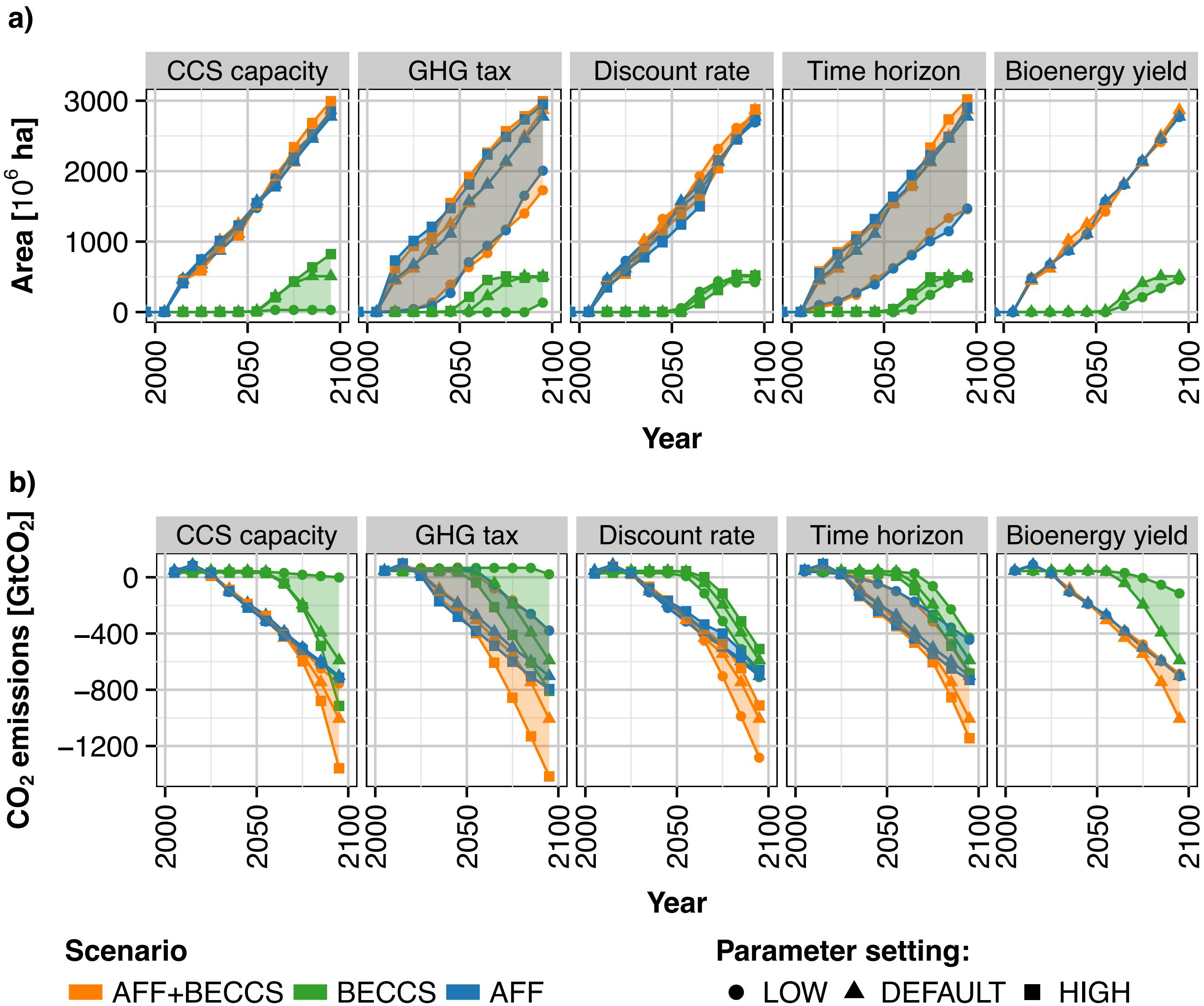
- Low: 4%
- Default: 7%
- High: 10%

Time horizon

- Low: 10 years
- Default: 30 years
- High: 50 years

Bioenergy yield

- Low: No TC on bioenergy crops
- Default: TC on food and bioenergy crops



Sensitivity analysis of herbaceous and woody bioenergy production (2095)

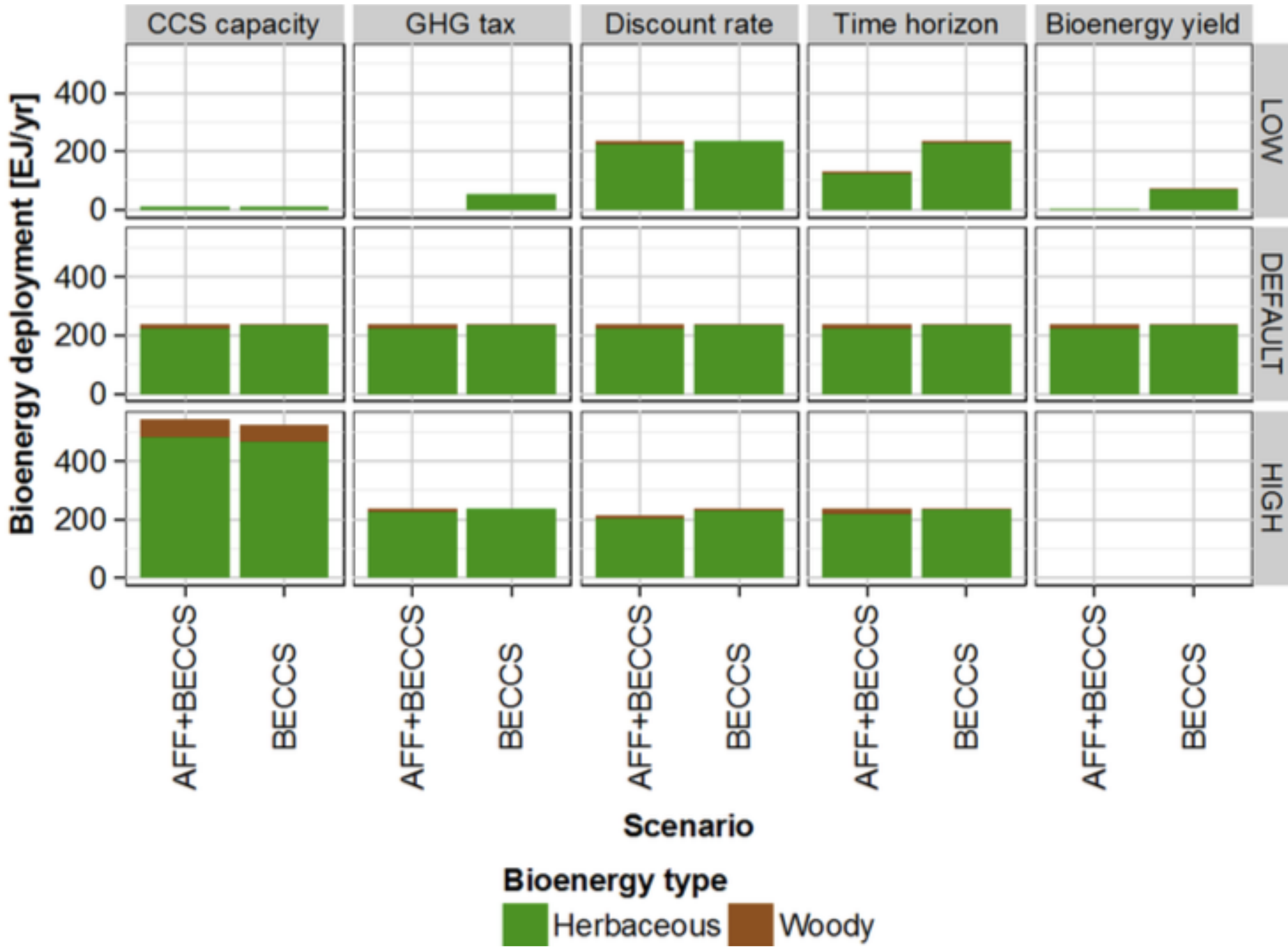
CCS capacity
- Low: 198 $GtCO_2$
- Default: 3960 $GtCO_2$
- High: 79200 $GtCO_2$

