Integrating trees in agricultural landscapes with agroforestry

Lars Graudal

World Agroforestry Centre (The International Centre for Research in Agroforestry, ICRAF)
and
University of Copenhagen (UCPH)

International Conference on Forest Landscape Restoration
A contribution to the implementation of the Bonn Challenge

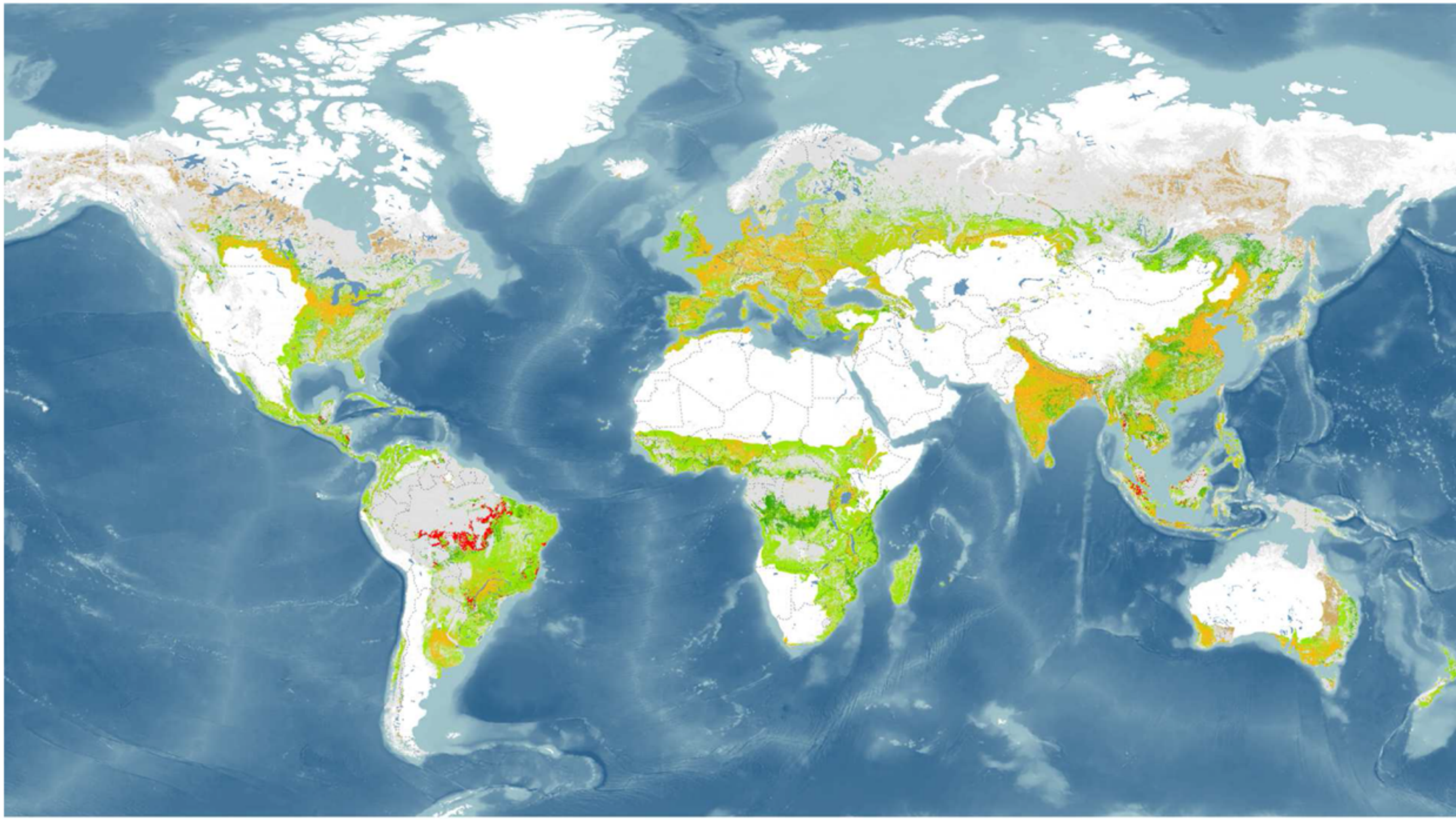
"Synthesising and sharing globally available forest-related scientific knowledge"

San Juan, Puerto Rico, 6-9 June 2017

Transforming lives and landscapes with trees

BONN CHALLENGE
on forests, climate change
and biodiversity 2011

A World of Opportunity
for Forest and Landscape Restoration



FOREST AND LANDSCAPE RESTORATION OPPORTUNITIES
- Wide-scale restoration
- Mosaic restoration
- Remote restoration

OTHER AREAS
- Agricultural lands
- Recent tropical deforestation
- Urban areas
- Forest without restoration needs

THE GLOBAL PARTNERSHIP ON FOREST LANDSCAPE RESTORATION | WORLD RESOURCES INSTITUTE | South Dakota State University | IUCN | PROFOR | Forestry Commission

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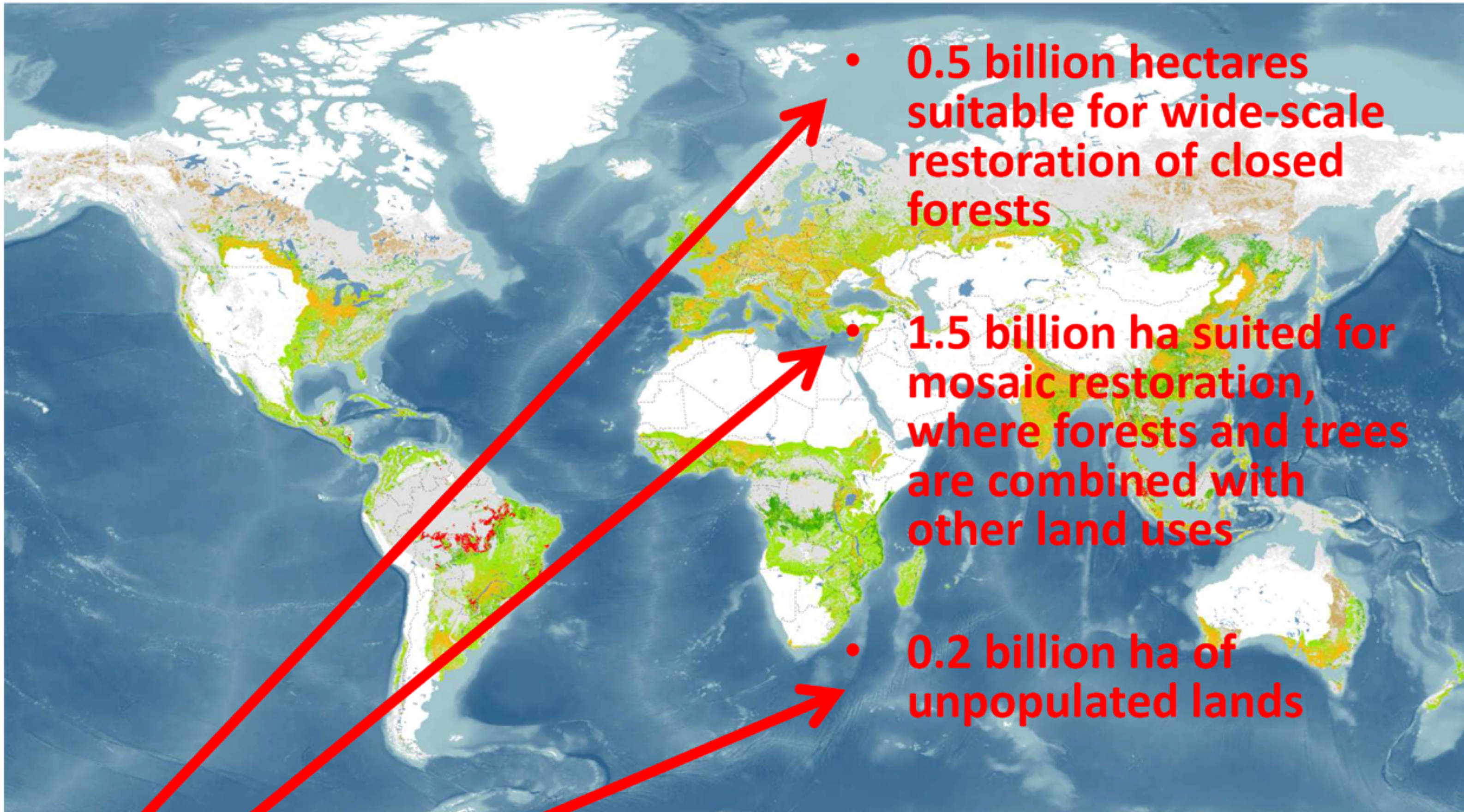

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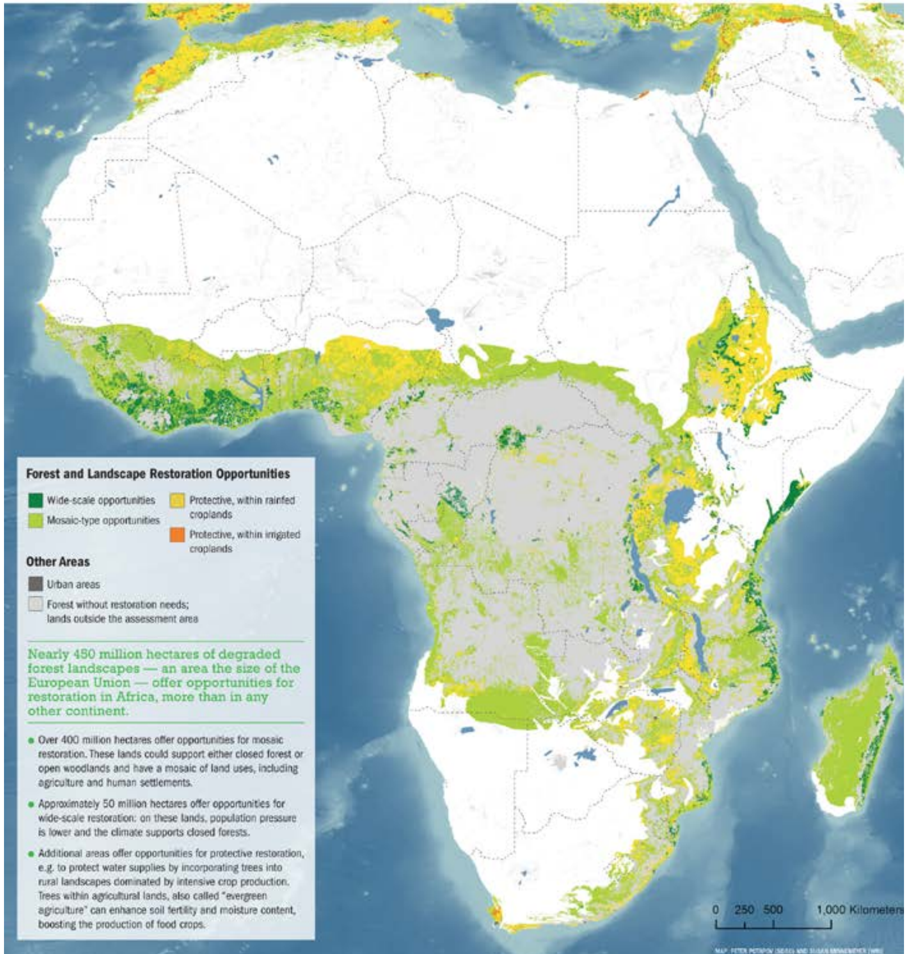
www

Opportunities for Forest and Landscape Restoration in Africa



Wide-scale restoration of forest landscapes is possible in sparsely populated areas without intensive land use. In these areas forests can regrow on a large scale once barriers to regeneration, such as fire or grazing, are controlled.

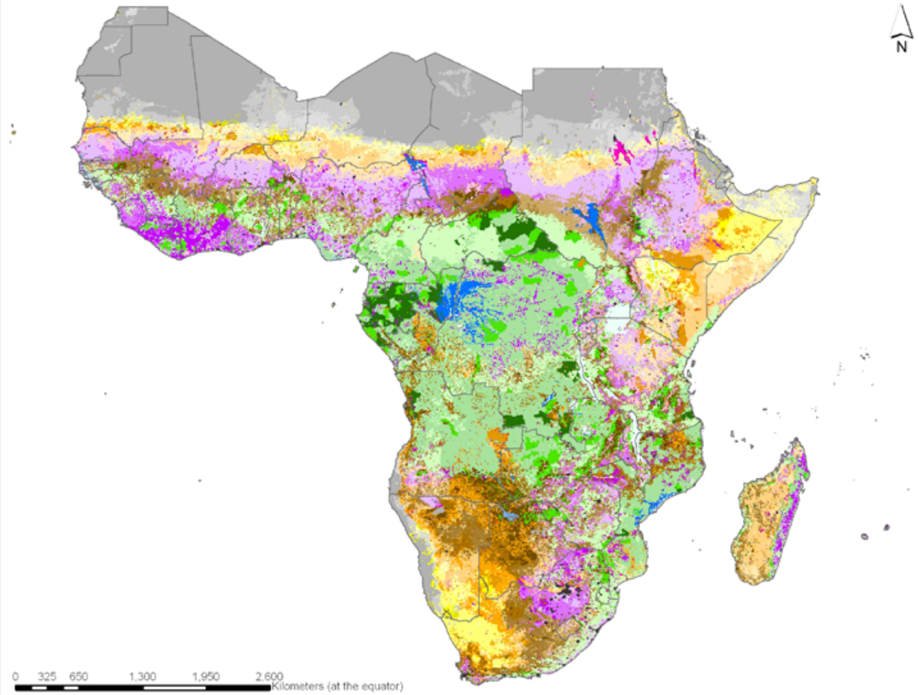
Mosaic-type restoration of woodlands and trees occurs at a smaller scale within landscapes that mix forest and non-forest land uses. Population density is higher, and remaining forests, often highly degraded, are interspersed with agriculture and other land uses.

Protective restoration is possible in densely populated and highly altered landscapes where most land is being used for intensive food production or settlements. In rural and urban landscapes, trees prevent soil erosion, protect waterways, and enhance soil moisture capacity.

LADA

Land use systems of the world

Sub-Saharan Africa



Land use systems legend

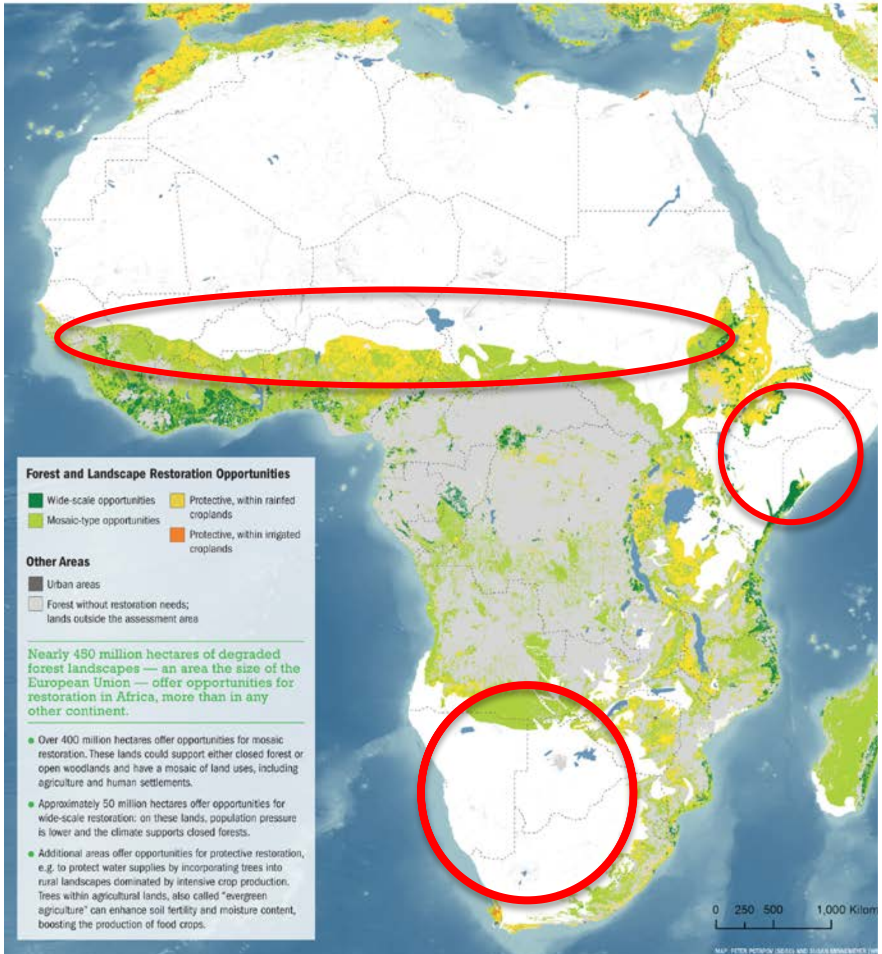
- 1 Forest virgin
- 2 Forest protected
- 3 Forest agricultural activities
- 4 Forest mod. or higher livestock density
- 7 Grasslands unmanaged
- 8 Grasslands protected
- 9 Grasslands low livestock density
- 10 Grasslands mod. livestock density
- 11 Grasslands high livestock density
- 13 Shrubs unmanaged
- 14 Shrubs protected
- 15 Shrubs low livestock density
- 16 Shrubs Mod. livestock density
- 17 Shrubs high livestock density
- 19 Rainfed crops (Subsistence / commercial)
- 20 Crops and mod. intensive livestock density
- 21 Crops and high livestock density
- 22 Crops, large scale irrigation, mod. int. livestock dens.
- 23 Agriculture Large scale irrigation
- 24 Agriculture protected
- 25 Urban land
- 26 Wetlands unmanaged
- 27 Wetlands protected
- 28 Wetlands mangroves
- 29 Wetlands with agricultural activities
- 30 Sparsely vegetated areas unmanaged
- 31 Sparsely vegetated areas protected
- 32 Sparsely vegetated areas low livestock density
- 33 Sparsely vegetated areas Mod. or higher livestock density
- 34 Bare areas unmanaged
- 35 Bare areas protected
- 36 Bare areas low livestock density
- 37 Bare areas Mod. or higher livestock density
- 38 Water unmanaged
- 39 Water protected
- 40 Water inland fisheries
- Country boundaries

Reference: LADA, 2008.Reference: LADA, 2008. "Mapping Land Use Systems at global and regional scales for Land Degradation Assessment Analysis". Nachtergaele F. & Petri M. LADA Technical report n.8, version 1.1.

The Land Use Database of the world was developed as part of the project Land Degradation Assessment in Drylands (LADA), a four-year project funded by the Global Environment Facility (GEF). The project is implemented by the United Nations Environment Programme (UNEP) and executed by the Food and Agriculture Organization of the United Nations (FAO).

UNEP GEF

Opportunities for Forest and Landscape Restoration in Afric



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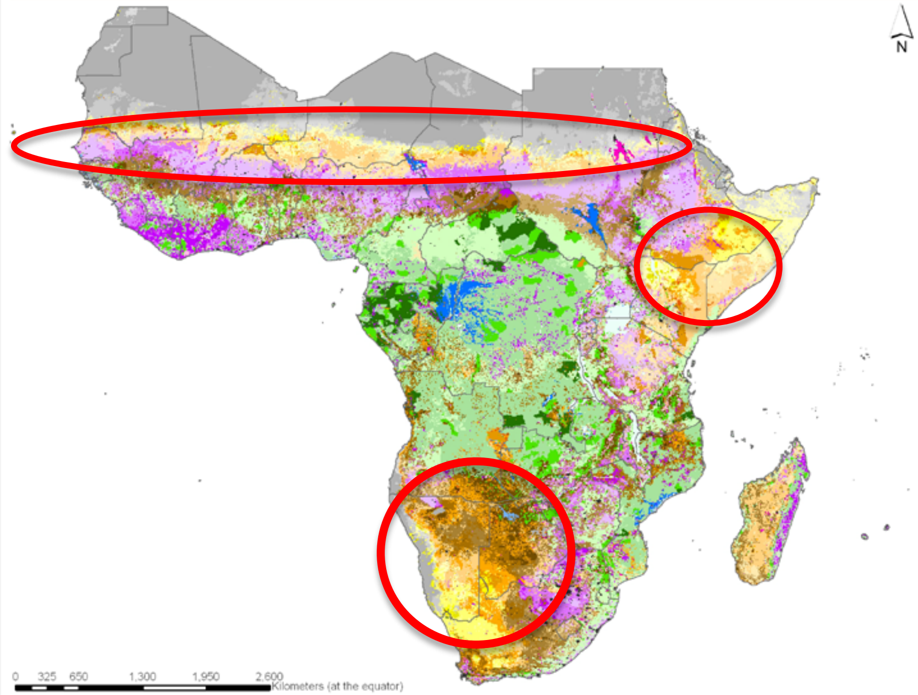

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Restoration – FLR - What does it mean?