GHG tax (growth rate 5%)
- Low: 5 $/$tCO_2$
- Default: 30 $/$tCO_2$
- High: 50 $/$tCO_2$

Discount rate
- Low: 4%
- Default: 7%
- High: 10%

Time horizon
- Low: 10 years
- Default: 30 years
- High: 50 years

Bioenergy yield
- Low: No TC on bioenergy crops
- Default: TC on food and bioenergy crops



Sensitivity analysis of global bioenergy production

CCS capacity
- Low: 198 $GtCO_2$
- Default: 3960 $GtCO_2$
- High: 79200 $GtCO_2$

GHG tax (growth rate 5%)
- Low: 5 $/tCO_2$
- Default: 30 $/tCO_2$
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Bioenergy yield
- Low: No TC on bioenergy crops
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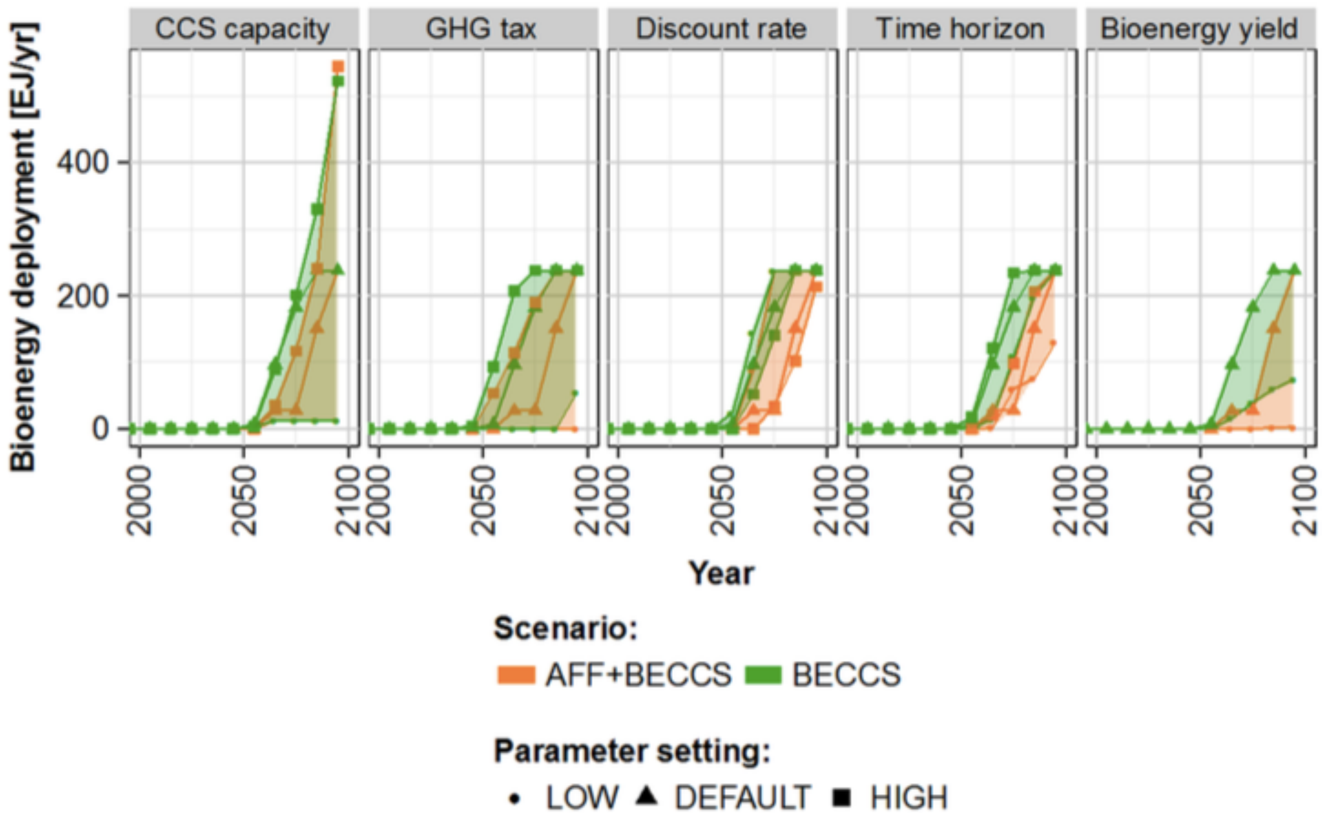
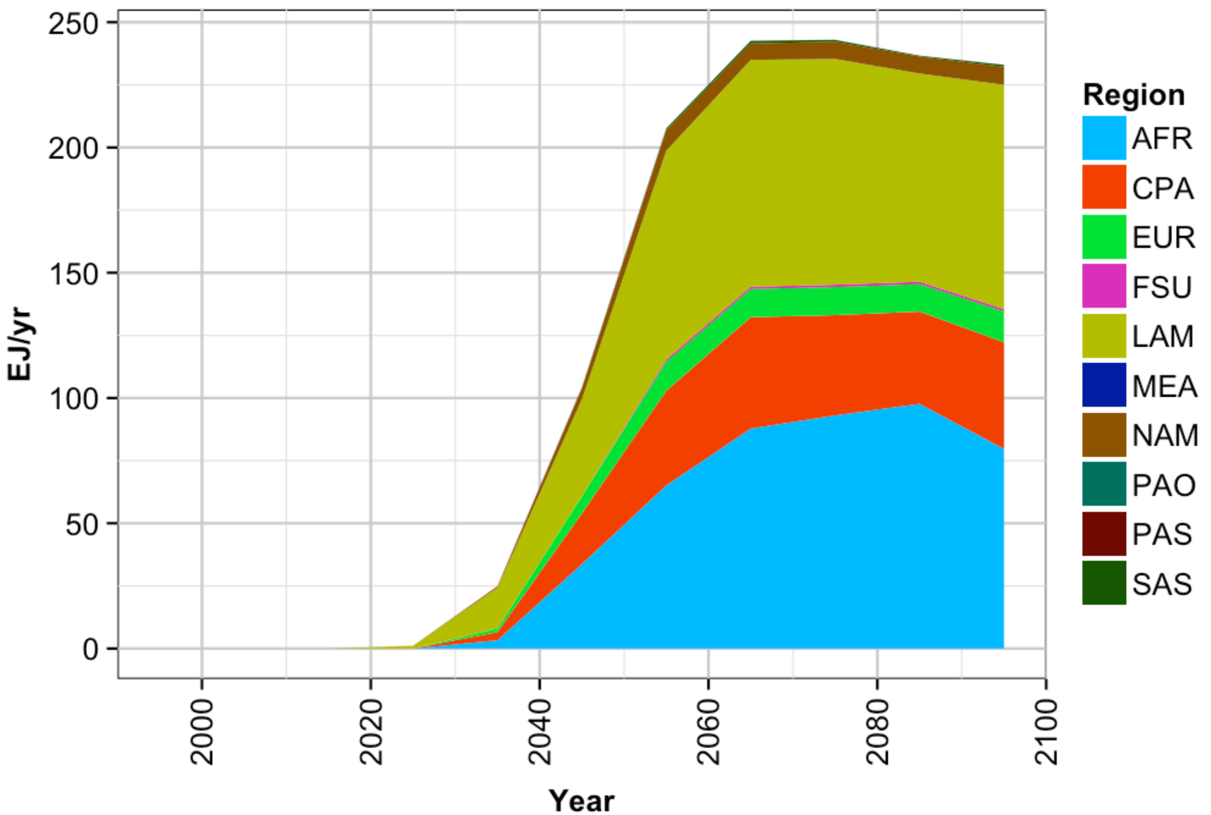
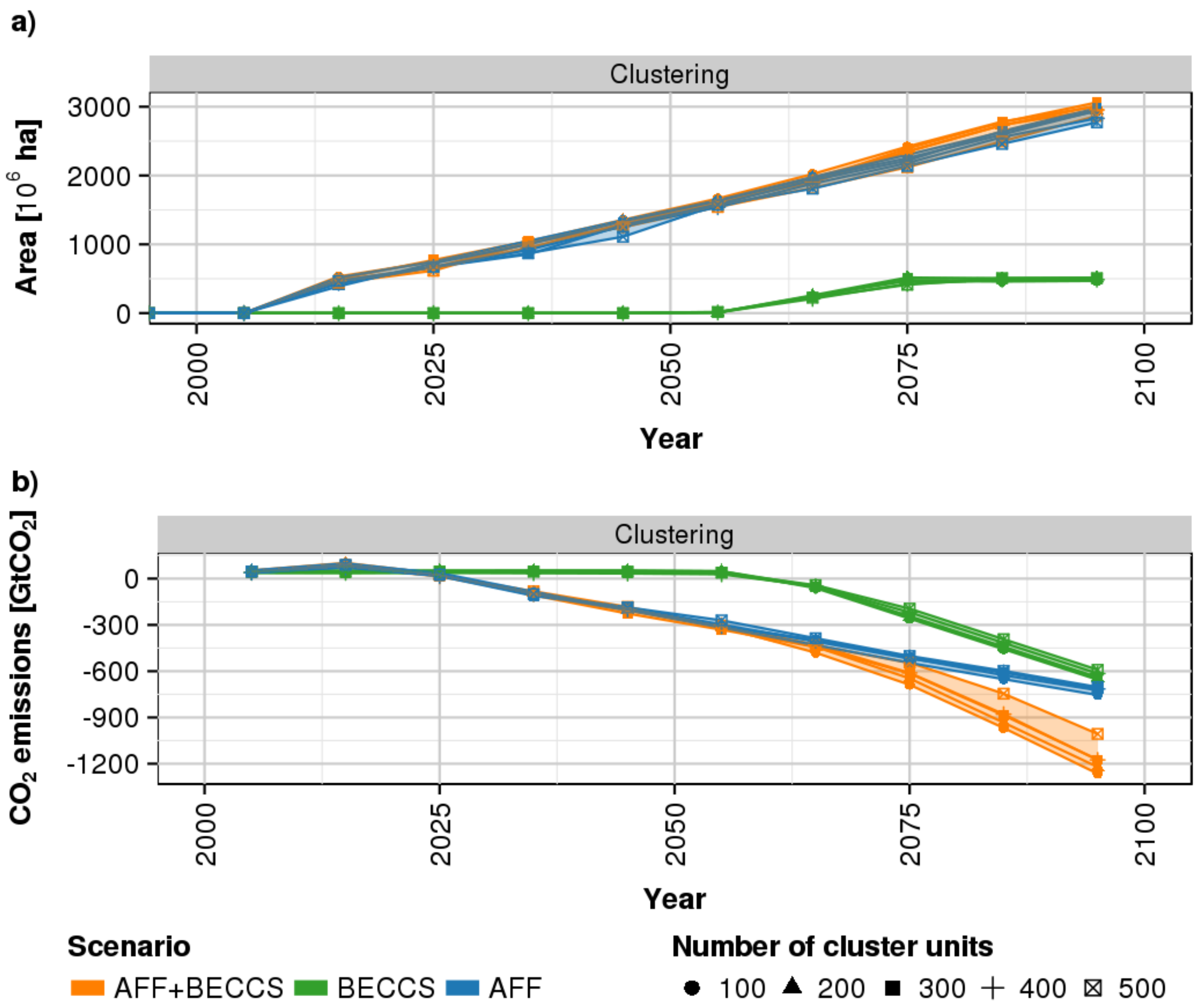


Exogenous bioenergy demand in Chapter VI (450 ppm scenario from REMIND)

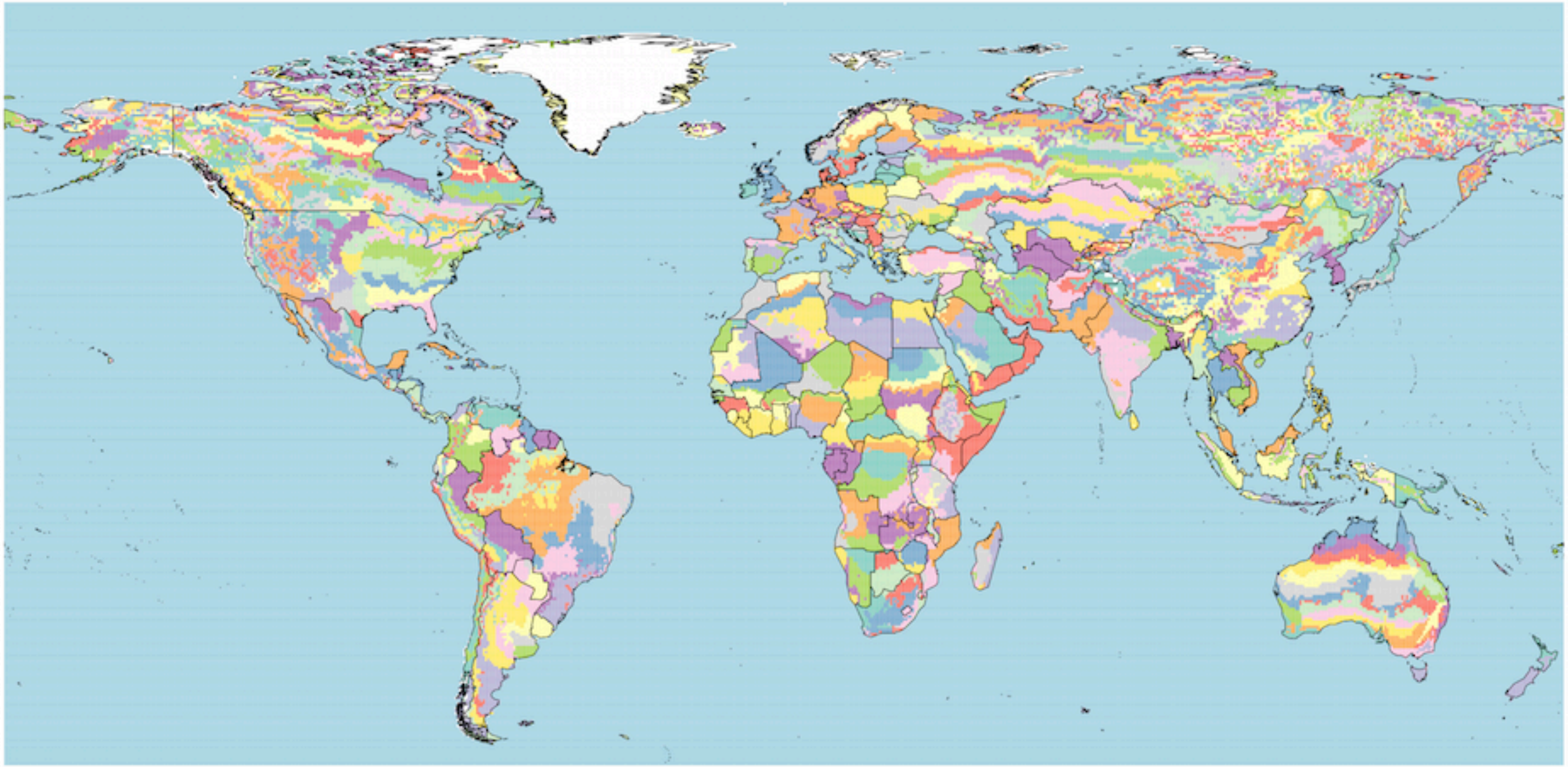


Popp A, Rose S K, Calvin K, van Vuuren D P, Dietrich J P, Wise M, Stehfest E, Humpenöder F, Kyle P, Vliet J V, Bauer N, Lotze-Campen H, Klein D and Kriegler E 2014 Land-use transition for bioenergy and climate stabilization: model comparison of