- “a [planned] process that aims to regain ecological integrity and enhance human wellbeing in a deforested or degraded forest landscape” (IUCN/WWF 2000)
- FLR broadens the scope of restoration to consider the entire landscape and explicitly incorporates human activities and needs (Mansourian et al., 2005; Lamb et al., 2012; Stanturf et al. 2015)

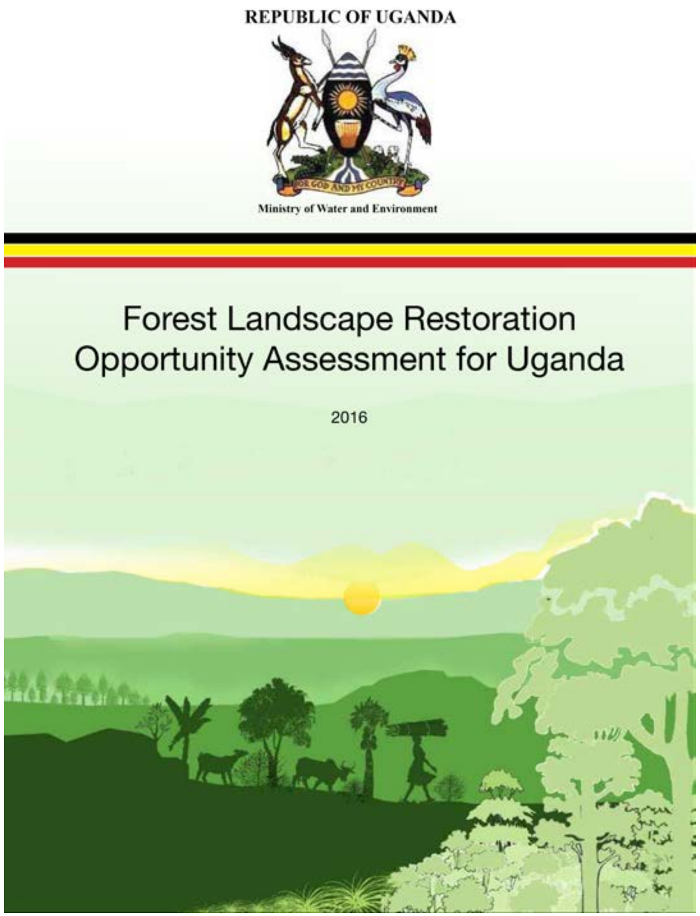
The broader scope of FLR integrates Agroforestry

- Agriculture with trees
  - Interaction of agriculture and forestry involving farmers, livestock, trees and forests at multiple scales
  - Focus on ‘polycultures’ with trees to produce food, fibre, fuel, timber and other products;
  - and to produce environmental services (shelter, soil and water conservation, carbon sequestration and biodiversity)

ICRAF – The World Agroforestry Centre

“Transforming Lives and Landscapes with Trees”

The importance of agroforestry in restoration confirmed by ROAM



- Like e.g. in Rwanda and Uganda, where Agroforestry comes up as one of the main priorities for restoration

Aspirations of agroforestry in FLR

1. Optimizing the contribution of trees to agricultural systems at nested scales will deliver multiple benefits to people and the planet;

2. Fine-scale variation and diversity of species, systems, life-forms, contexts and options are assets rather than hurdles;

3. It is possible to go to scale up agroforestry in time because we have the tools, evidence and an understanding of the kinds of partnerships that will succeed. However, challenges remain.

Prabhu et al. 2015 Agroforestry: Realizing the promise of an agroecological approach

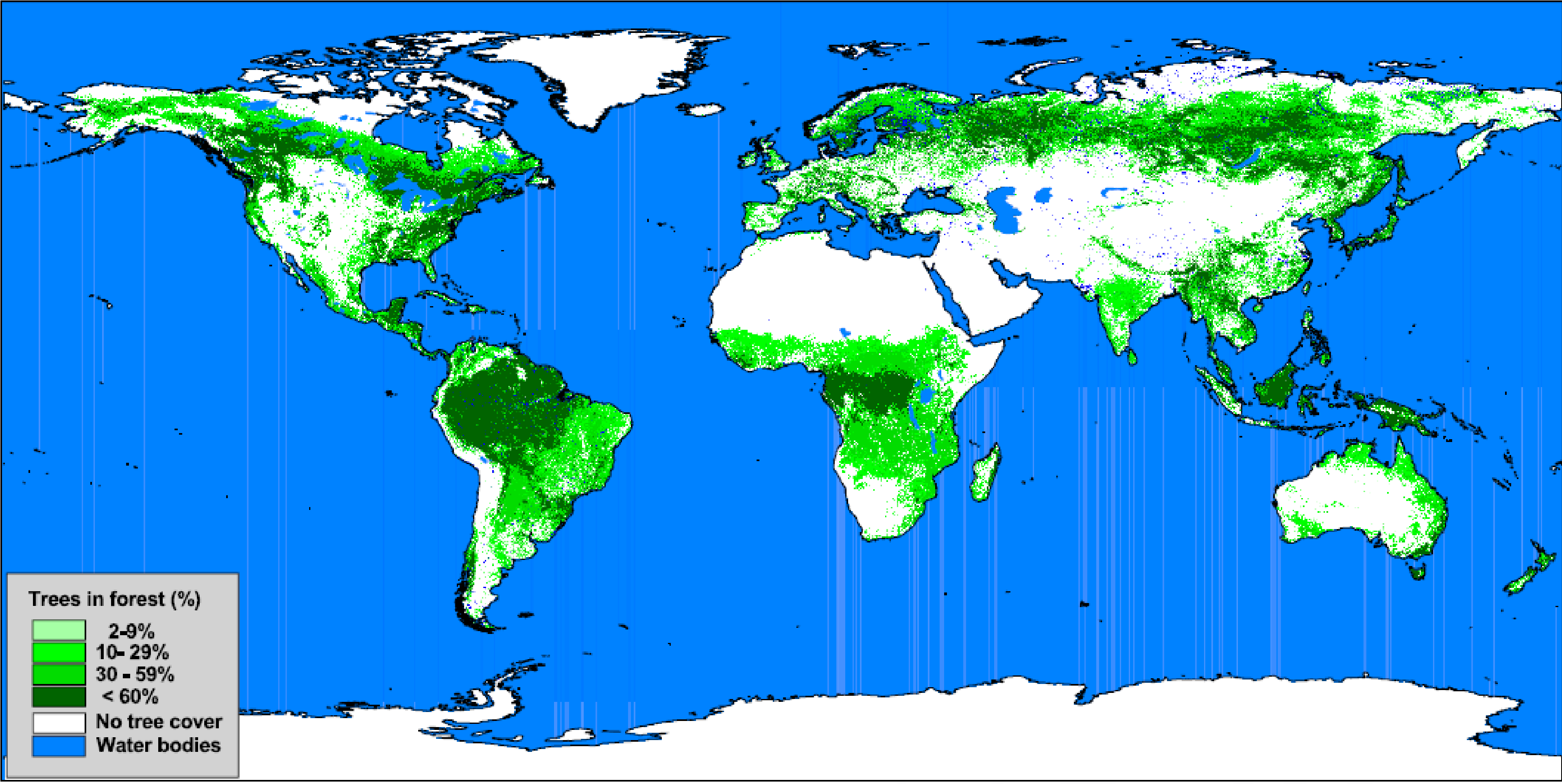
Foci of agroforestry in restoration

(overview of this presentation)

- Mitigation of climate change
  - Biochemical (carbon sequestration)
  - Biophysical (radiative and non-radiative effects (water))

- Adaptation
  - Environmental and economic resilience (biodiversity, soils, ROI)
    - Productivity of mixed systems
    - Closing the yield gap

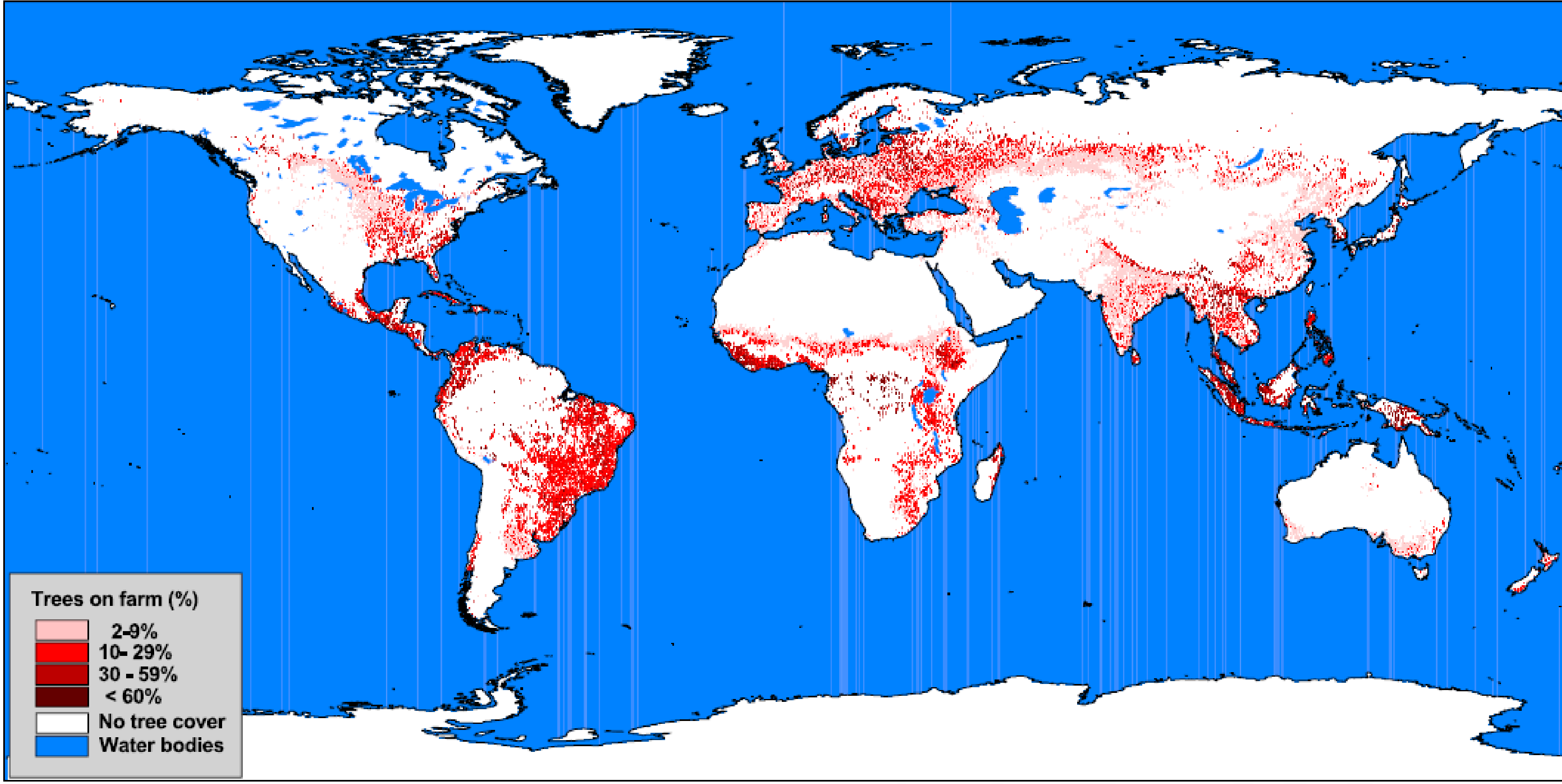
- Adequate planting material ("tree genetic resources" often constitutes a bottleneck in (successful) large-scale restoration (e.g. Broadhearst et al. 2016, BioScience 66: 73–79. doi:10.1093/biosci/biv155)
  - The seed challenge



The foresters' view of the world : global forest area

(Source: CGIAR Consortium research program 6 Forests, trees and agroforestry: Livelihoods, landscapes and governance)

FAO Forest Resources Assessment

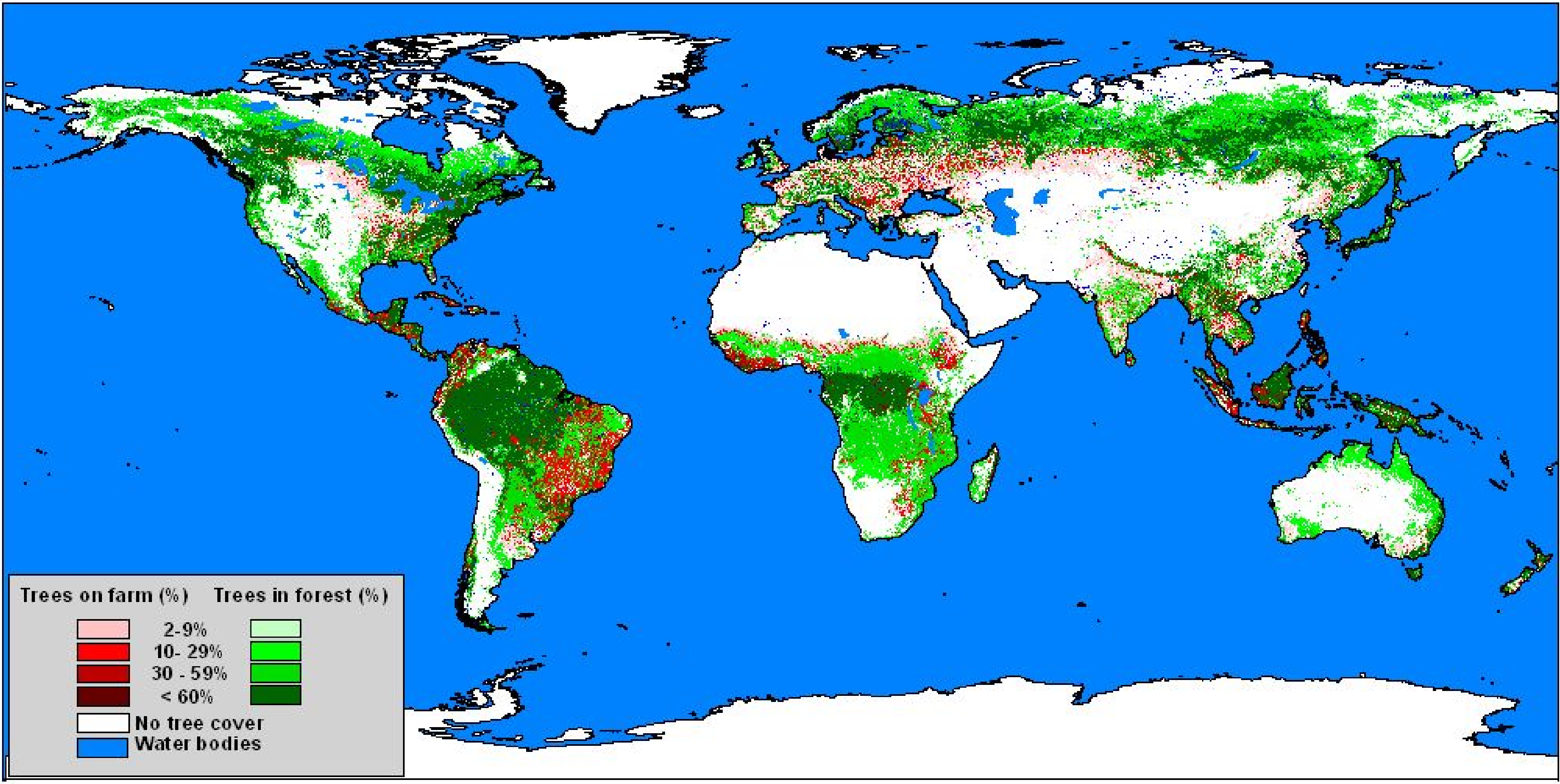


The agroforestry view of the world: trees outside forests

(Source: CGIAR Consortium research program 6 Forests, trees and agroforestry: Livelihoods, landscapes and governance)

www.worldagroforestry.org

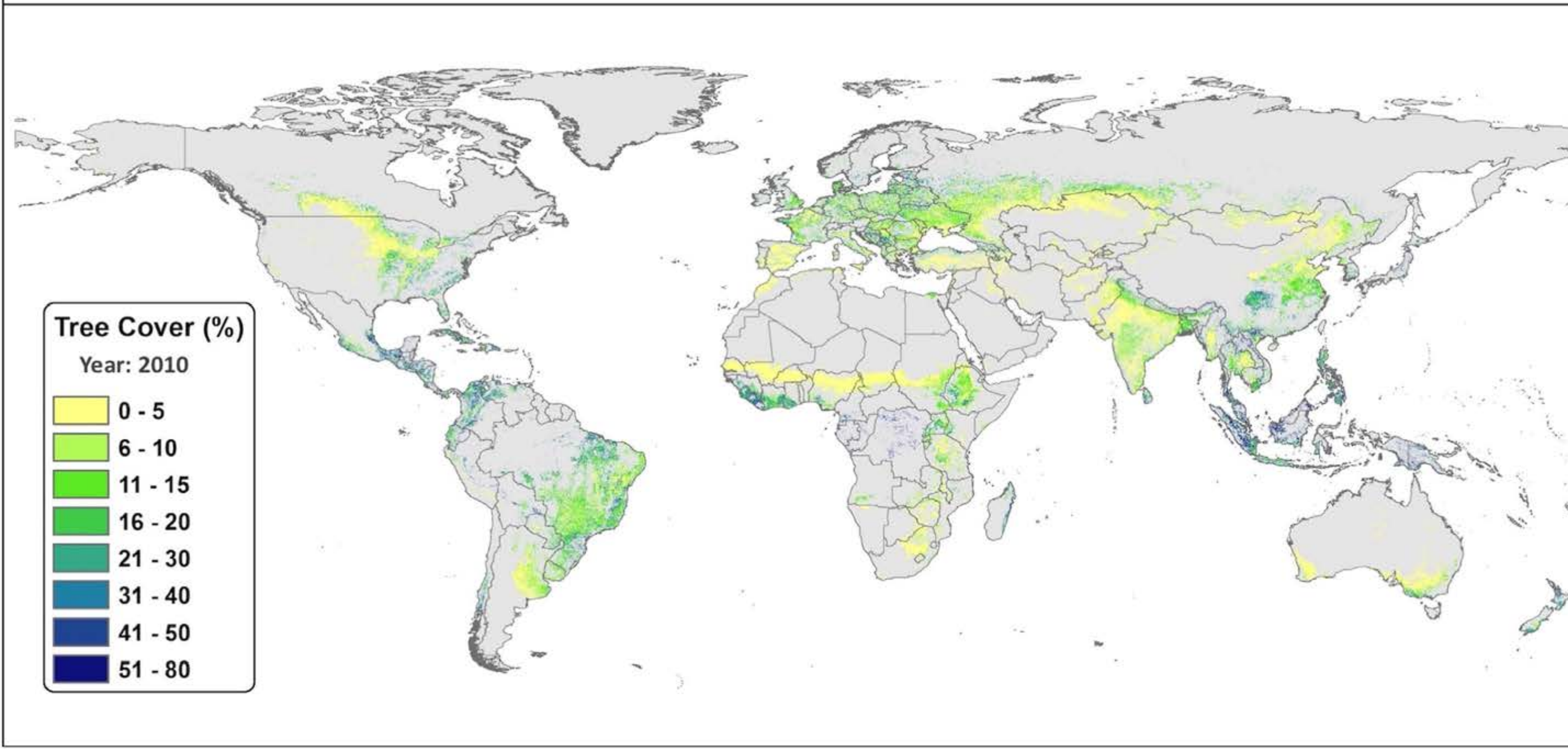
Zomer et al 2009, 2014, 2016



The Tree Diversity view of the world

(Source: CGIAR Consortium research program 6 Forests, trees and agroforestry: Livelihoods, landscapes and governance)