drivers, impacts and interactions with other land use based mitigation options Climatic Change 123 495–509

Sensitivity analysis of cluster / simulation units

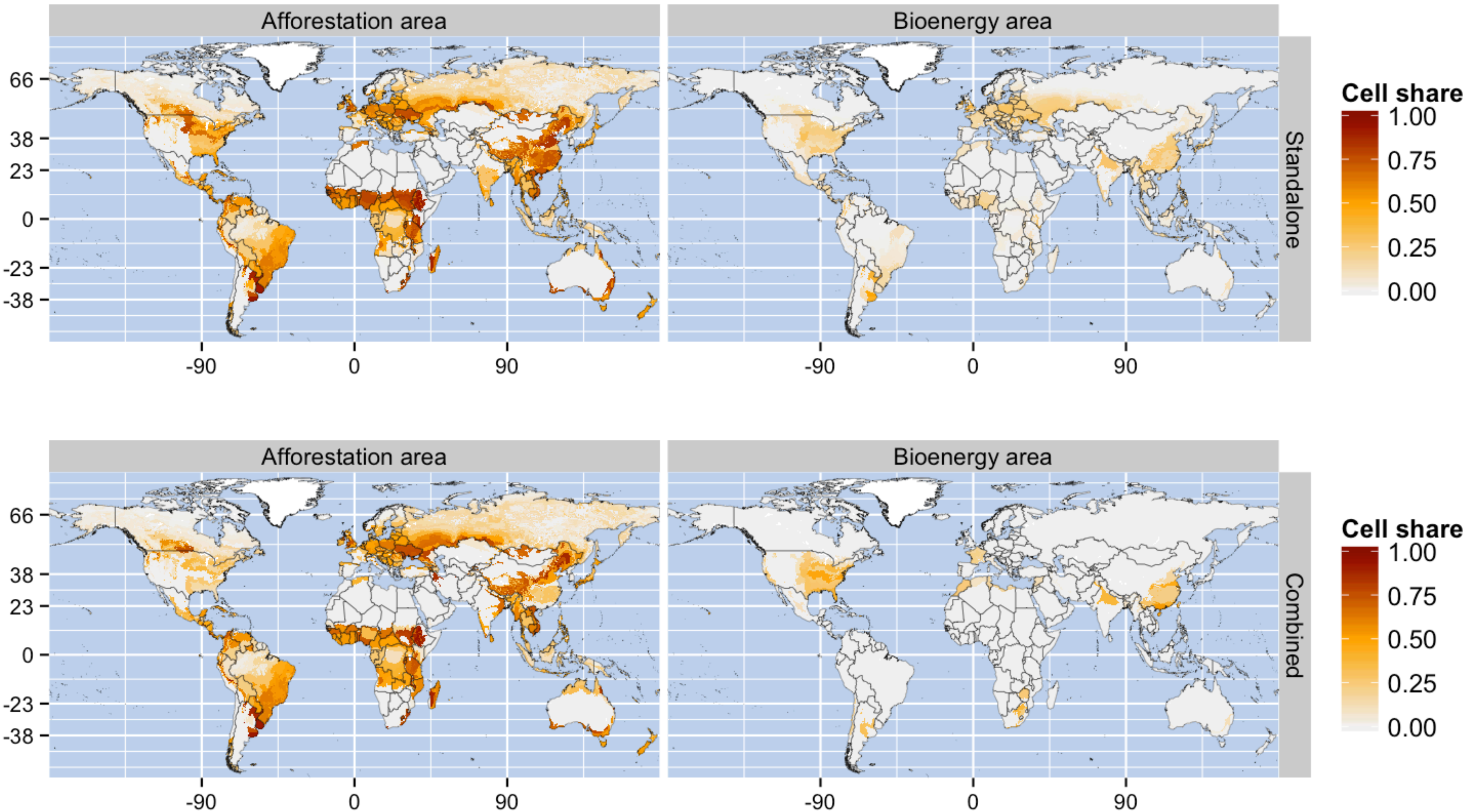


MAgPIE cellular level (500 clusters / simulation units)



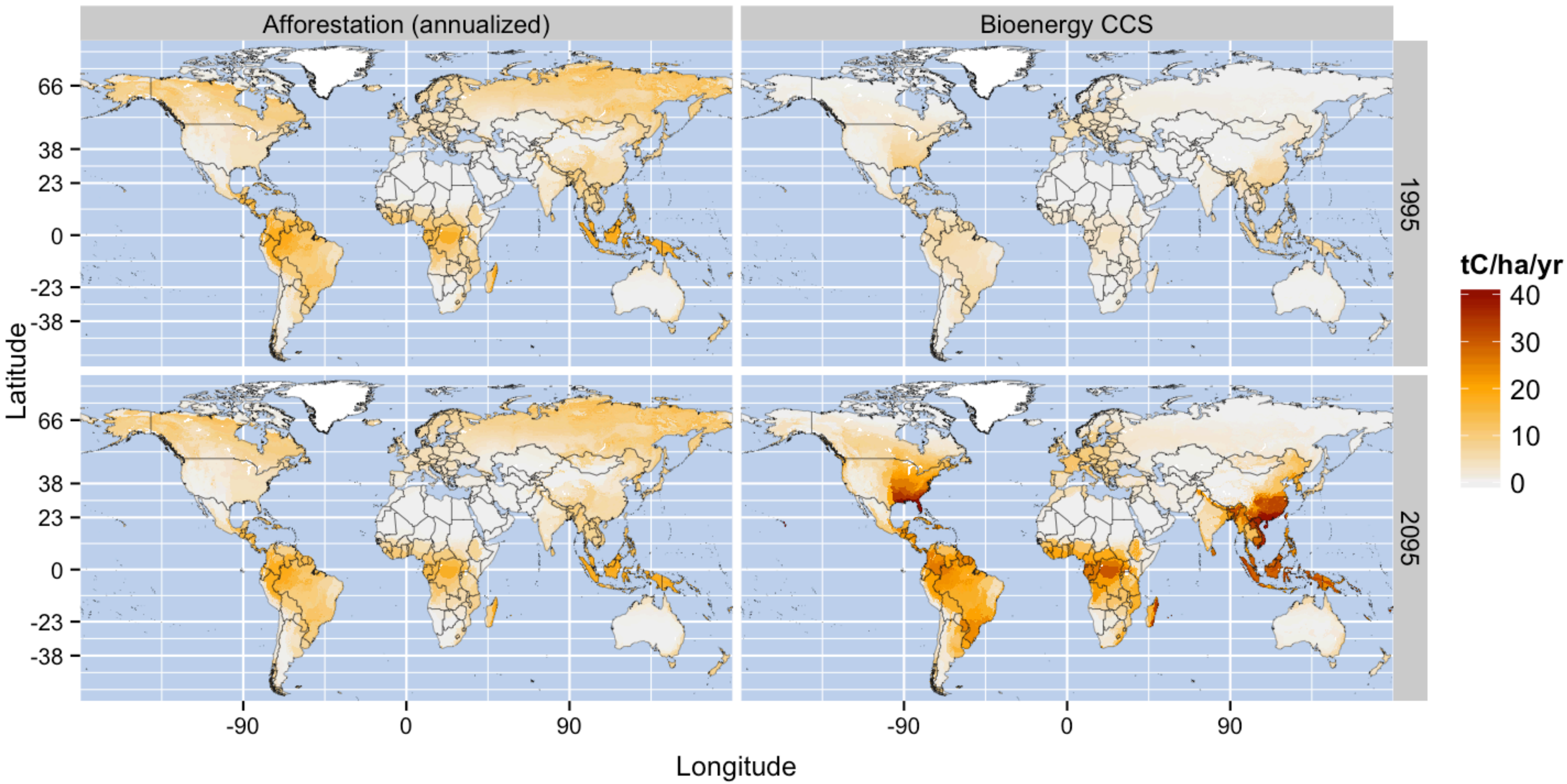
Based on Humpenöder et al. (2014), Environ. Research Letters

Afforestation and bioenergy area in 2095

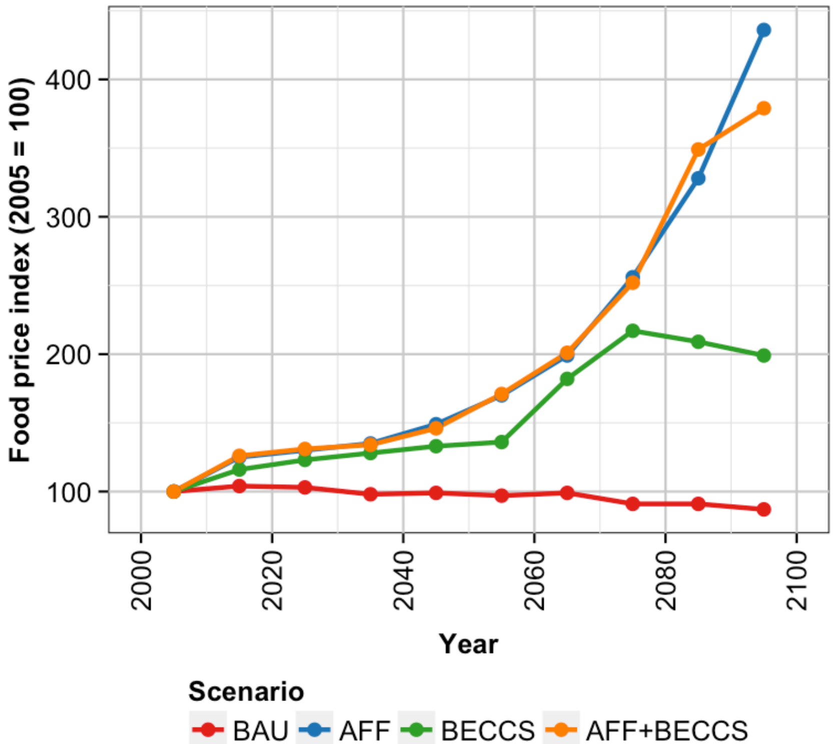


Humpenöder et al. (2014), Environ. Research Letters

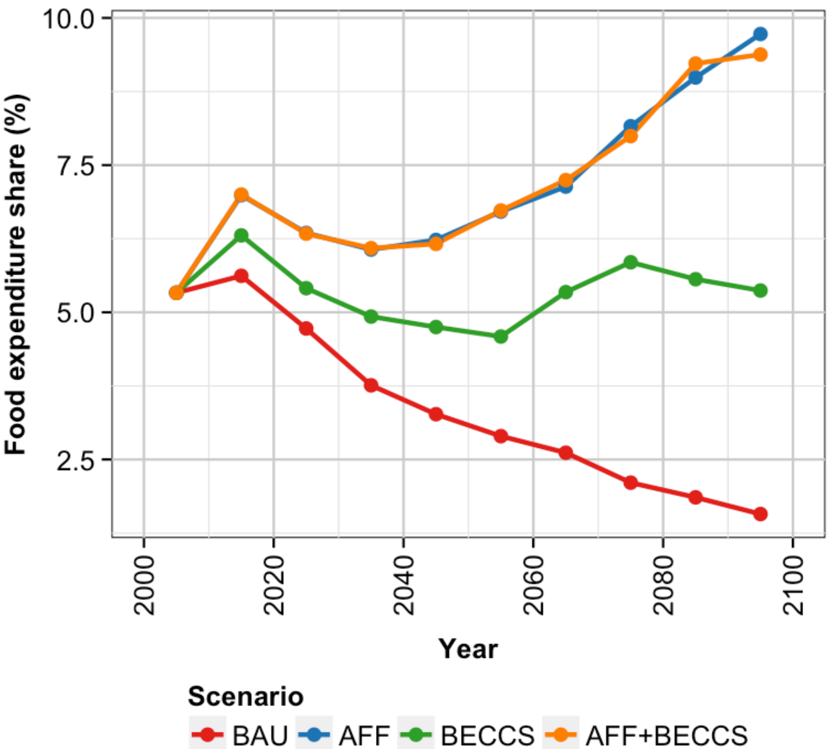
Potential CDR rates



Food price index

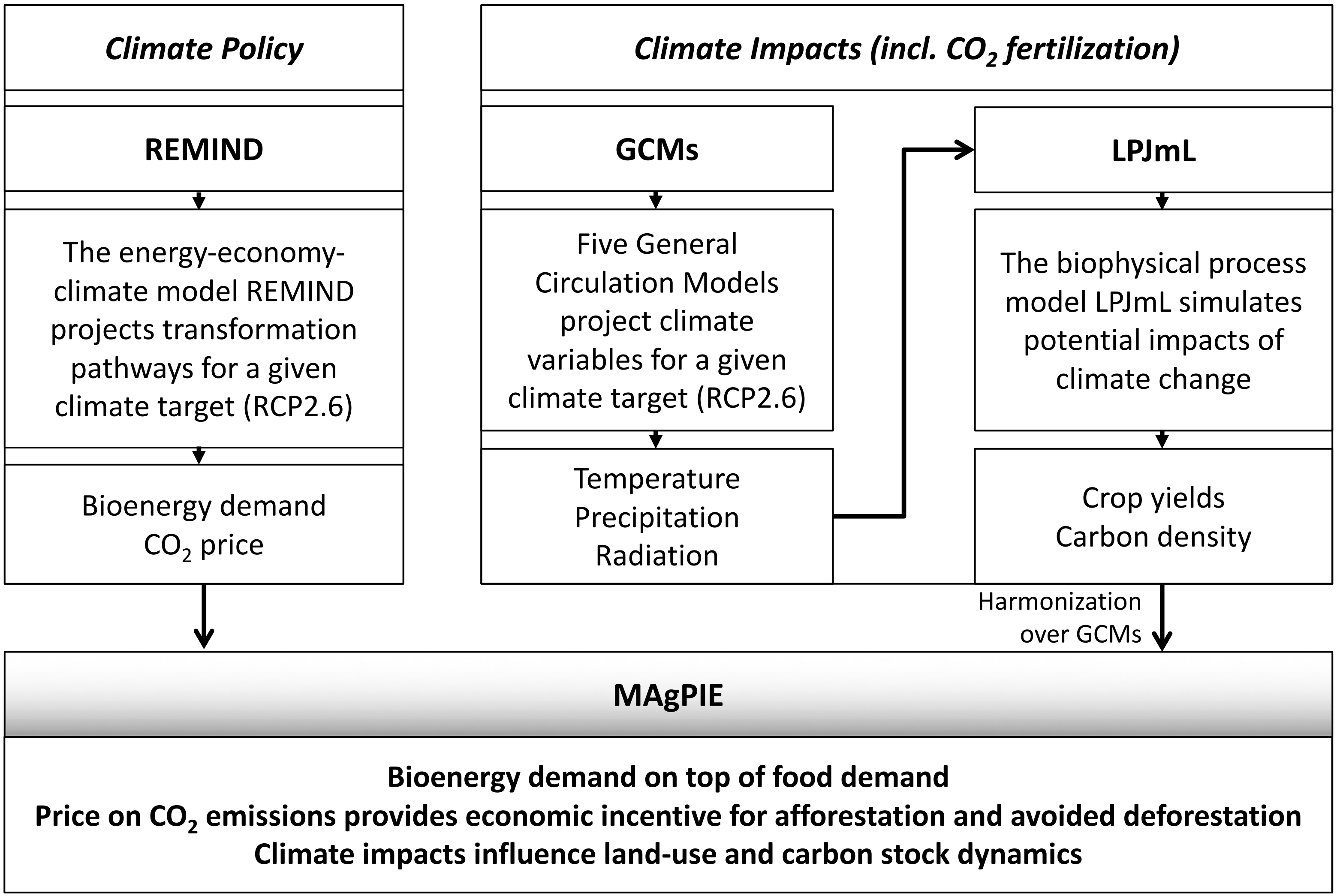