Global tree cover inside and outside forest, according to the Global Land Cover 2000 dataset, the FAO spatial data on farms versus forest, and the analysis by Zomer et al. (2009, 2014)



Zomer et al. 2016

Global tree cover on agricultural land 2010. Approximately 40% of all agricultural land in the year 2000 had at least 10% tree cover (which corresponds to the FAO definition of forest). This increased by 3.7% by the 2010, to account for more than 43% of all agricultural land under some variation of agroforestry approaches. Based on this current analysis, these land-use types represent over **1 billion hectares** of land and provide subsistence to more than 900 million people

Zomer et al. 2016 NATURE Scientific Reports | 6:29987 | DOI: 10.1038/srep29987

Foci of agroforestry in restoration

(overview of this presentation)

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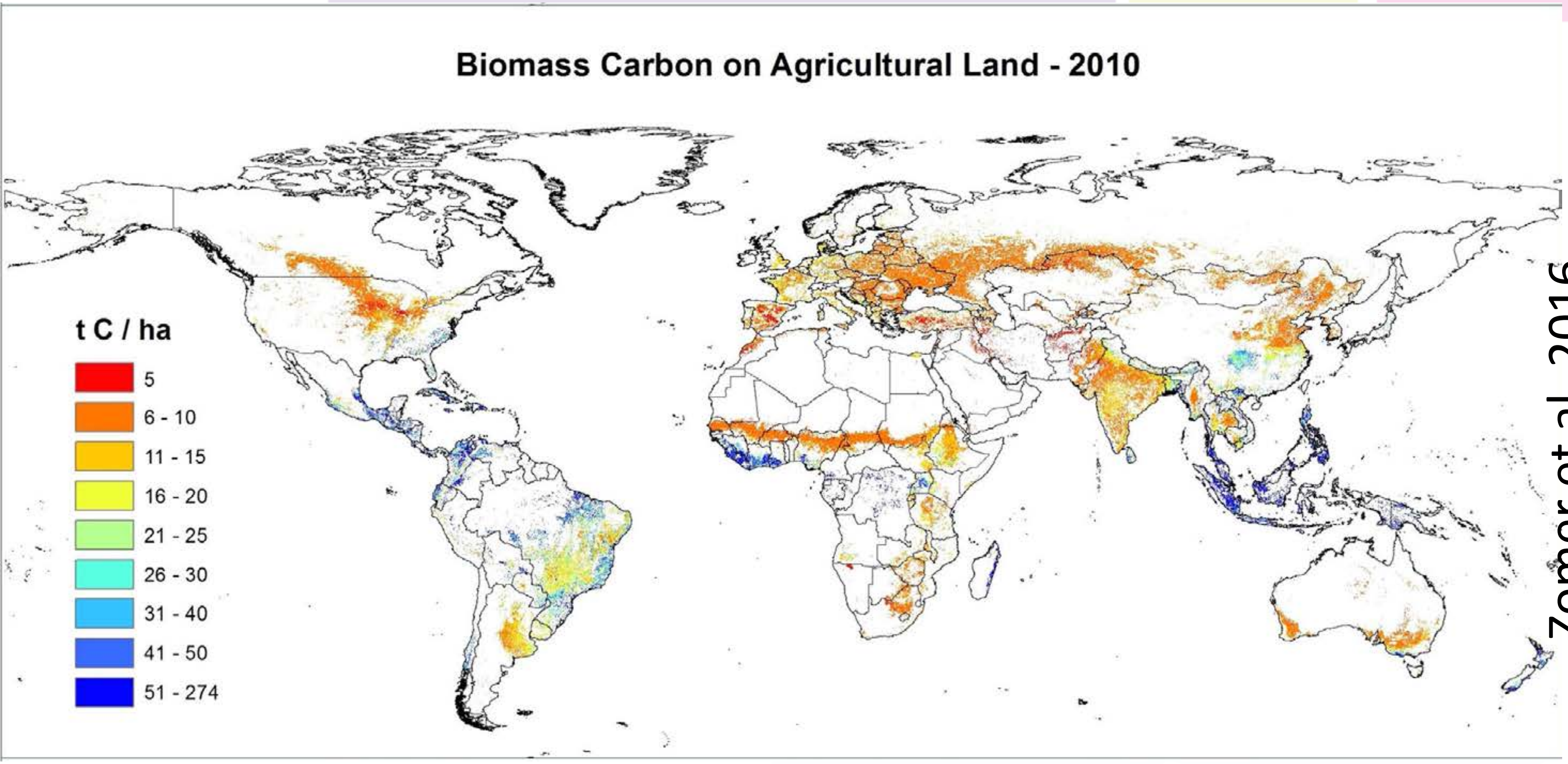
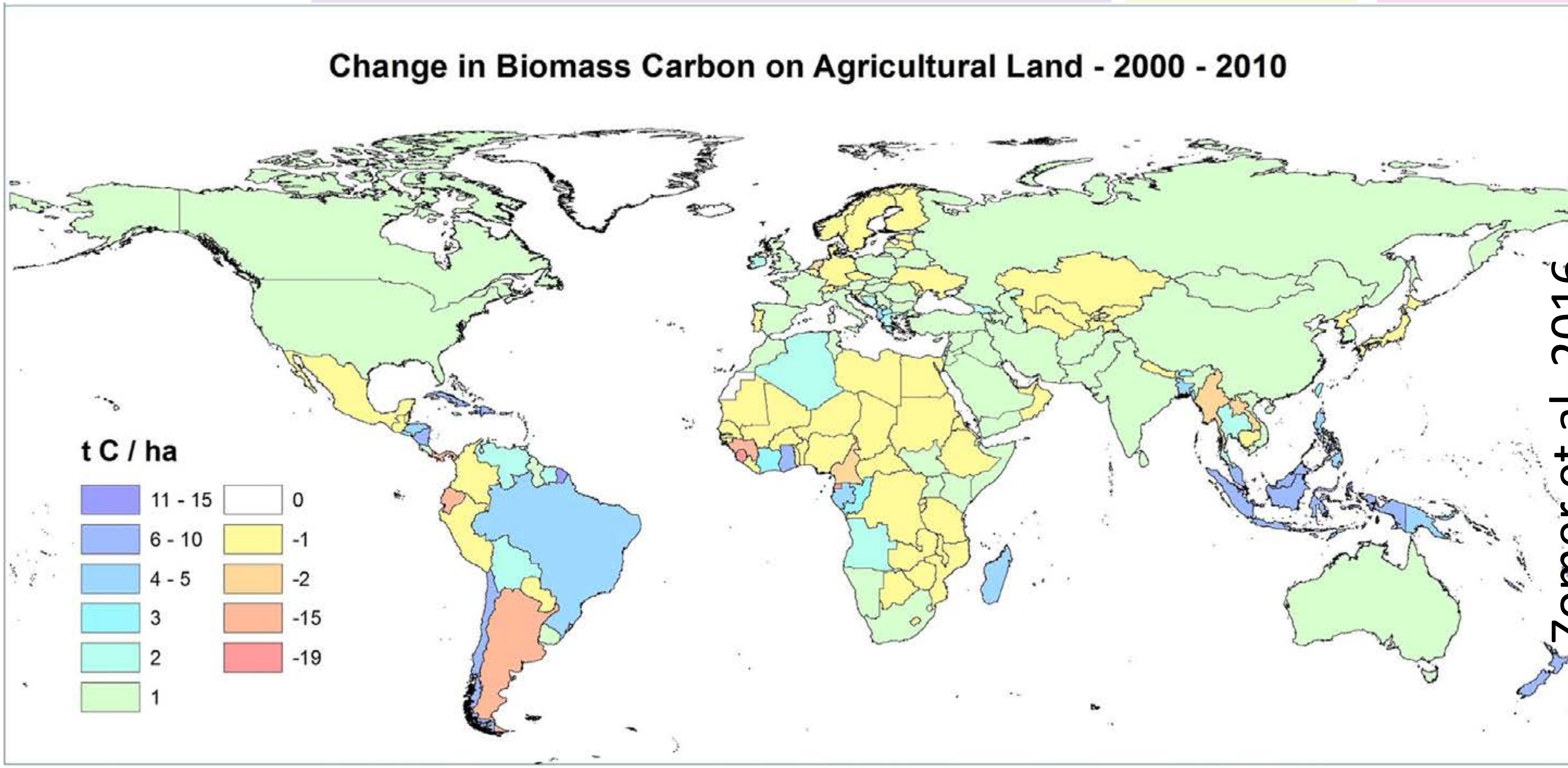


Zomer et al. 2016

- IPCC estimate 5 t/ha on average (above and below ground)
- Zomer et al. estimate 21.4 t/ha in 2010
- Large regional variation
- Potential for increase remain

Zomer et al. 2016 NATURE Scientific Reports | 6:29987 | DOI: 10.1038/srep



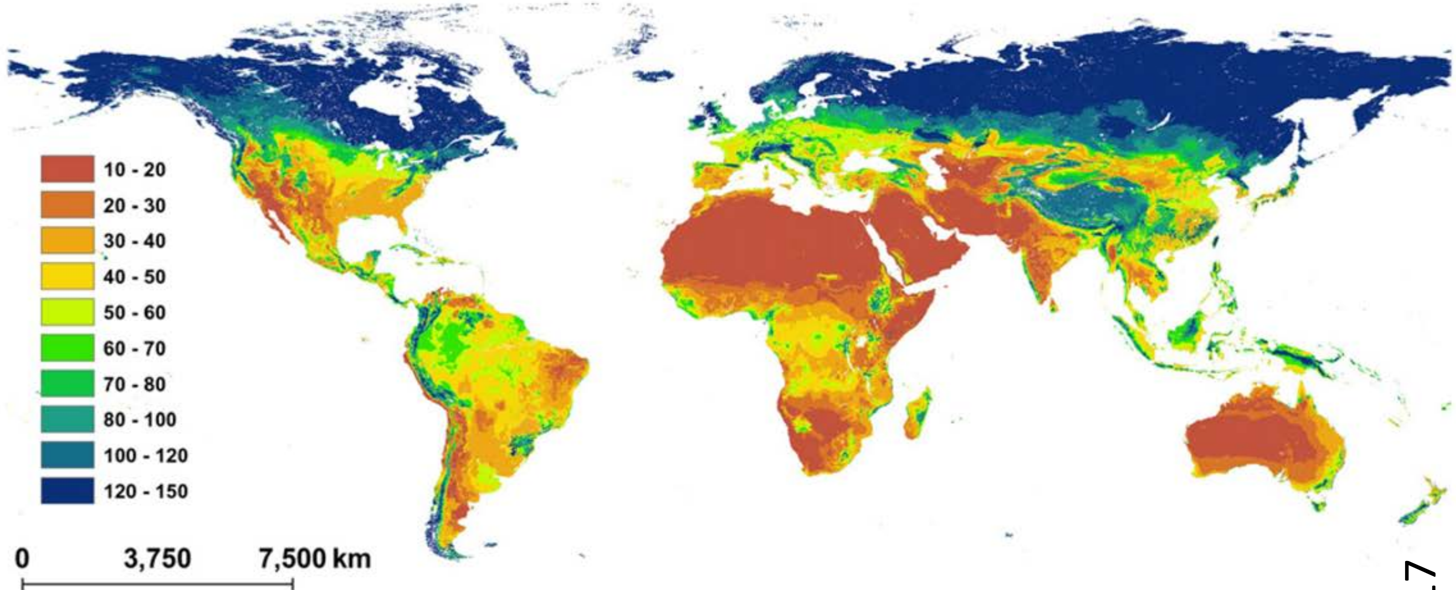
Zomer et al. 2016

- Change varies over time: stable, increasing or decreasing
- What makes the difference?
- Interactions between climate and soil and crop production (moisture, temperature, nutrient levels, N fixation)
- Management regimes favouring both above ground biomass and SOC

Zomer et al. 2016 NATURE Scientific Reports | 6:29987 | DOI: 10.1038/srep29987

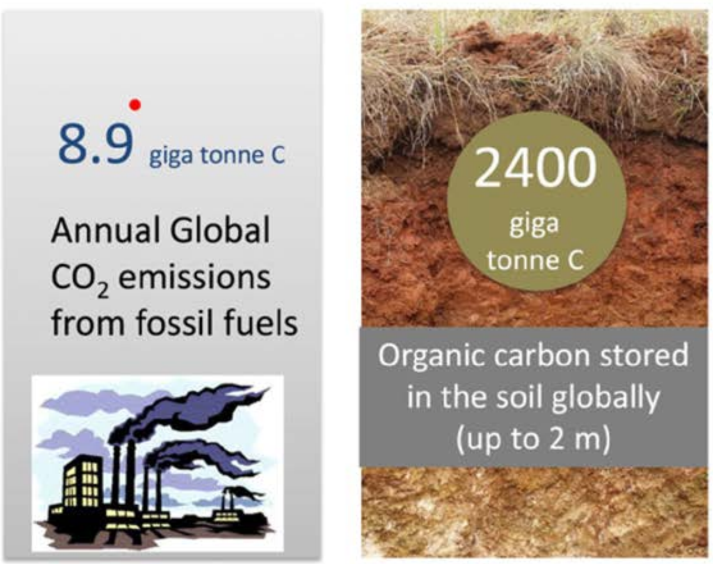
Soil C stocks of the world's topsoil (0–0.3 m) in tonne C per hectare.

(The map was generated based on global datasets of C stock from the study of Stockmann et al. (2015))



Minasny et al 2017

Only a small increase of SOC is required to offset global CO_2 emissions



$$8.9 / 2400 = 4‰$$

Amount of C stock increase needed to offset CO_2 emission

B. Minasny et al. / Geoderma 292 (2017) 59–86

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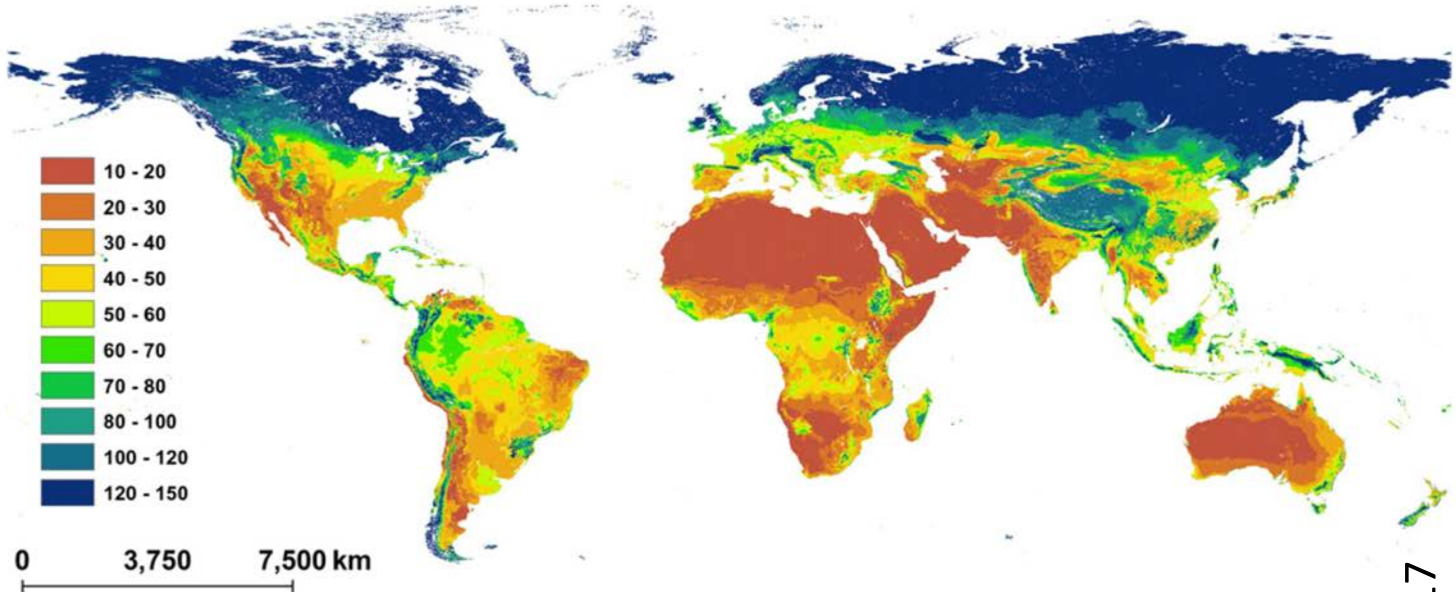

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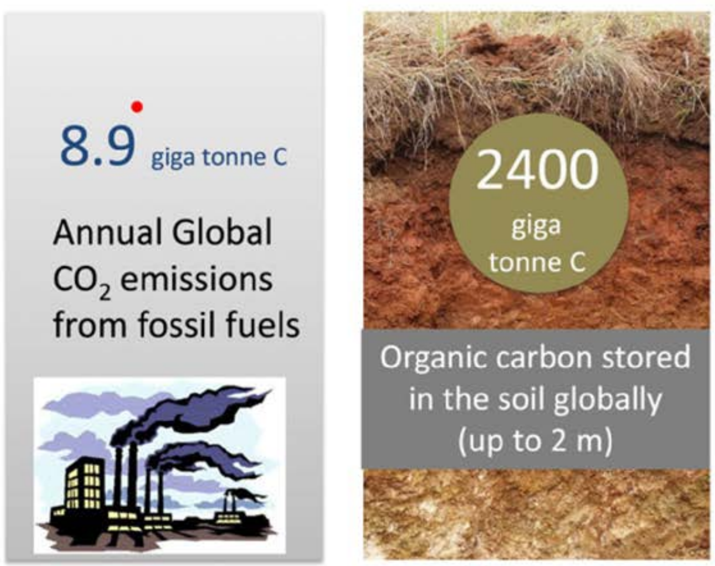

$$8.9 / 2400 = 4\text{‰}$$

Amount of C stock increase needed to offset CO_2 emission

For comparison Pan et al. 2011 quote a figure of 861 Gt in the worlds forests (incl. soil to a depth of 1 m). The amount of C stock increase needed to offset CO_2 emission would here be 1%

B. Minasny et al. / Geoderma 292 (2017) 59–86

AGU PUBLICATIONS

Earth's Future

RESEARCH ARTICLE

10.1002/2016EF000469

The limits to global-warming mitigation by terrestrial carbon removal

Lena R. Boysen[1,2,3,4], **Wolfgang Lucht**[1,2,3], **Dieter Gerten**[1,2], **Vera Heck**[1,2], **Timothy M. Lenton**[5], **and Hans Joachim Schellnhuber**[1,6]

[1]Research Domain I: Earth System Analysis, Potsdam Institute for Climate Impact Research, Potsdam, Germany, [2]Department of Geography, Humboldt-Universität zu Berlin, Berlin, Germany, [3]Integrative Research Institute on Transformations of Human-Environment Systems, Berlin, Germany, [4]Land in the Earth System, Max-Planck Institute for Meteorology, Hamburg, Germany, [5]College of Life and Environmental Sciences, Geography, University of Exeter, Exeter, UK, [6]Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden

Key Points:
- Terrestrial Carbon Dioxide Removal (tCDR) is not a viable option for countering unabated anthropogenic greenhouse gas emissions
- Even in the RCP2.6 scenario, the tCDR amount needed to hold the 2°C warming line requires massive inputs including extensive irrigation
- Profound trade-offs of tCDR include loss of natural ecosystems, reductions in food production, and adverse effects of heavy fertilizer application

Supporting Information:
- Supporting Information S1

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Citation:
Boysen, L. R., W. Lucht, D. Gerten, V. Heck, T. M. Lenton, and H. J. Schellnhuber (2017), The limits to global-warming mitigation by terrestrial carbon removal, *Earth's Future*, *5*, doi:10.1002/2016EF000469.