Food expenditure share

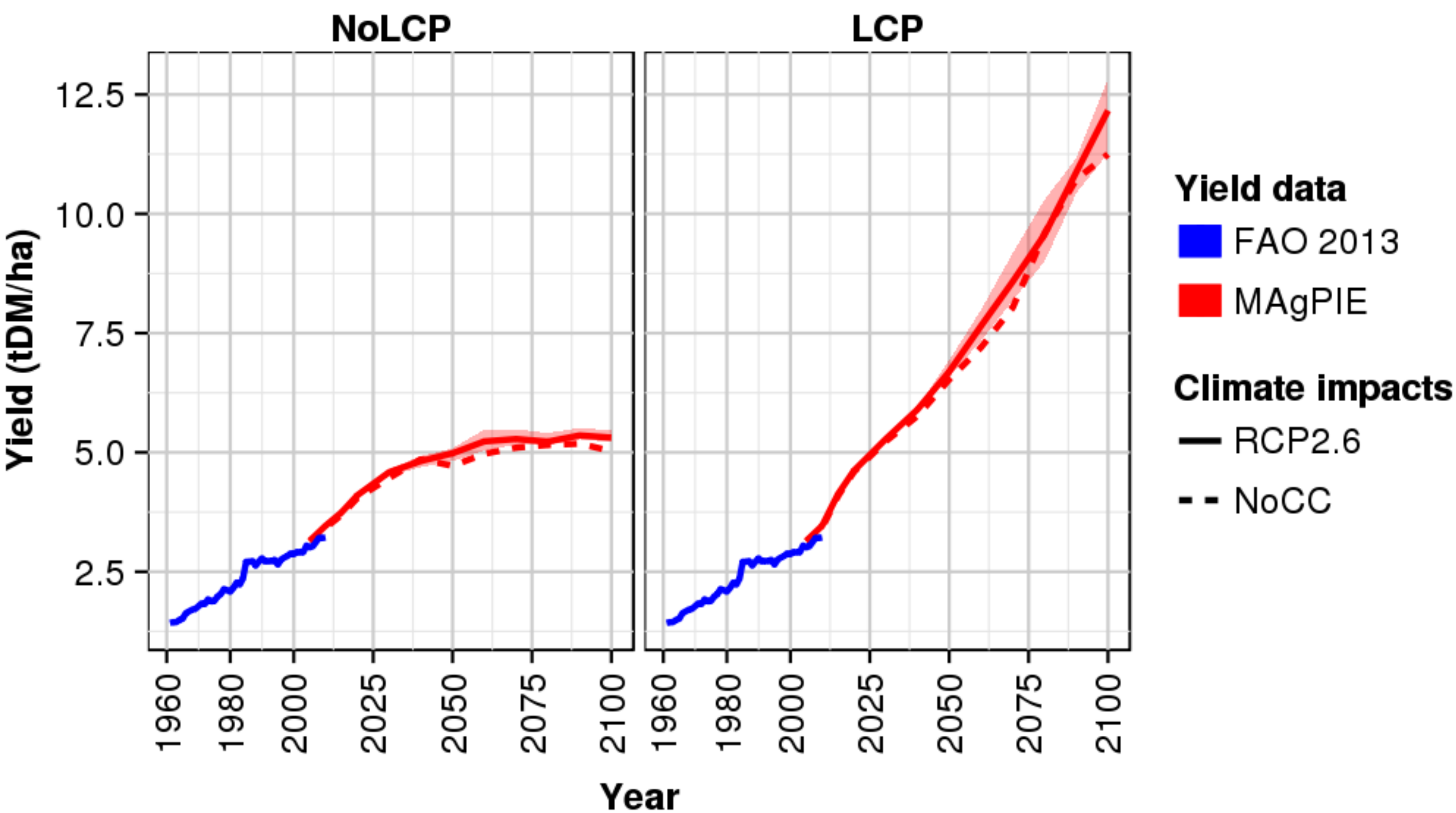


Based on Humpenöder et al. (2014), Environ. Research Letters

Chapter VI - Study design



Agricultural yields



Humpenöder et al. (2015), Environ. Sci. Technol.