Received 9 SEP 2016
Accepted 28 MAR 2017

Abstract Massive near-term greenhouse gas emissions reduction is a precondition for staying "well below 2°C" global warming as envisaged by the Paris Agreement. Furthermore, extensive terrestrial carbon dioxide removal (tCDR) through managed biomass growth and subsequent carbon capture and storage is required to avoid temperature "overshoot" in most pertinent scenarios. Here, we address two major issues: First, we calculate the extent of tCDR required to "repair" delayed or insufficient emissions reduction policies unable to prevent global mean temperature rise of 2.5°C or even 4.5°C above pre-industrial level. Our results show that those tCDR measures are unable to counteract "business-as-usual" emissions without eliminating virtually all natural ecosystems. Even if considerable (Representative Concentration Pathway 4.5 [RCP4.5]) emissions reductions are assumed, tCDR with 50% storage efficiency requires >1.1 Gha of the most productive agricultural areas or the elimination of >50% of natural forests. In addition, >100 MtN/yr fertilizers would be needed to remove the roughly 320 GtC foreseen in these scenarios. Such interventions would severely compromise food production and/or biosphere functioning. Second, we reanalyze the requirements for achieving the 160–190 GtC tCDR that would complement strong mitigation action (RCP2.6) in order to avoid 2°C overshoot anytime. We find that a combination of high irrigation water input and/or more efficient conversion to stored carbon is necessary. In the face of severe trade-offs with society and the biosphere, we conclude that large-scale tCDR is not a viable alternative to aggressive emissions reduction. However, we argue that tCDR might serve as a valuable "supporting actor" for strong mitigation if sustainable schemes are established immediately.

Boysen et al (2017), Earth's Future, 5, doi:10.1002/2016EF000469

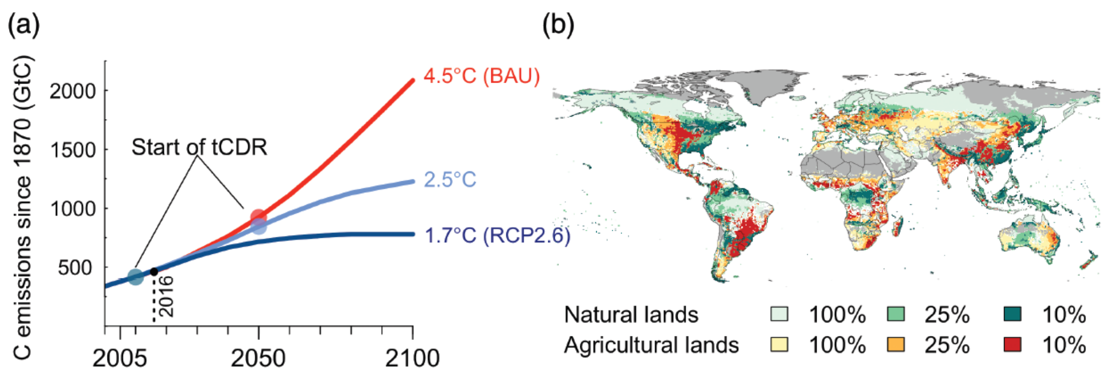

Figure 1. (a) Cumulative emission pathways leading to a mean global warming of 1.7°C (Representative Concentration Pathway 2.6 [RCP2.6]), 2.5°C, and 4.5°C by 2100, respectively. Dots indicate the starting points of terrestrial carbon dioxide removal (tCDR) assumed here. Climate projections for the upper two graphs were retrieved with a pattern-scaling approach applied on five CMIP3 models [*Heinke et al.*, 2013] while the RCP2.6 climate was retrieved from CMIP5 simulations. (b) Areas considered for tCDR in the studied conversion scenarios. Values are given as % fraction of 0.5° × 0.5° grid cells for scenarios listed in Table 1. Note that only the dominant fraction of either natural or agricultural land in each cell is displayed.

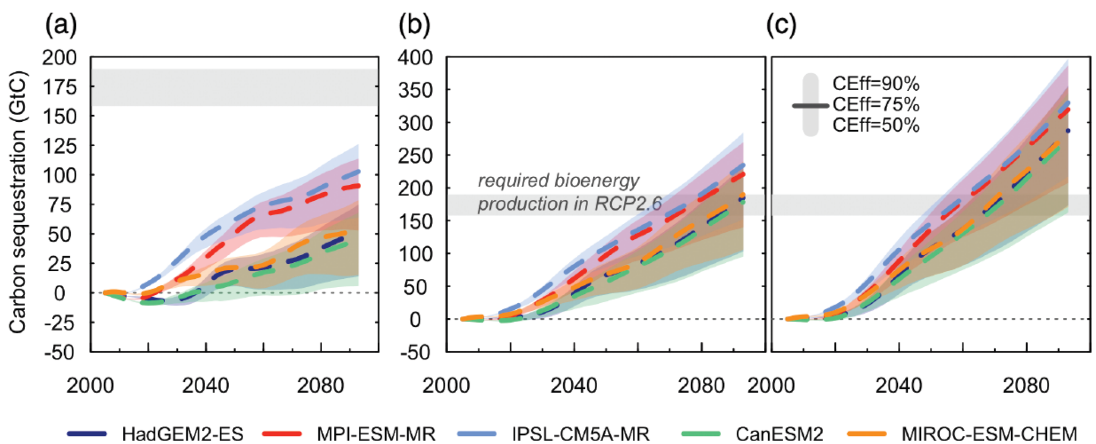

Figure 3. Terrestrial carbon dioxide removal (tCDR) potentials (GtC) for rain-fed (a), sustainably (b) and unrestrictedly irrigated (c) biomass-producing plantations in combination with conversion efficiencies (CEff) of 50%, 75%, and 90% (shading) and for different climate models input for LPJmL (colors). The gray horizontal bar denotes the required tCDR of Representative Concentration Pathway 2.6 of 160–190 GtC.

In the face of severe trade-offs with society and the biosphere, we conclude that **large-scale tCDR is not a viable alternative to aggressive emissions reduction**. However, we argue that tCDR might serve as **a valuable "supporting actor" for strong mitigation** if sustainable schemes are established immediately.

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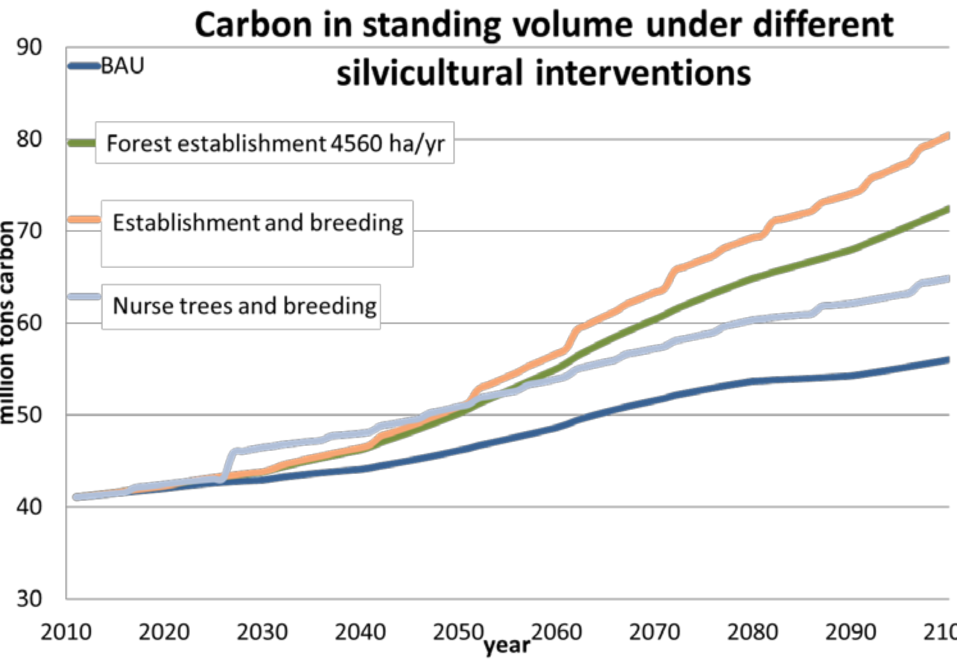
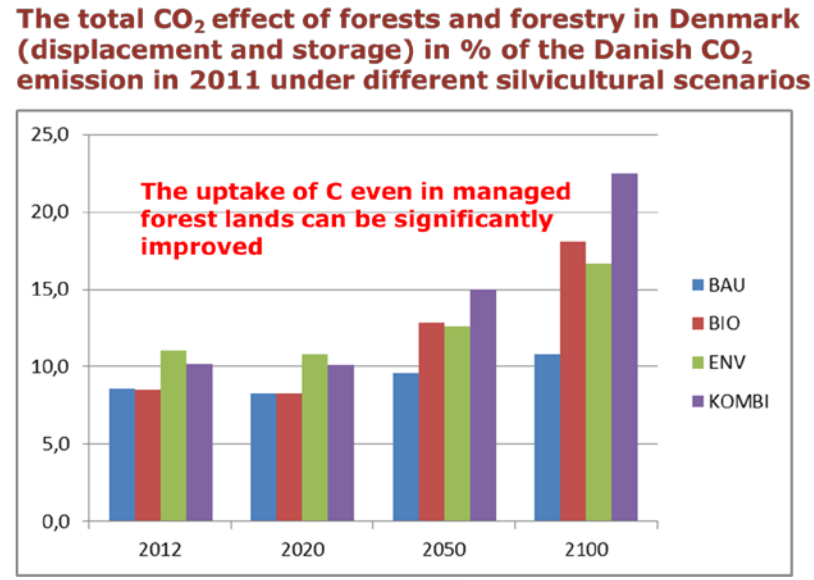


Danish Forest Estate approx. 600.000 ha

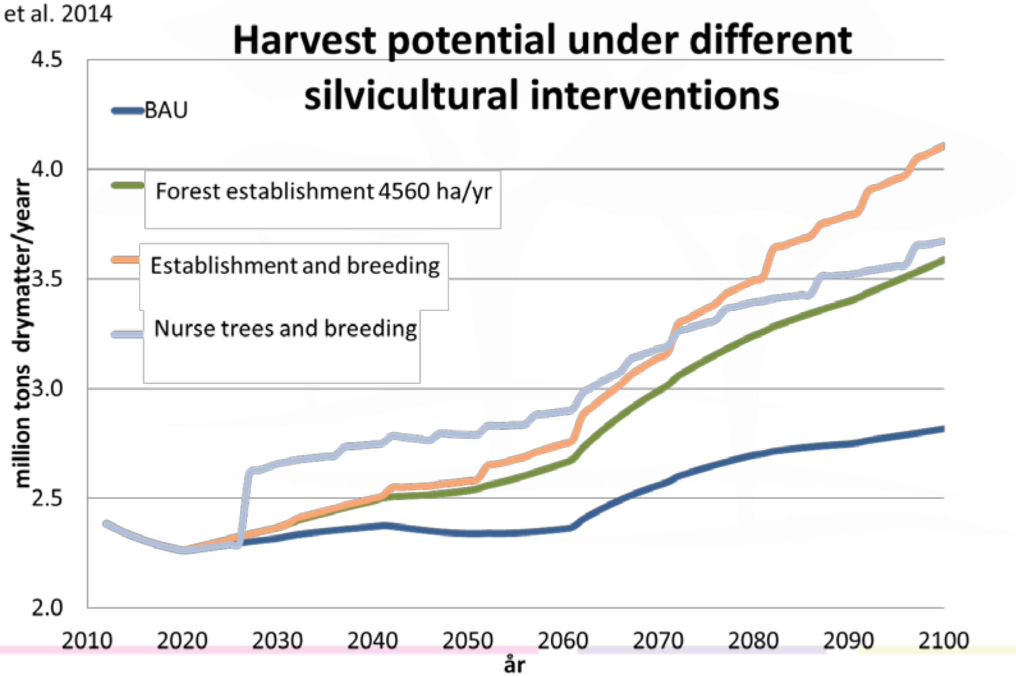
Graudal et al. 2014



Danish Forest Estate approx. 600.000 ha

Graudal et al. 2014

Increasing productivity, carbon storage and diversity in the Danish forest estate (600 000 ha)



Danish Forest Estate approx. 600.000 ha

Graudal et al. 2014

The global carbon budget (Gt C per year) for two periods

Sources and sinks (Gt/yr)	1990–1999	2000–2007	
Sources (C emissions)			
• Fossil fuel and cement	6.5 ± 0.4	7.6 ± 0.4	
• Land-use change	1.5 ± 0.7	1.1 ± 0.7	
• Total sources	8.0 ± 0.8	8.7 ± 0.8	
Sinks (C uptake)			**Pan et al. 2011**
• Atmosphere	3.2 ± 0.1	4.1 ± 0.1	
• Ocean	2.2 ± 0.4	2.3 ± 0.4	
• **Terrestrial (‘established’ forests)**	**2.5 ± 0.4**	**2.3 ± 0.5**	
• Total sinks	7.9 ± 0.6	8.7 ± 0.7	
• Global residuals	0.1 ± 1.0	0.0 ± 1.0	

- Famous table published by Pan et al in Science 2011
- Established forest lands not just as a stock but as a persistent sink for carbon of high importance for the stability of our climate

(after Pan et al. 2011) and in 2010 (CO_2 Earth, http://co2now.org/Current-CO2/CO2-Now/global-carbon-emissions.html)

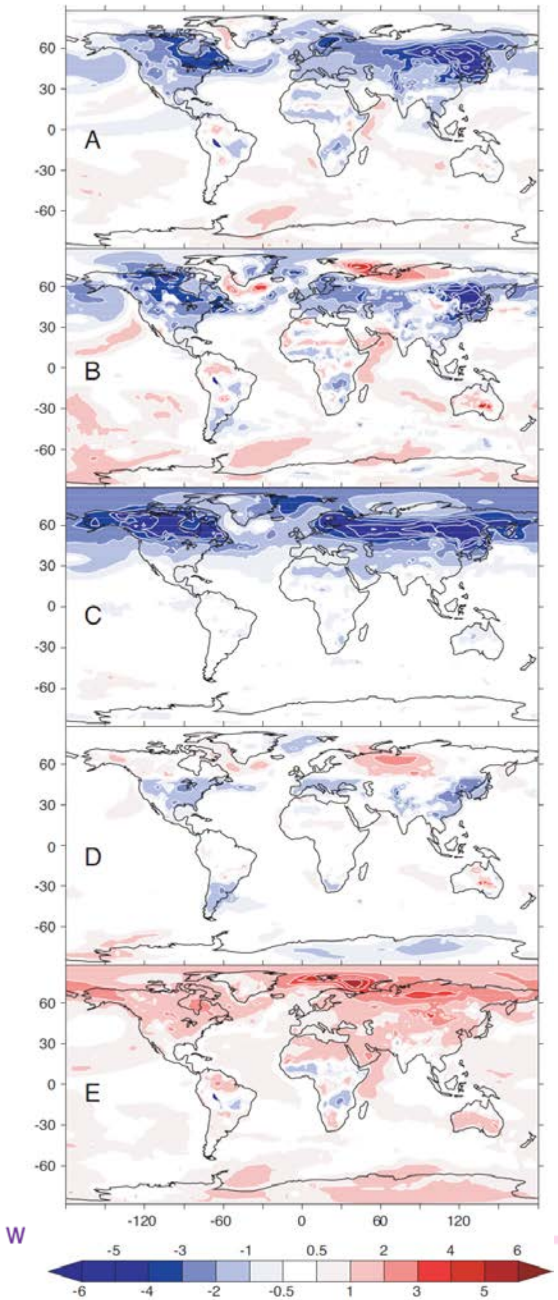
The global carbon budget (Gt C per year)

Sources and sinks (Gt/yr)	1990–1999	2000–2007	2010	2014	
Sources (C emissions)					
Fossil fuel and cement	6.5 ± 0.4	7.6 ± 0.4	9.1	9.8	
Land-use change	1.5 ± 0.7	1.1 ± 0.7	0.9	1.1	
Total sources	8.0 ± 0.8	8.7 ± 0.8	10	10.9	
Sinks (C uptake)					**Pan et al. 2011, CO_2 Earth, Global CO_2 emmissions website**
Atmosphere	3.2 ± 0.1	4.1 ± 0.1	5.0	3.9	
Ocean	2.2 ± 0.4	2.3 ± 0.4	2.4	2.9	
Residual terrestrial sink	2.6	2.4	2.6	4.1	
Total sinks	7.9 ± 0.6	8.7 ± 0.7	10	10.9	
Terrestrial ('established forests')	**2.5 ± 0.4**	**2.3 ± 0.5**	**2.6**	**?**	
Planted Forests/Trees	**1.2**	**1.4**	**1.6**	**?**	**Carle & Holmgren 2008**
Restoration				**0.29**	**IUCN 2011 (150 million ha over 50 years)**
TOF/Agroforestry		**0.2**	**0.2**	**?**	**Zomer et al. 2009, 2014, 2016**

- The table by Pan et al with added rows and columns based on different sources
- The potential of planted forests, restoration and agroforestry is huge

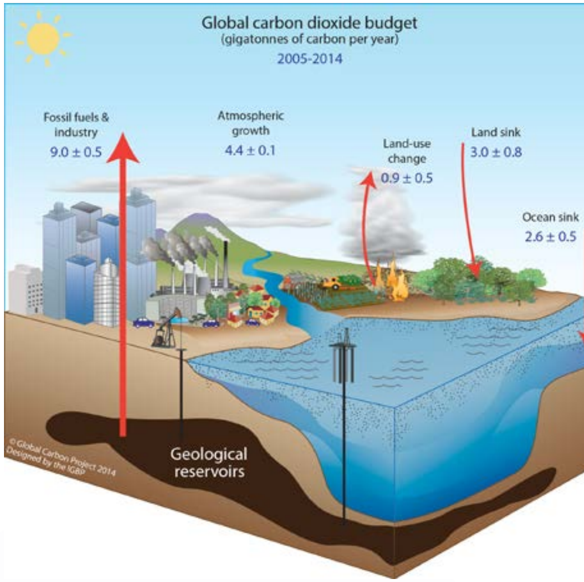
Bala et al. 2007. Proc. Natl. Acad. Sci. 104, 6550–6555. doi:http://dx.doi.org/10.1073/ pnas.0608998104.