Chapter VI - summary of scenario results

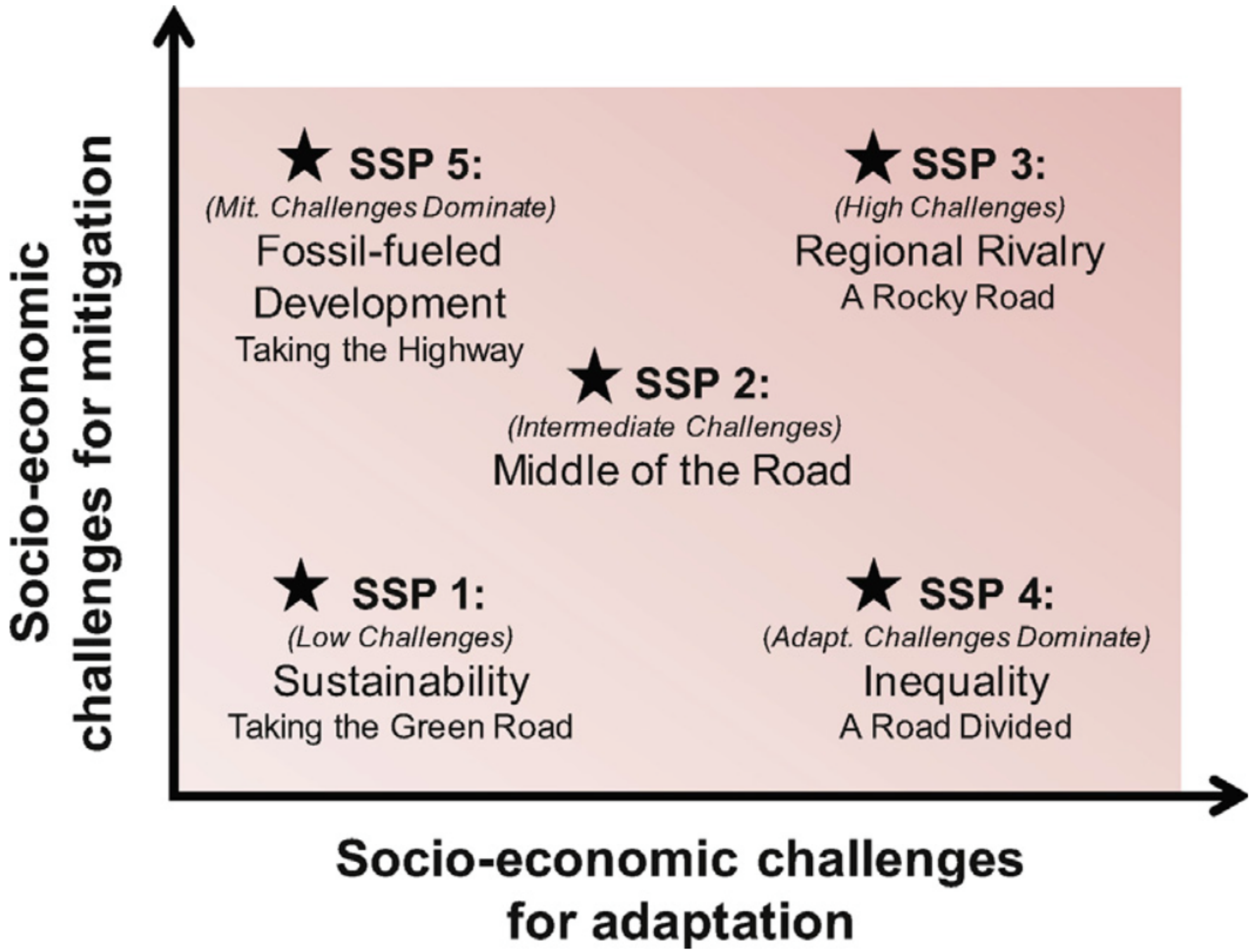
	NoLCP		LCP	
NoCC	*reference*		*LCP only*	
	Δ carbon stock	full effect	Δ carbon stock	full effect
	−90 GtC	0 GtC	101 GtC	191 GtC
RCP2.6	*RCP2.6 only*		*combined setting*	
	Δ carbon stock	full effect	Δ carbon stock	full effect
	−12 GtC	78 GtC	185 GtC	275 GtC

191 GtC + 78 GtC = 269 GtC ~ 275 GtC

Carbon stock changes and full carbon mitigation effect in GtC. Carbon stock changes show the net effect of land management and (direct) climate change between 1995 and 2100 at the global scale. The full carbon mitigation effect reflects the difference in these carbon stock changes between the respective scenario and the reference scenario.

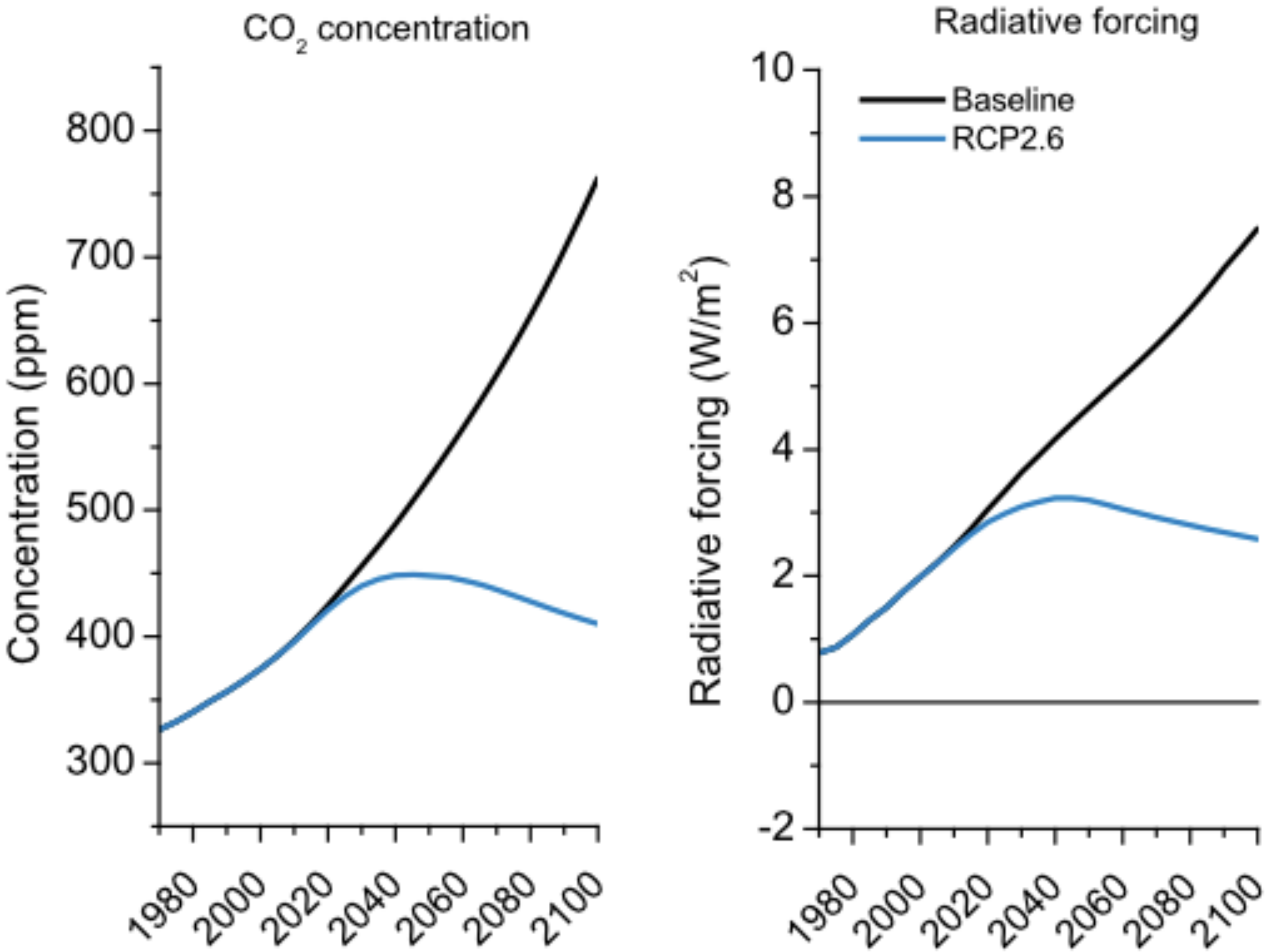
Humpenöder et al. (2015), Environ. Sci. Technol.