Albedo



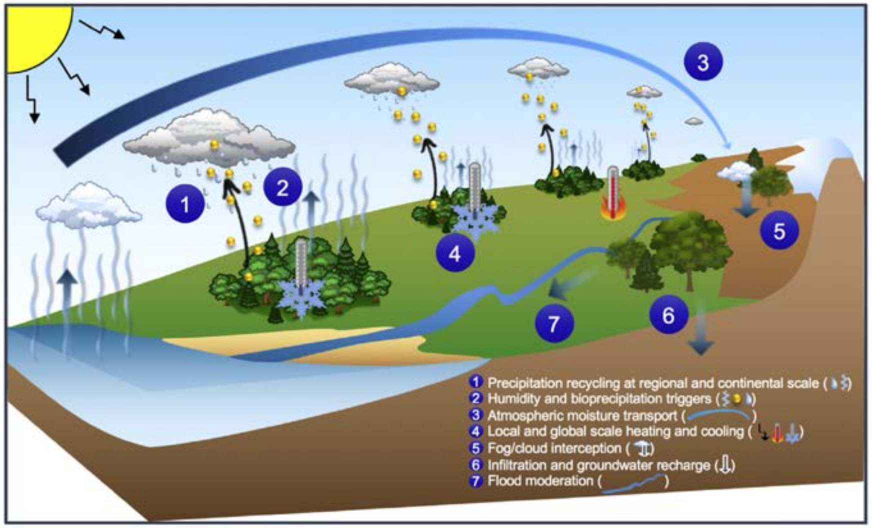
The global biochemical effect of C storage on temperature may be adjusted by biophysical effects of radiation (albedo) and non-radiative processes (evapotranspiration and turbulence)

Biochemical effect



Le Quéré et al. 2015Earth Syst. Sci. Data, 7, 349–396, 2015, www.earth-syst-sci-data.net/7/349/2015/

Non-radiative processes



Ellison et al. 2017 Global Environmental Change 43 (2017) 51–61, http://dx.doi.org/10.1016/j.gloenvcha.2017.01.002

The biophysical role of tree cover in the energy and water cycles

Change in soil moisture (green) and surface temperature (blue) during summer (dark) and over the year (light) as a result of restoration (increasing savanna woodlands under a global warming scenario)

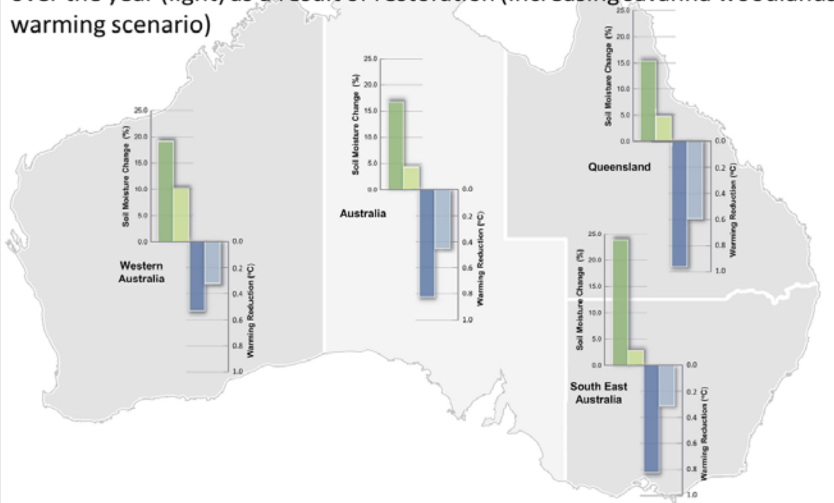


Figure 5. Summary of simulated changes in surface temperatures and near surface soil moisture between Partial Restoration and Maximum Crop for the 2056–2075 period under RCP8.5. Area average changes over restored regions of Australia (all restored regions), Western Australia, Queensland and southeast Australia are presented for summer (darker colour) and annual (lighter colour). Figure was created using Adobe Illustrator Version CC2015(19.2.0), (http://www.adobe.com/au/products/illustrator.html#).

Syktus and McAlpine 2016 More than carbon sequestration: Biophysical climate benefits of restored savanna woodlands Nature Scientific Reports | 6:29194 | DOI: 10.1038/srep29194

Syktus and McAlpine 2016

A modelling study of woodland restoration in Australia show that restoration increases soil moisture and decreases temperature

The biophysical role of tree cover in the energy and water cycles

Net-effect of LCMC on radiative and non-radiative) forces

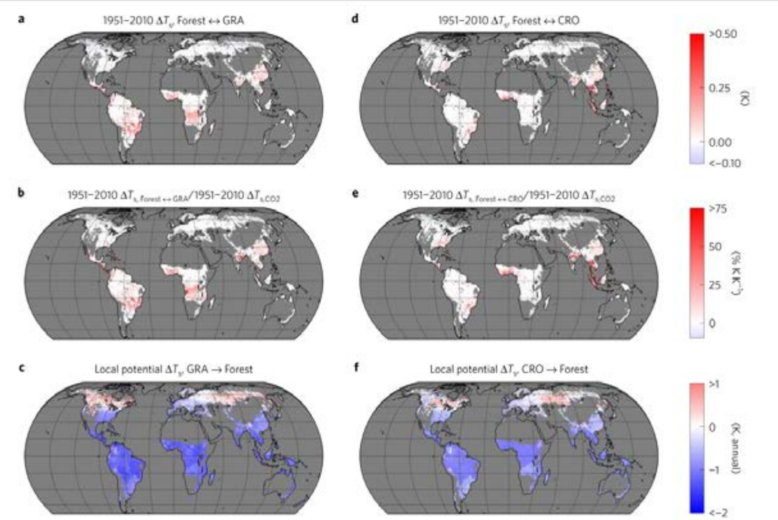


Figure 4 | Local effectiveness of local re-/afforestation. a,d, The grid cell ΔT_s attributable to the net conversion of forests to/from grasslands or croplands between 1951 and 2010. **b,e**, The grid cell ΔT_s from LCMC relative to that which is attributable to the global mean CO_2 radiative forcing between 1951 and 2010. **c,f**, The local ΔT_s from the re-/afforestation of grasslands or croplands (see Methods and Supplementary Information). 'Forests' equal the mean of ENF and DBF in the boreal and temperate zones, and EBF in the tropics.

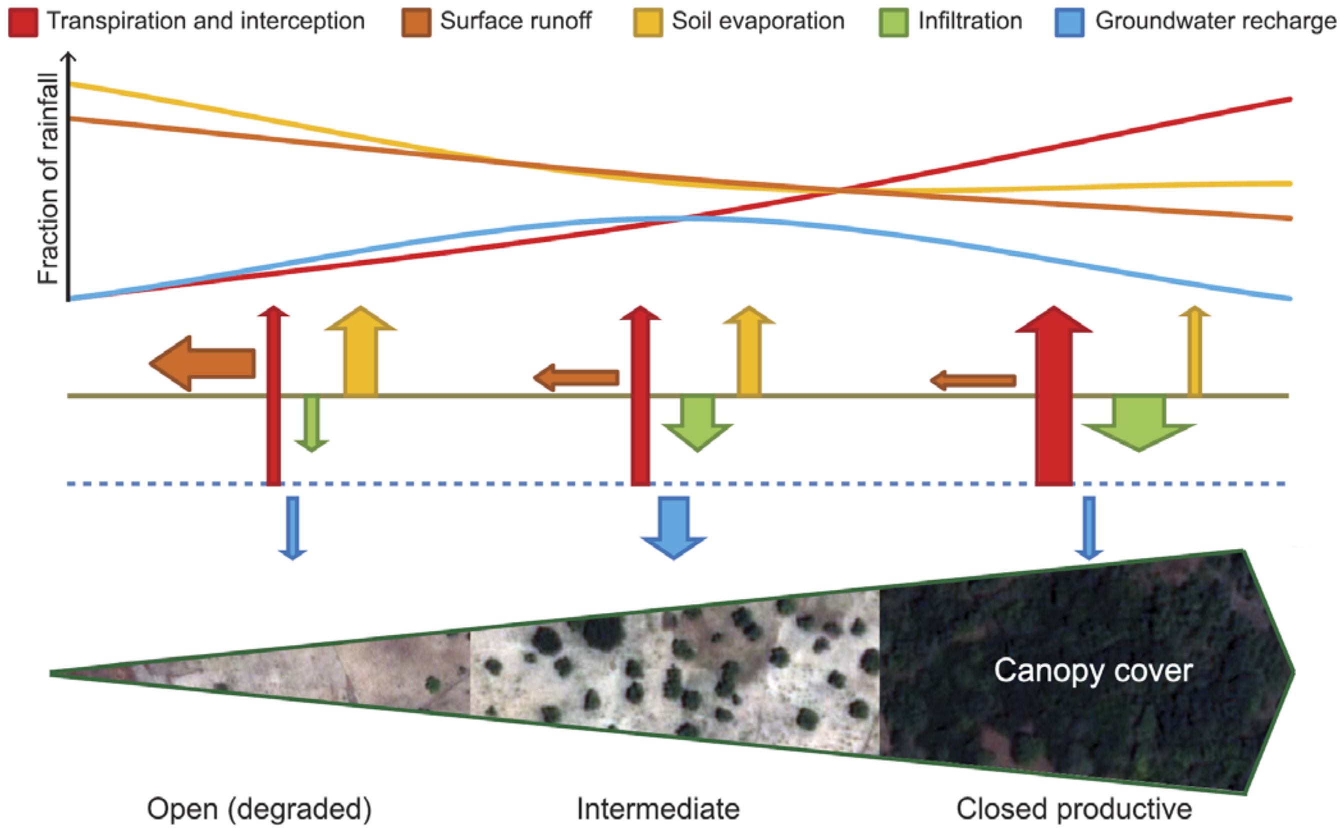
Forest cover gain in most regions south of the northern temperate latitudes leads to notable local annual cooling

Bright et al. 2017

Global simulation of the combined effect of land cover and land management change (LCMC) on temperature : forest cover gain in most regions south of the northern temperate latitudes leads to notable local annual cooling

Bright et al. 2017 NATURE CLIMATE CHANGE DOI: 10.1038/NCLIMATE3250

Tree density and ground water recharge in the seasonally dry tropics



In the tropics, agroforestry result in increased infiltration capacity (Ilstedt et al., 2007).

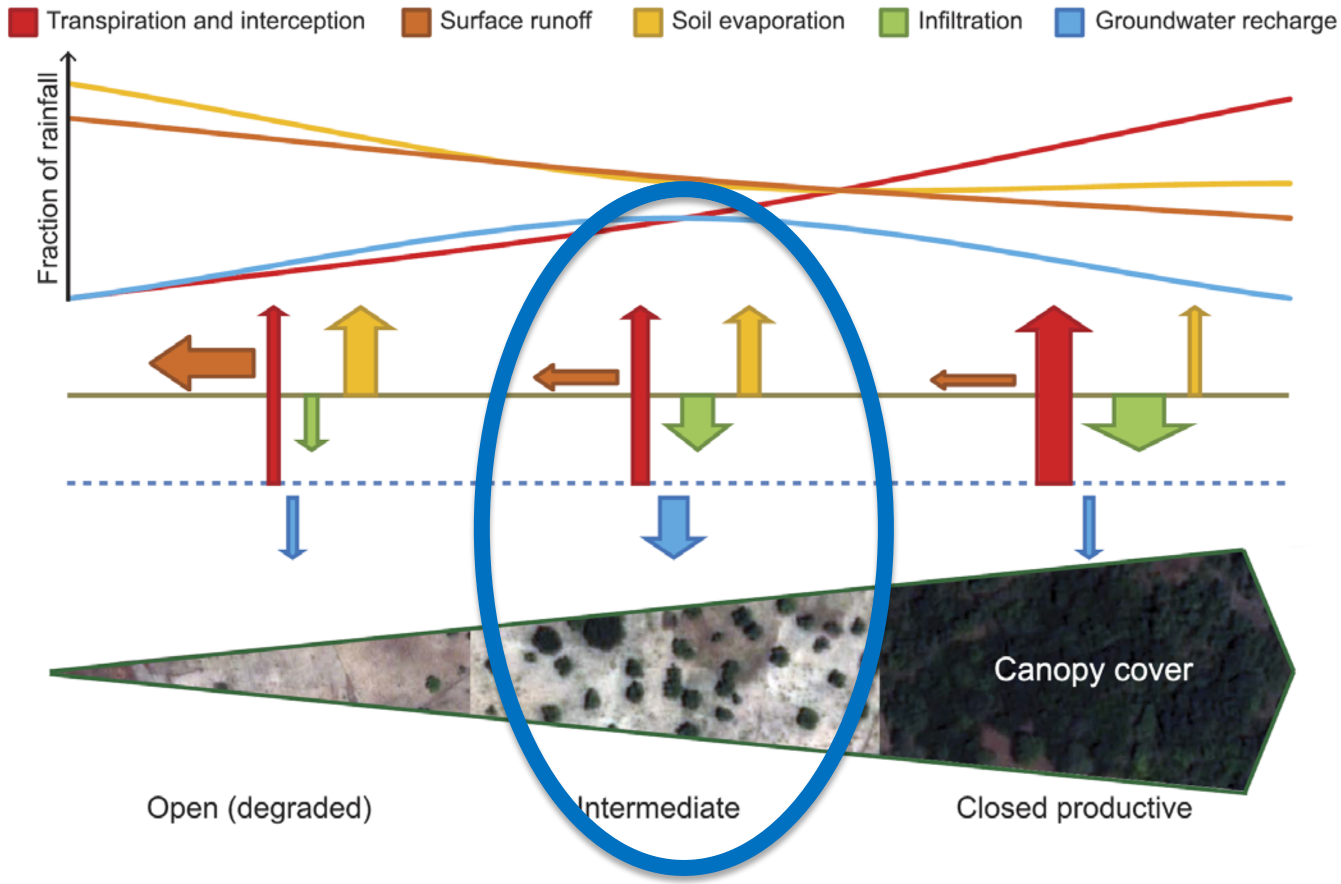
Intermediate tree densities on degraded lands may maximize groundwater recharge (Ilstedt et al., 2016).

Figure 1. Conceptual water budget of the *optimum tree cover theory*. Optimum groundwater recharge occurs at intermediate tree cover in seasonally dry tropical areas. Without trees, surface runoff and soil evaporation are high, leading to low groundwater recharge despite low transpiration. In closed productive forests, despite low surface runoff and soil evaporation, total transpiration and interception are high, again leading to low groundwater recharge. At an intermediate canopy cover, low surface runoff and evaporation as well as intermediate transpiration optimize groundwater recharge. The pan-sharpened satellite images were created from a WorldView-2 image from 21 October 2012 using ERDAS Imagine 2013 software (http://www.hexagongeospatial.com/products/producer-suite/erdas-imagine).

Ilstedt et al. 2016 Nature Scientific Reports | 6:21930 | DOI: 10.1038/srep21930

Ellison et al. 2017 Global Environmental Change 43 (2017) 51–61, http://dx.doi.org/10.1016/j.gloenvcha.2017.01.002

Tree density and ground water recharge in the seasonally dry tropics



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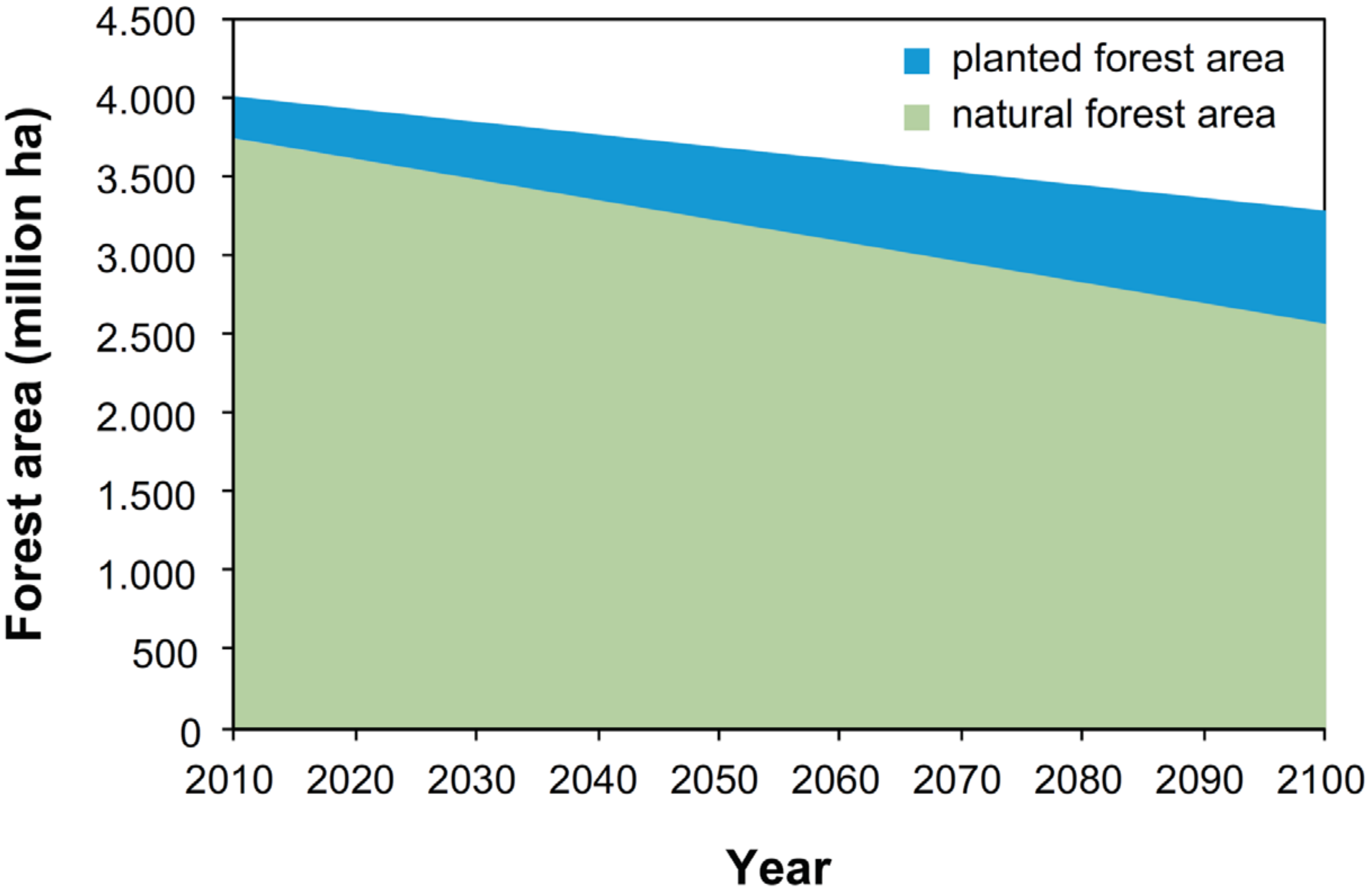
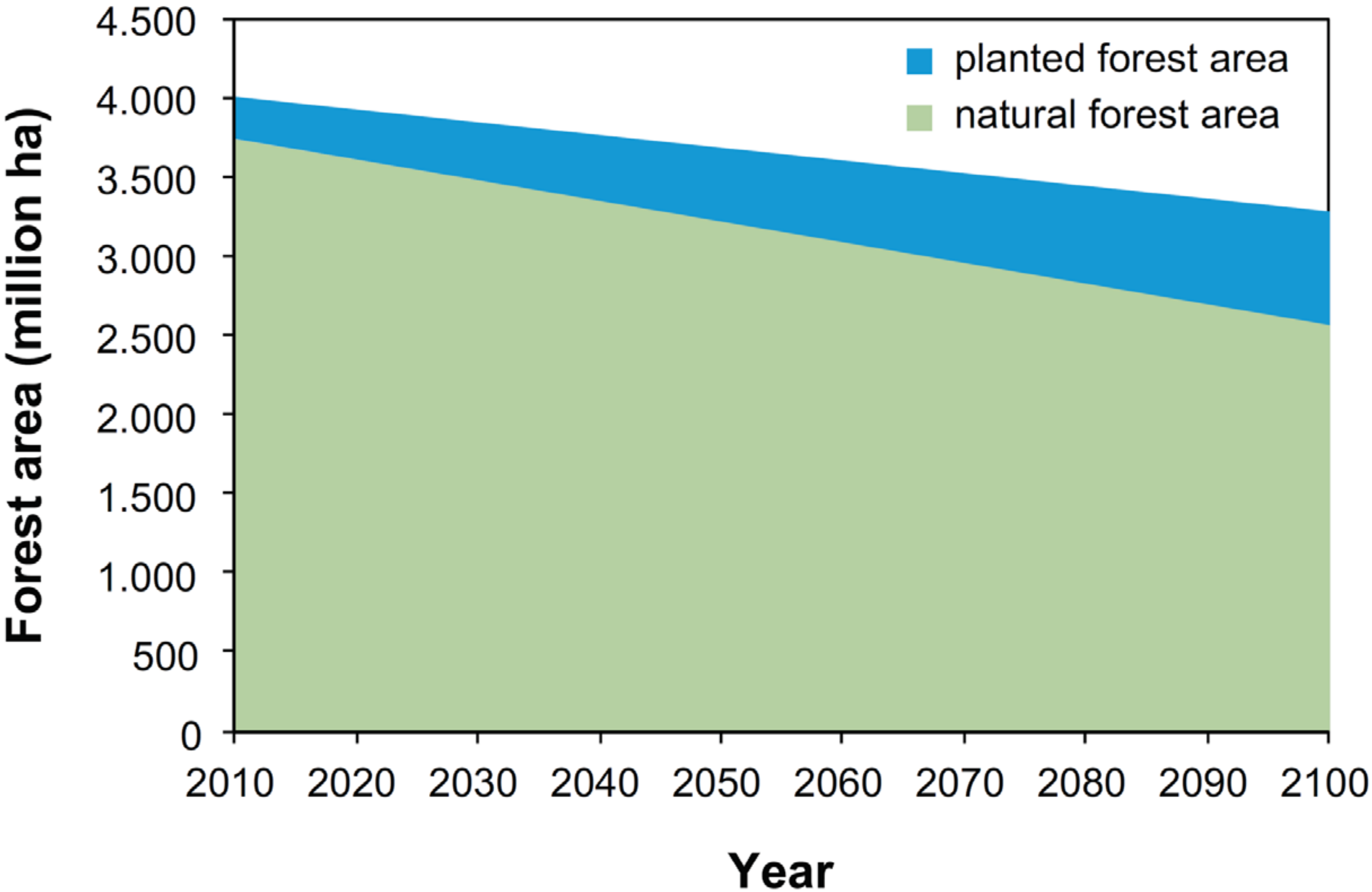
The global perspective of forest area composition



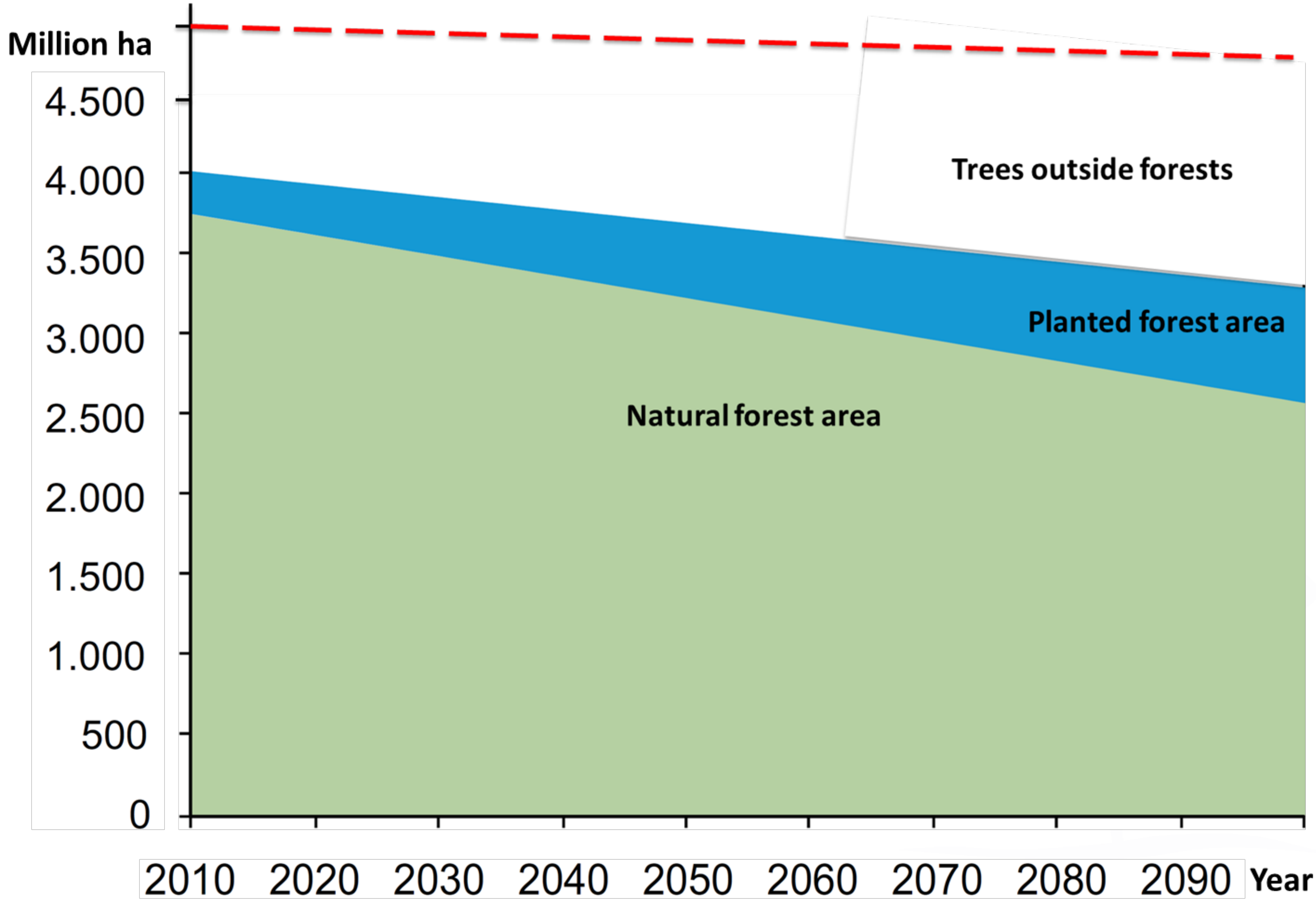
Brockerhoff et al 2012

The global perspective of forest area composition



Brockerhoff et al 2012

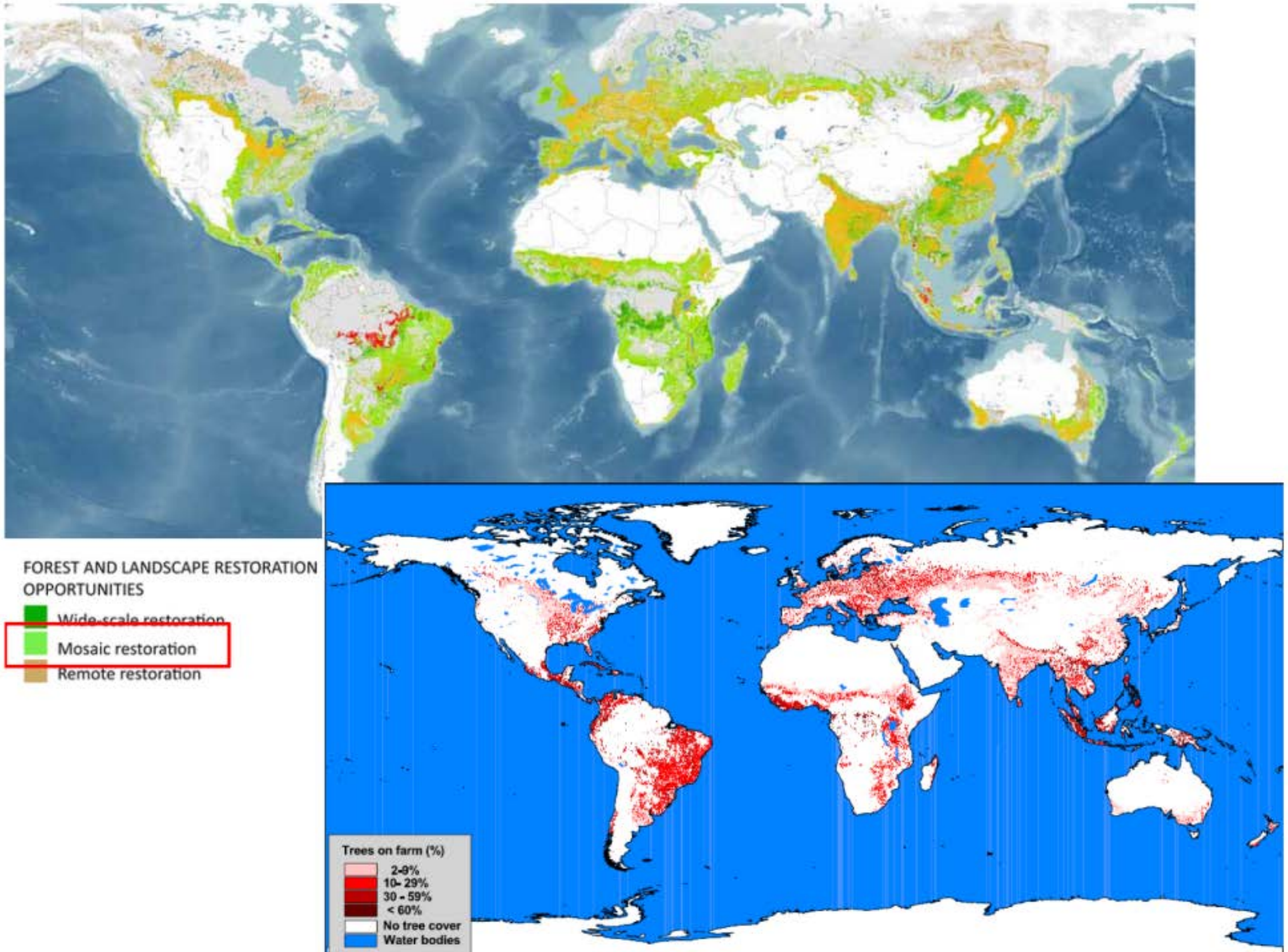
+ Trees out side forests/agroforests

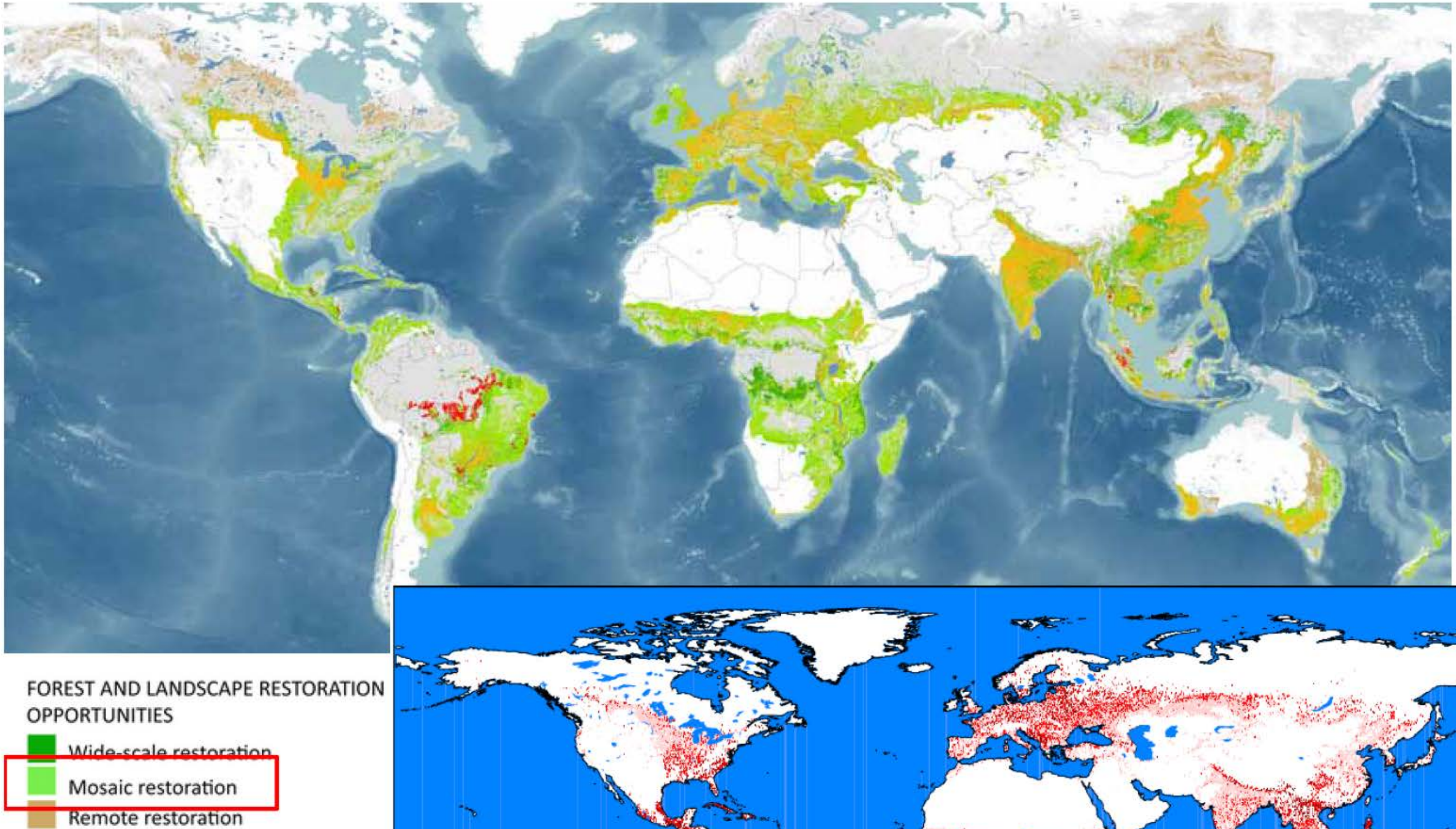

Million ha
4.500
4.000
3.500
3.000
2.500
2.000
1.500
1.000
500
0
Trees outside forests
Planted forest area
Natural forest area
2010
2020
2030
2040
2050
2060
2070
2080
2090
Year

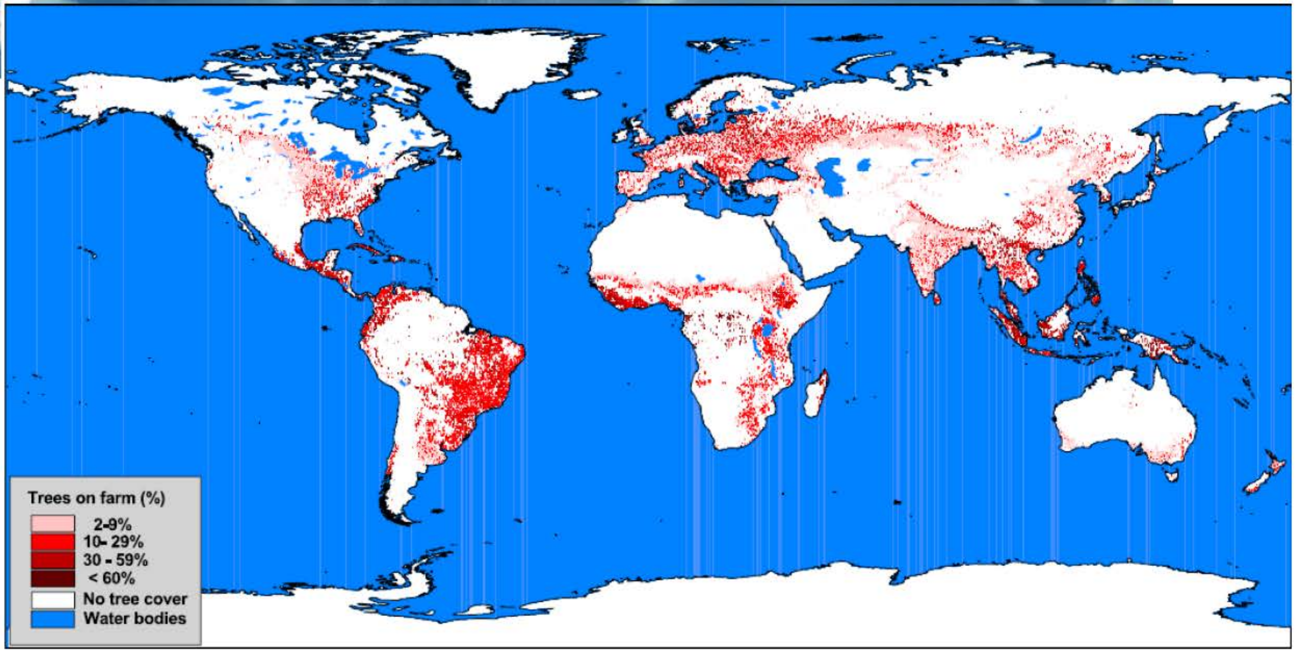

BONN CHALLENGE
on forests, climate change and biodiversity 2011
A World of Opportunity
for Forest and Landscape Restoration
FOREST AND LANDSCAPE RESTORATION OPPORTUNITIES
Wide-scale restoration
Mosaic restoration
Remote restoration
OTHER AREAS
Agricultural lands
Recent tropical deforestation
Urban areas
Forest without restoration needs
WORLD RESOURCES INSTITUTE
South Dakota State University
IUCN
PROFOR
Forestry Commission

WRI 2011

Most restoration needs are in the ‘mosaic’ (agroforestry) zone







TOF/ Agroforestry

Foci of agroforestry in restoration

(overview of this presentation)

- Mitigation of climate change
  - Biochemical (carbon sequestration)
  - Biophysical (radiative and non-radiative effects (water))

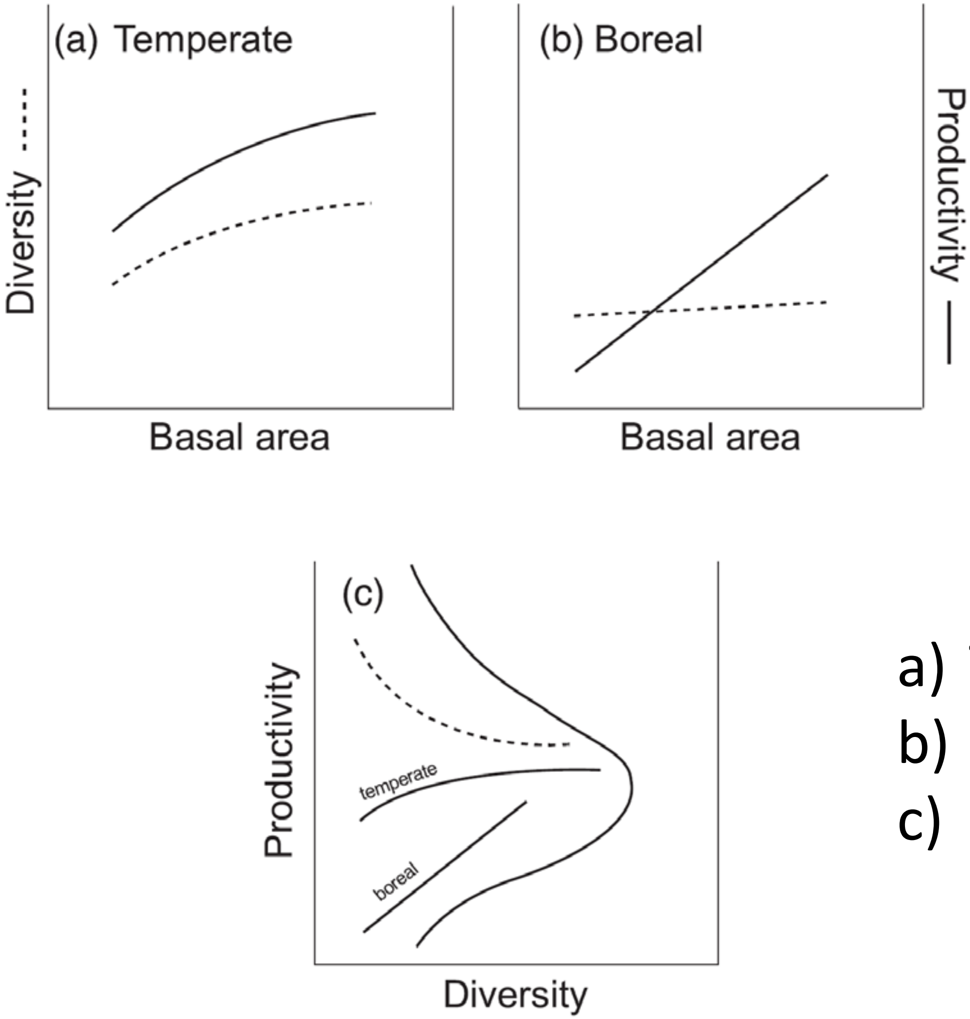
- Adaptation
  - Environmental and economic resilience (biodiversity, soils, ROI)
    - Productivity of mixed systems
    - Closing the yield gap

- Adequate planting material ("tree genetic resources" often constitutes a bottleneck in (successful) large-scale restoration
  - The seed challenge