Shared Socio-economic Pathways (SSPs)



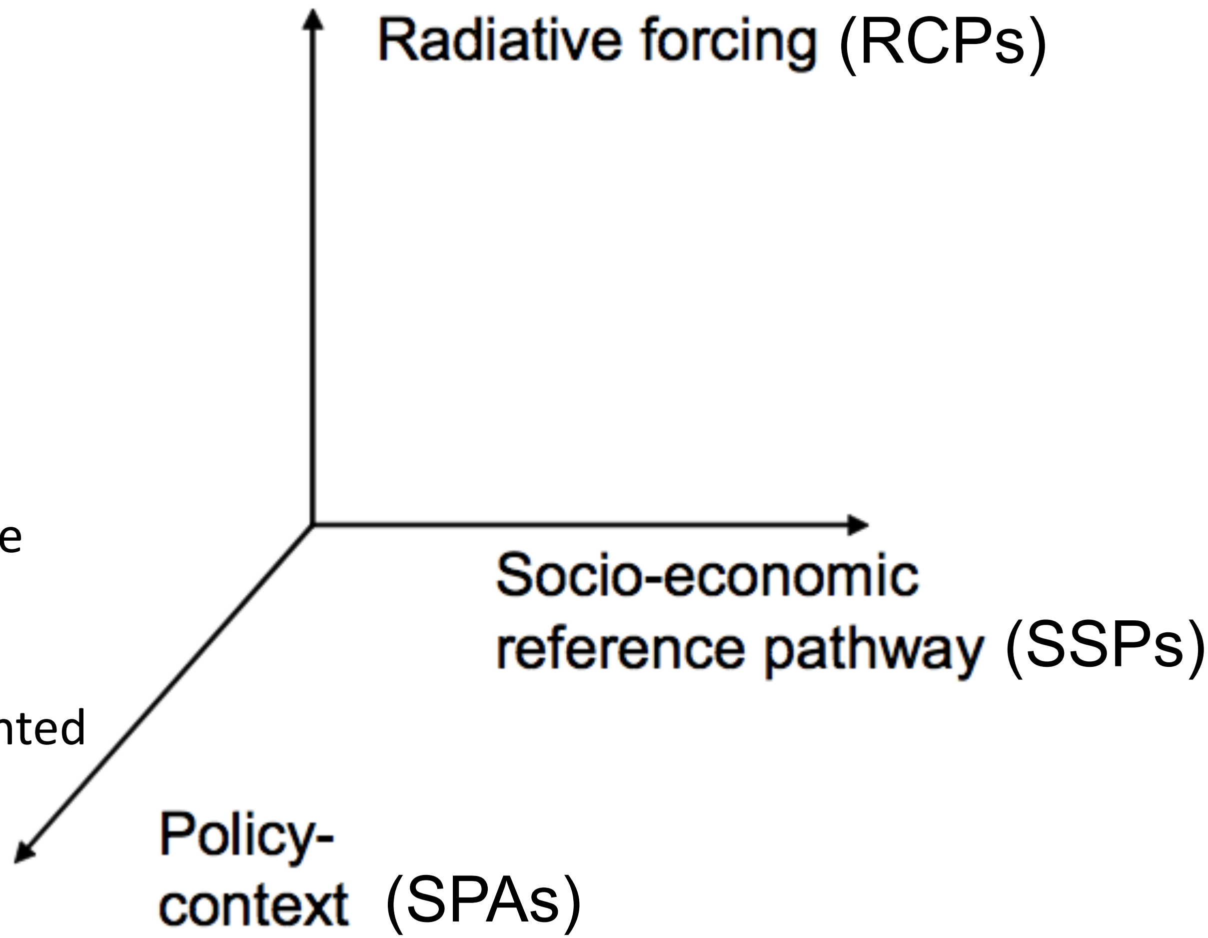
O'Neill B C, Kriegler E, Ebi K L, Kemp-Benedict E, Riahi K, Rothman D S, van Ruijven B J, van Vuuren D P, Birkmann J, Kok K, Levy M and Solecki W 2015 The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century Global Environmental Change

RCP 2.6



van Vuuren D P, Stehfest E, Elzen M G J den, Kram T, van Vliet J, Deetman S, Isaac M, Goldewi K, Hof A, Beltran A M, Oostenrijk R and van Ruijven B 2011 RCP2.6: exploring the possibility to keep global mean temperature increase below 2˚C *Climatic Change* **109** 95–116

SSP x RCP x SPA



Immediate climate action

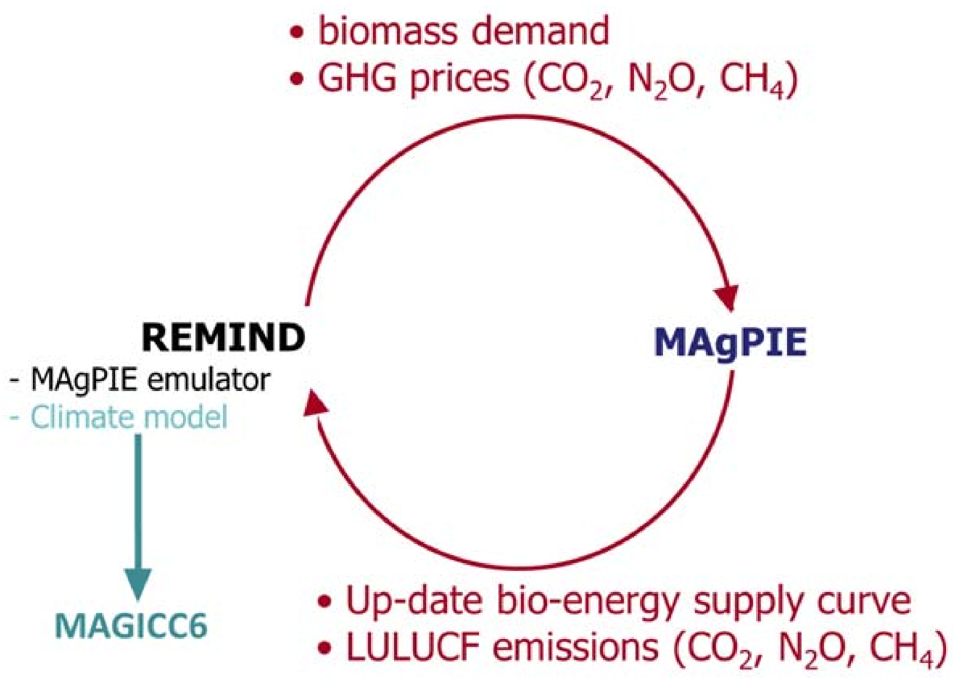
or

Delayed and fragmented climate action

Based on Kriegler E, Edmonds J, Hallegatte S, Ebi K L, Kram T, Riahi K, Winkler H and van Vuu D P 2014 A new scenario framework for climate change research: the concept of shared climate policy assumptions *Climatic Change* 1–14

REMIND-MAgPIE coupling

- **Currently, the coupling of REMIND (energy-economy) and MAgPIE (land-use) aims to find consistent price and quantity paths for bioenergy production and GHG emissions**



Bauer N, Klein D, Luderer G, et al. (2014) Climate change stabilization and the energy-land nexus. Submitted to IEW'14.

Challenges in forest carbon accounting

- **Additionality**
  - **Removal or sink in addition to what would have occurred in the absence of a project**
- **Permanence**
  - **Natural disturbance (e.g. hurricane, wildfire) or management activities (e.g. harvesting) that release carbon back to the atmosphere**
- **Leakage**
  - **Deforestation is displaced to locations without emission control**

Angelsen A and Center for International Forestry Research 2008 Moving ahead with REDD: issues, options and implications (Bogor, Indonesia: Center for International Forestry Research)

END