Advantages of mixed systems

- Mixed systems are often 'resource conserving'
  - Nutrient recycling, Microclimate modification, Water-use efficiency, Species diversity, Reduced agrochemical pollution (Prabhu et al. 2015)
- Many recent studies support that mixed species or varieties ('biodiverse') systems are often more productive than single species or variety systems
    - Cardinale et al. 2011, Paquette and Messier 2011, Zeller et al. 2012, Hulvey et al. 2013, Pretzsch et al. 2013a,b,c, and 2015, Zuppinger-Dingley et al. 2014
  - Over-yielding and over-density possibly result from several different types of interactions (light-, water-, and nutrient-related).
  - A better understanding of the underlying causes of over-yielding/under-yielding is essential for both science and practice (Pretzch et al. 2015)

The productivity-diversity debate

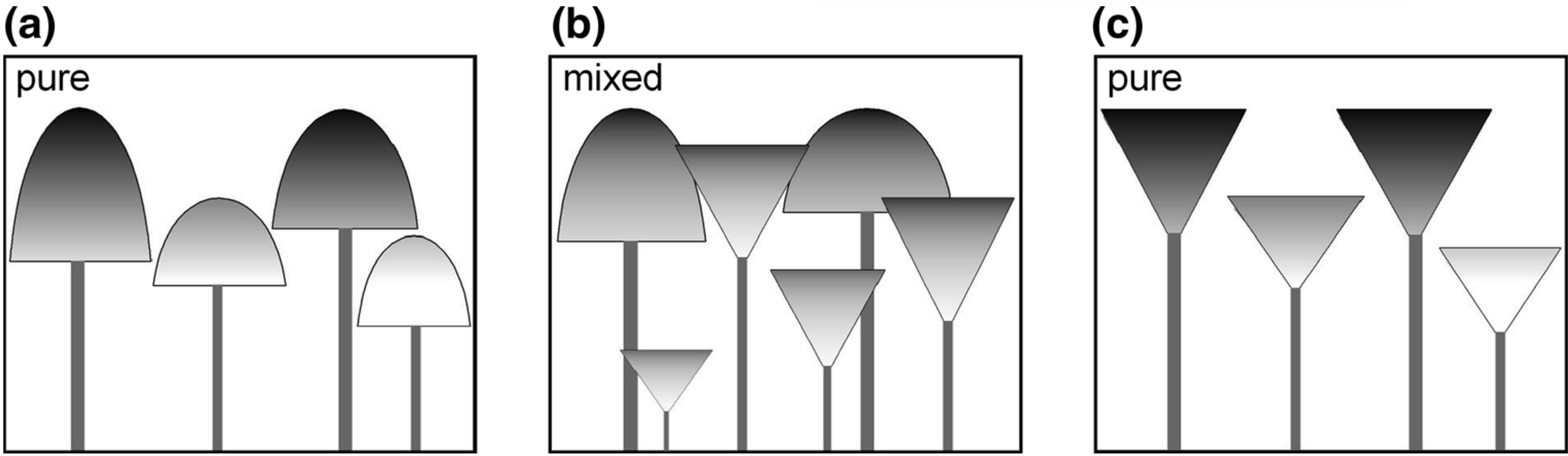


a) Temperate forest
b) Boreal forest
c) Fertile and ruderal habitats

A. Paquette and C. Messier 2011, Global Ecology and Biogeography, 20, 170–180, DOI: 10.1111/j.1466-8238.2010.00592.x

Biodiverse intensification

- Wider tree crown extension, multi-layering, and higher stocking density may all contribute to 'overyielding'
- Mixing can increase mean tree productivity (dry matter) up to 60% and stand density up to 50%
- On average productivity increases by 25–50%
- Effects in terms of over-yielding are the highest on poor sites and diminish the better the sites are

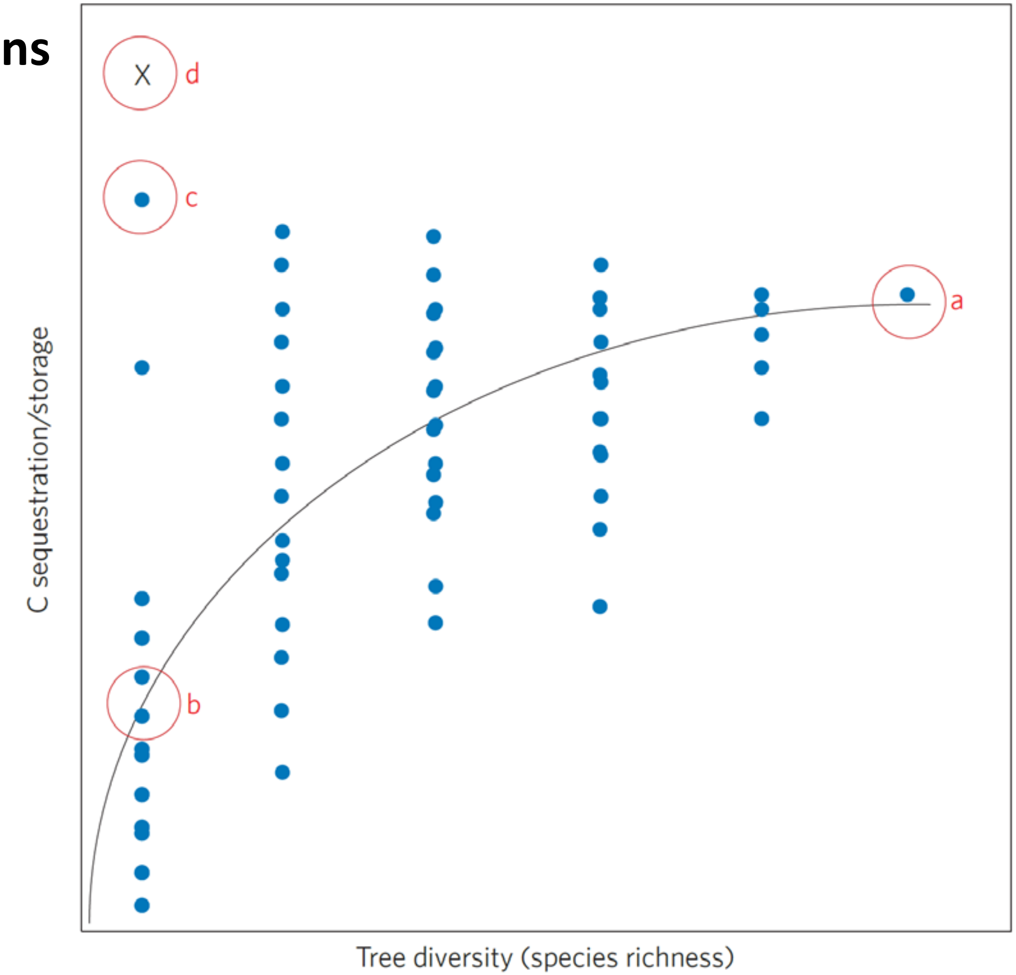


(Fig. 3, Pretzsch et al 2015)
Pretch et al. (2013-2015)

C sequestration and storage comparisons in mixed versus monoculture plantings

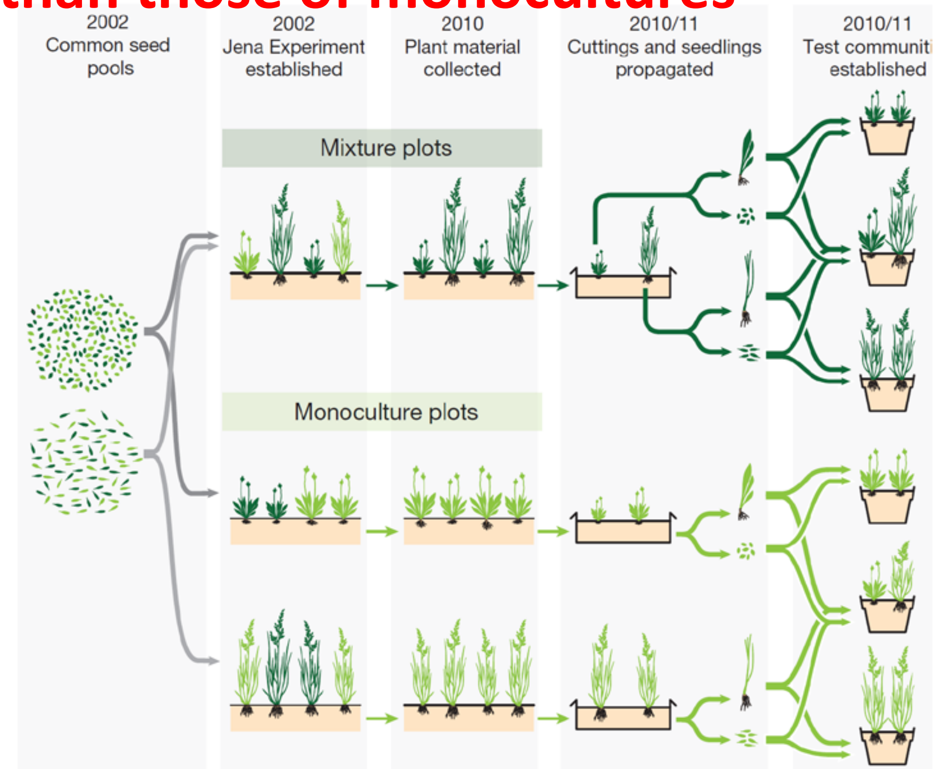
- Tree mixes stored ≥ carbon as monocultures of the mixture's most productive species.
- In mixed stands, in particular nitrogen-fixing trees increased stand biomass.
- Tree richness further includes the contribution of diversity to total forest carbon-pool development, carbon-pool stability and the provision of extra ecosystem services.
- **Suggest for carbon plantings: (1) increased tree species richness; and (2) the addition of species that contribute to carbon storage and other target functions.**

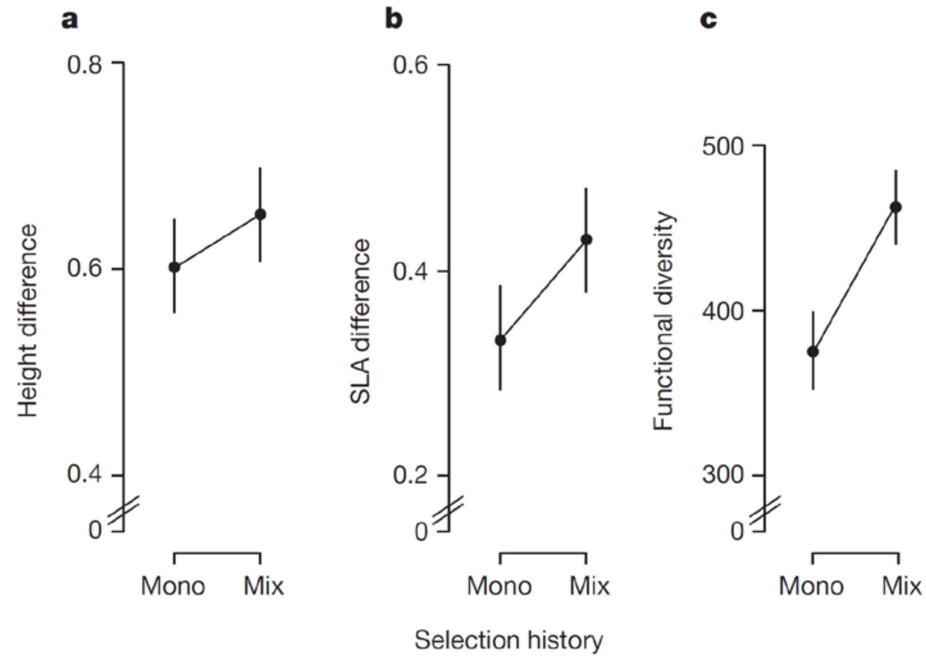
Hulvey et al 2013 NATURE CLIMATE CHANGE | VOL 3 | OCTOBER 2013 | www.nature.com/natureclimatechange, DOI: 10.1038/NCLIMATE1862



X; Monoculture of high-productivity trees not included in other treatments.
a; C sequestration/storage in most diverse mixture.
b; Average C sequestered/stored in monocultures (excluding 'X').
c; Most productive monoculture included in mixtures.
d; C sequestered/stored in X.

In grassland plants the yields of diverse plant communities are larger than those of monocultures





Plants selected in mixtures show character displacement between species when grown in mixture.

Diverse plant communities enable higher crop yields than monocultures because of selection for niche differentiation; plant species in communities occupy all niches available in ecosystems, enabling a more effective use of soil nutrients, light and water.

12 species over 8 years, four functional groups (grasses, small and tall herbs, and legumes

Zuppinger-Dingley et al 2014. Selection for niche differentiation in plant communities increases biodiversity effects. *Nature*, 515: 108-111.

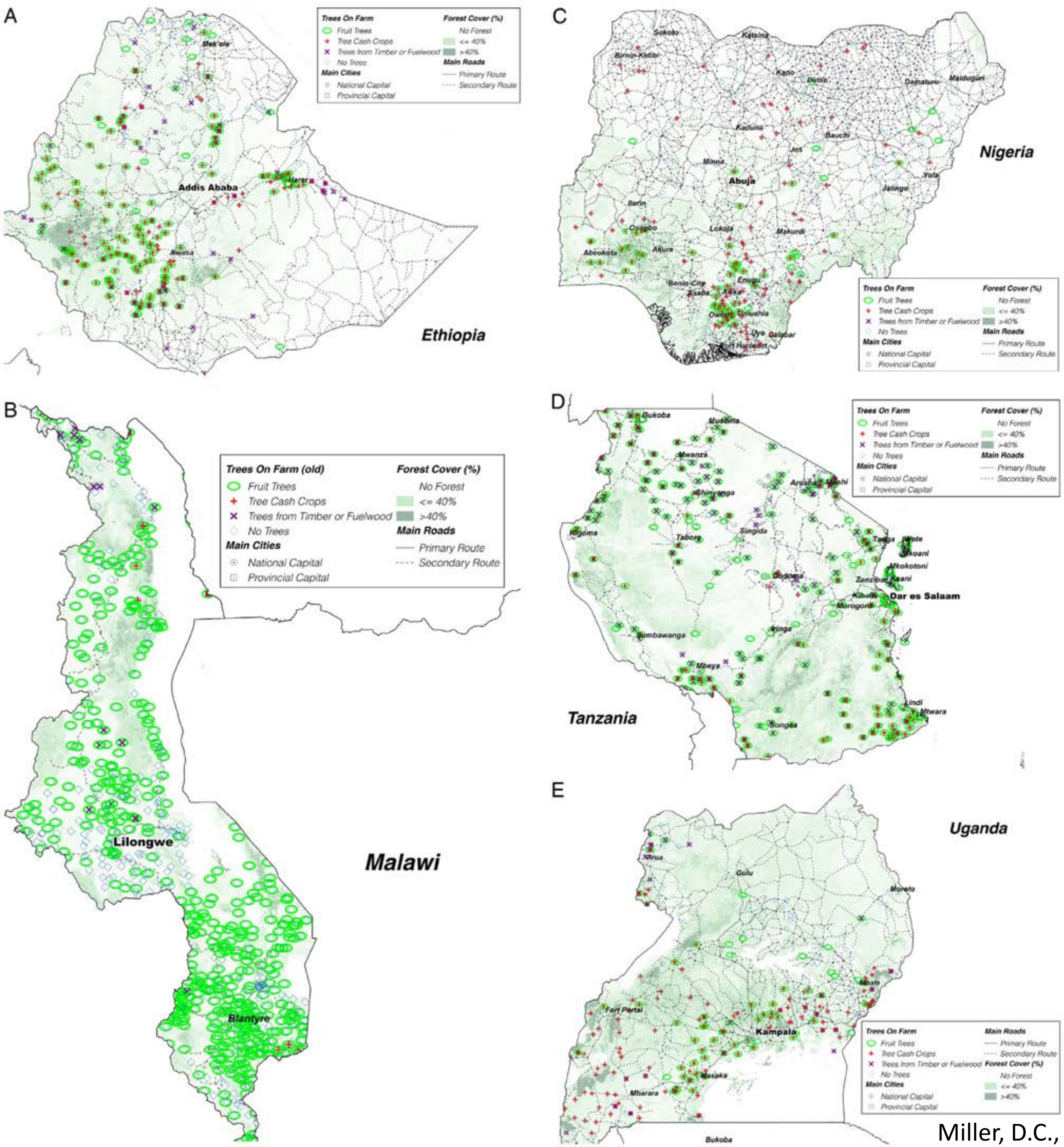
The economy of mixed systems

The economic benefits of agroforestry accrue to smallholders through

- increased on-farm profitability
- higher and more diversified income flows from the sale of agroforestry products and services
- once lesser-known agricultural products have rapidly emerged from obscurity to become globally known, high value crops demanded at home and abroad
- capacity to invest their scarce productive assets in more intensive production systems

Prabhu et al. 2015 Agroforestry: Realizing the promise of an agroecological approach

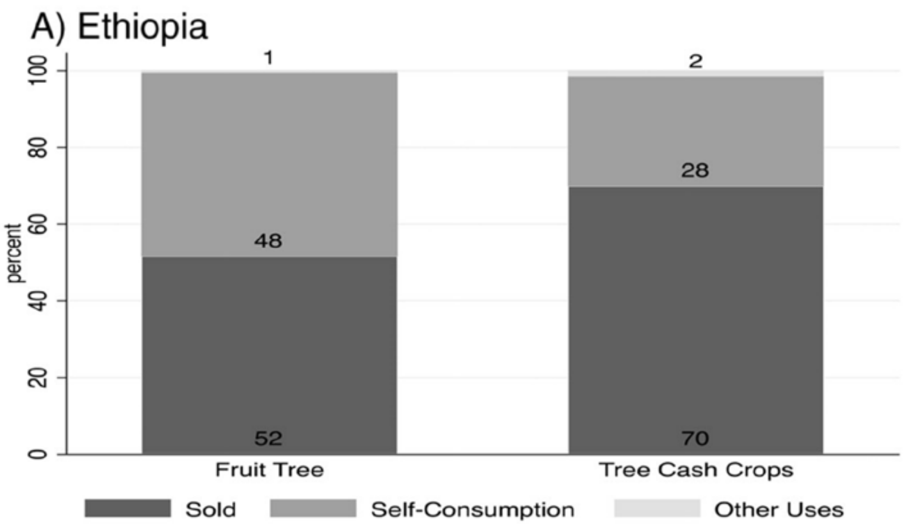
Prevalence, Economic Contribution, and Determinants of Trees on Farms across Sub-Saharan Africa

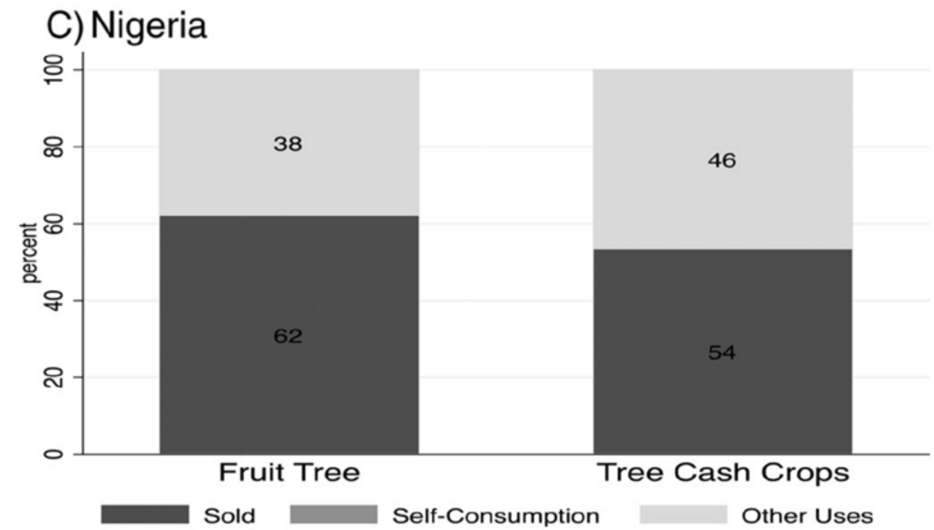


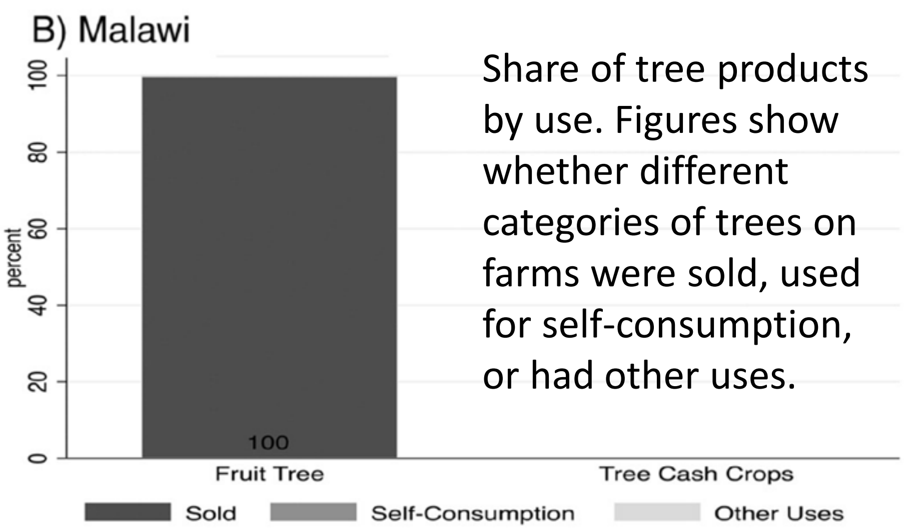
- Trees on farms are widespread.
- On average, almost a third of rural smallholders grow trees.

Miller, D.C., et al., Forest Policy and Economics (2016), http://dx.doi.org/10.1016/j.forpol.2016.12.005

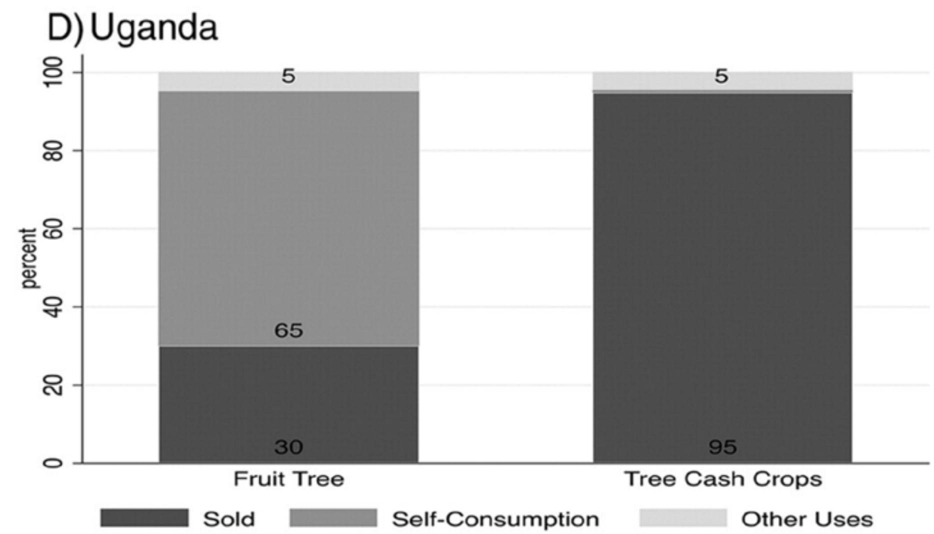
Prevalence, Economic Contribution, and Determinants of Trees on Farms across SSA







Share of tree products by use. Figures show whether different categories of trees on farms were sold, used for self-consumption, or had other uses.



- **Trees account for an average of 17% of total annual gross income for tree-growing households** and 6% for all rural households

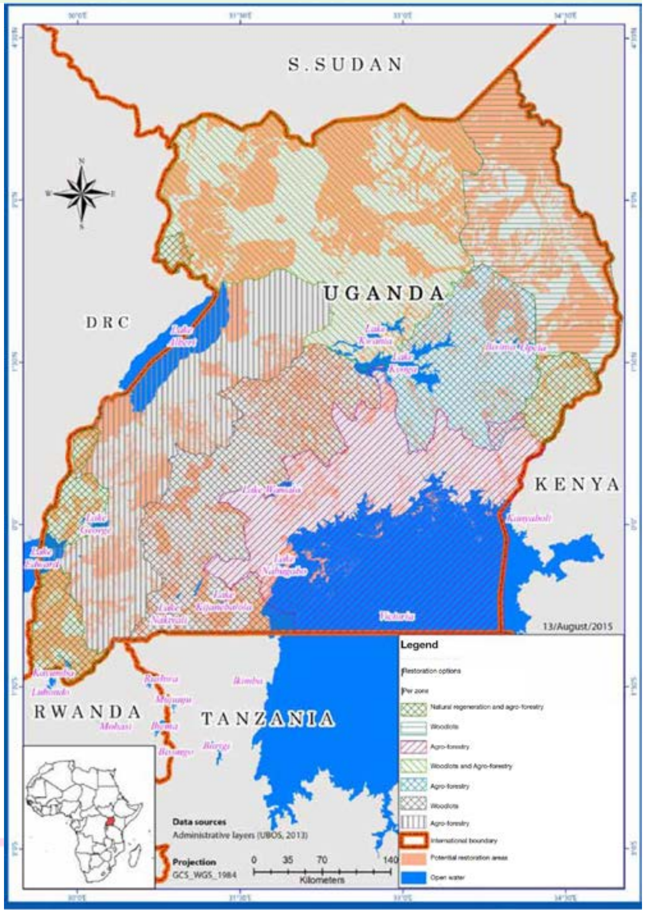
Miller, D.C., et al., Forest Policy and Economics (2016), http://dx.doi.org/10.1016/j.forpol.2016.12.005

Table 14: Results from Cost Benefit Analysis of Restoration Activities in Uganda

	Agroforestry		Woodlots		Natural regeneration	
Discount Rate	10%	16%	10%	16%	10%	16%
	Value (UGX/Ha)	Value (UGX/Ha)	Value (UGX/Ha)	Value (UGX/Ha)	Value (UGX)	Value (UGX)
Present Value of Costs	1,274,893	908,642	5,377,609	3,567,785	94,269	61,772
Present Value of Benefits	17,334,162	8,135,547	7,993,122	4,502,454	2,967,154	1,542,919
NPV	16,059,269	7,226,905	2,615,513	934,669	2,872,885	1,481,147
Benefit Cost Ratio	13.60	8.95	1.49	1.26	31.48	24.98

Cost-benefit analyses are made as part of some ROAM planning exercises, here shown for Uganda

All restoration interventions (agroforestry, woodlots and natural regeneration) **have positive benefit cost ratios** with natural regeneration being highest, agroforestry second and woodlots lowest.



Forest Landscape Restoration Opportunity Assessment Report for Uganda (2016), Ministry of Water and Environment – Uganda; IUCN. x + 42pp.

However, the **revenue of natural regeneration is solely dependent on assumed payment for environmental services** of carbon sequestration and watershed protection

Table 13 Enterprise Budget for Agroforestry, Woodlots, and Natural Regeneration

	Agroforestry **Value (UGX/Ha)**	**Woodlots** **Value (UGX /Ha)**	**Natural regeneration Value (UGXha)**
Variable costs			
Pruning	20,000	50,000	-
Seedlings	50,000	555,500	-
Planting	10,000	222,200	-
Thinning	-	300,000	-
Timber harvest	3,000,000	6,000,000	-
Fixed costs			
Site preparation	300,000	300,000	-
Weeding	60,000	360,000	-
Protection/Patrolling	10,000	10,000	10,000
Revenue			
Crop yields	1,250,000	-	
Timber	35,000,000	10,500,000	
Firewood	200,000	400,000	100,000
Firewood from second thinning	-	400,000	
Firewood from third thinning	-	10,800,000	
Above ground biomass carbon	840,000	1,680,000	1,680,000
Belowground biomass carbon	1,400,000	1,400,000	1,400,000
Watershed protection (quantity and quality)	346,000	346,000	346,000

Forest Landscape Restoration Opportunity Assessment Report for Uganda (2016), Ministry of Water and Environment – Uganda; IUCN. x + 42pp.

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  - Biochemical (carbon sequestration)
  - Biophysical (radiative and non-radiative effects (water))
- Adaptation
  - Environmental and economic resilience (biodiversity, soils, ROI)
    - Productivity of mixed systems
    - Closing the yield gap
- Adequate planting material ("tree genetic resources" often constitutes a bottleneck in (successful) large-scale restoration
  - The seed challenge

The Seed challenge

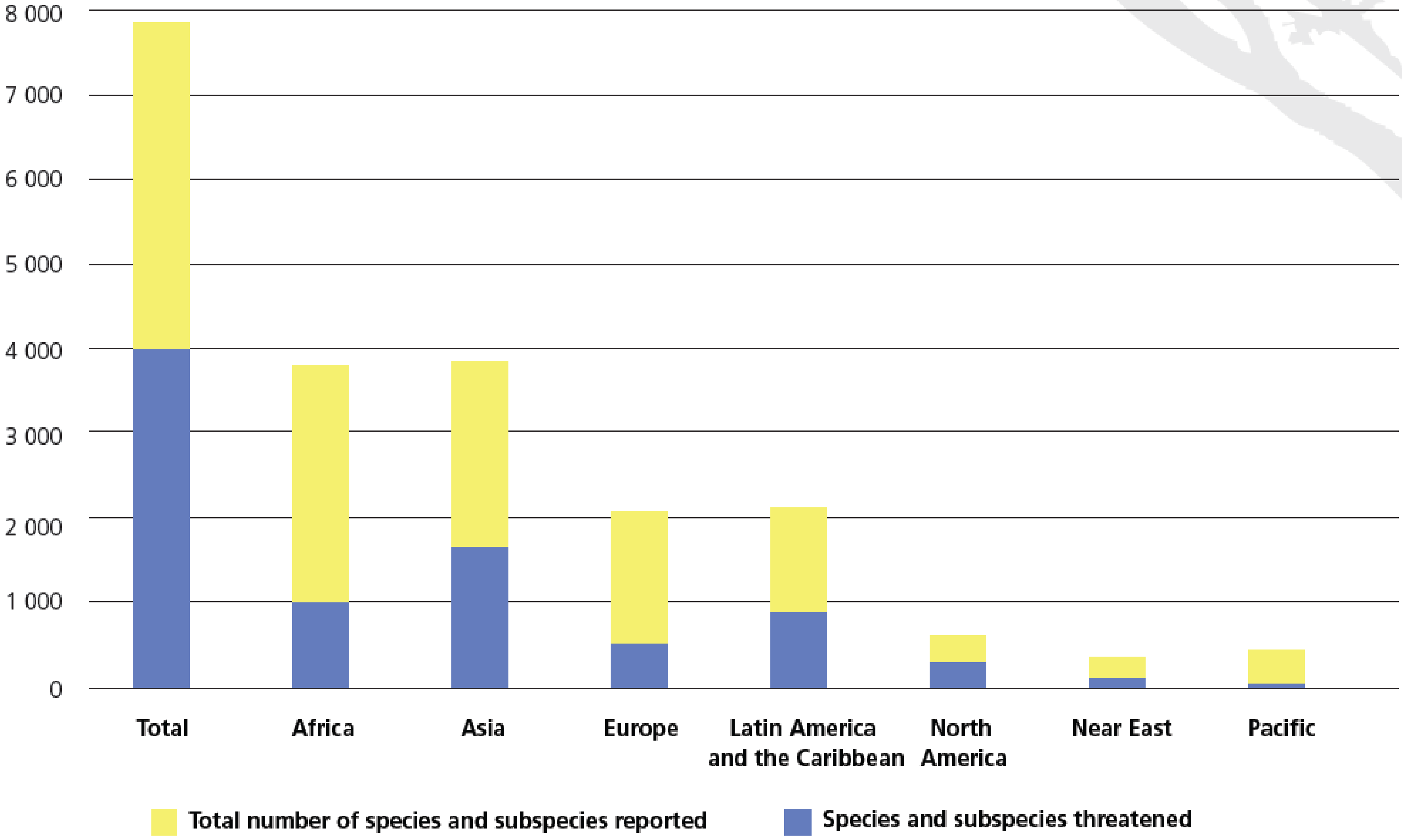
A 'back of the envelope' estimate based on the case of Ethiopia

- Restoration applying a mix of planting, direct sowing and natural regeneration will require some 250-1000 tons of seed per million ha.
- At country level a typical range of species will be in the order of 10-20 species
- At global level this may increase to several hundreds of species and **in the order of billions of tons of seed**, not to forget large amounts of vegetative material

Tree species diversity and within species variation and selection

- Some 70,000 woody species exist (50,000-100,000)
- Around 8,000 are mentioned in SoW FGR (2014)
- Some 2,400 are reported as actively managed
- Around 3,000 are of known value in agroforestry
- Around 700 are included in tree improvement programmes
- Genetic level information is available for 500-600 species; 240 are included in biotechnology research
- Very few are intensively bred
- Conservation **status of the genetic resources of most species are not well known**

FAO 2014 SoW FGR 2014



About half of the nearly 8000 species in SoW FGR are reported as threatened

FAO 2014

ECOLOGY

Estimating the global conservation status of more than 15,000 Amazonian tree species

10.1126/sciadv.1500936

Hans ter Steege,[1,2]* Nigel C. A. Pitman,[3,4] Timothy J. Killeen,[5] William F. Laurance,[6] Carlos A. Peres,[7] Juan Ernesto Guevara,[8,9] Rafael P. Salomão,[10] Carolina V. Castilho,[11] Iêda Leão Amaral,[12] Francisca Dionízia de Almeida Matos,[12] Luiz de Souza Coelho,[12] William E. Magnusson,[13] Oliver L. Phillips,[14] Diogenes de Andrade Lima Filho,[12] Marcelo de Jesus Veiga Carim,[15] Mariana Victória Irume,[12] Maria Pires Martins,[12] Jean-François Molino,[16] Daniel Sabatier,[16] Florian Wittmann,[17] Dairon Cárdenas López,[18] José Renan da Silva Guimarães,[15] Abel Monteagudo Mendoza,[19] Percy Núñez Vargas,[20] Angelo Gilberto Manzatto,[21] Neidiane Farias Costa Reis,[22] John Terborgh,[4] Katia Regina Casula,[22] Juan Carlos Montero,[12,23] Ted R. Feldpausch,[14,24] Euridice N. Honorio Coronado,[14,25] Alvaro Javier Duque Montoya,[26] …

We show that the trends observed in Amazonia apply to trees throughout the tropics, and we predict that most of the world's >40,000 tropical tree species now qualify as globally threatened

Ter Stege et al 2016, Sci. Adv.

Estimates of extinction risk for Amazonian plant and animal species are rare and not often incorporated into land-use policy and conservation planning. We overlay spatial distribution models with historical and projected deforestation to show that at least 36% and up to 57% of all Amazonian tree species are likely to qualify as globally threatened under International Union for Conservation of Nature (IUCN) Red List criteria. If confirmed, these results would increase the number of threatened plant species on Earth by 22%. We show that the trends observed in Amazonia apply to trees throughout the tropics, and we predict that most of the world's >40,000 tropical tree species now qualify as globally threatened. A gap analysis suggests that existing Amazonian protected areas and indigenous territories will protect viable populations of most threatened species if these areas suffer no further degradation, highlighting the key roles that protected areas, indigenous peoples, and improved governance can play in preventing large-scale extinctions in the tropics in this century.

INTRODUCTION

Amazonian forests have lost ~12% of their original extent and are projected to lose another 9 to 28% by 2050 (*1*, *2*). The consequences of ongoing forest loss in Amazonia (here all rainforests of the Amazon basin and Guiana Shield) are relatively well understood at the ecosystem level, where they include soil erosion (*3*, *4*), diminished ecosystem services (*5*–*8*), altered climatic patterns (*5*, *7*, *9*–*11*), and habitat degradation. By contrast, little is known about how historical forest loss has affected the population sizes of plant and animal species in the basin and how ongoing deforestation will affect these populations in the future.

RESEARCH ARTICLE

ECOLOGY

10.1126/sciadv.1500936

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oost F. Duivenvoord
. Comiskey,[36] Gabrie
Vincentini,[13] Thais
er,[43] Leandro Valle F
,[13] Fernanda Coelho
o,[13] Eduardo Ventic
nkel,[53] Eliana M. Jim
a,[12] Marcos Silveira,
des,[62] Naara Ferreir
Castaño Arboleda,[18]
Fernando Phillips,[68]
Matos Bonates,[12]
net,[72] Bruce Hoffmar
mir R. Ruschell,[76] Nat
elo Trindade Nascim
Milton Tirado,[85]
Vriesendorp,[3] Opheli
n-Rios,[65] Cid Ferreira
do,[26] Daniel Villarroe
uamantupa-Chuquim
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INTRODUCTION

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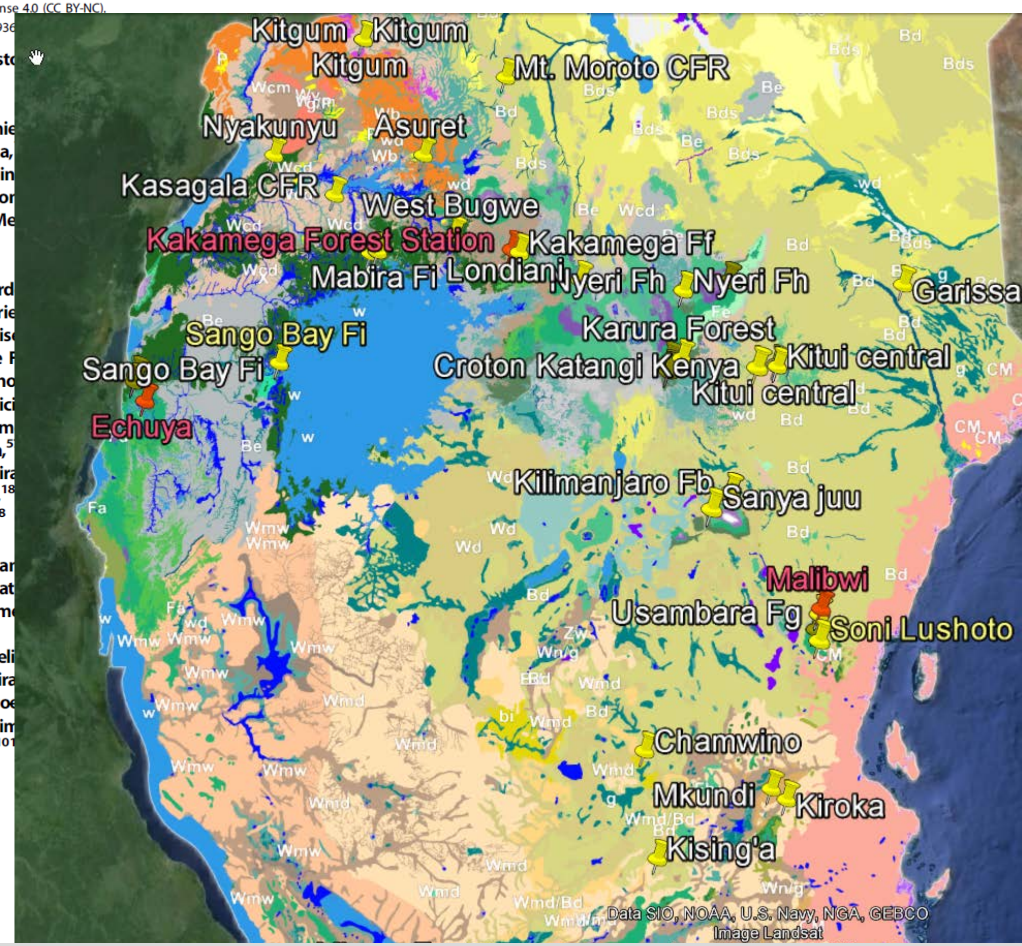
Mobilization and characterization of the resource is critical



Croton megalocarpus (NTSC collaboration Kenya, Uganda, Tanzania)

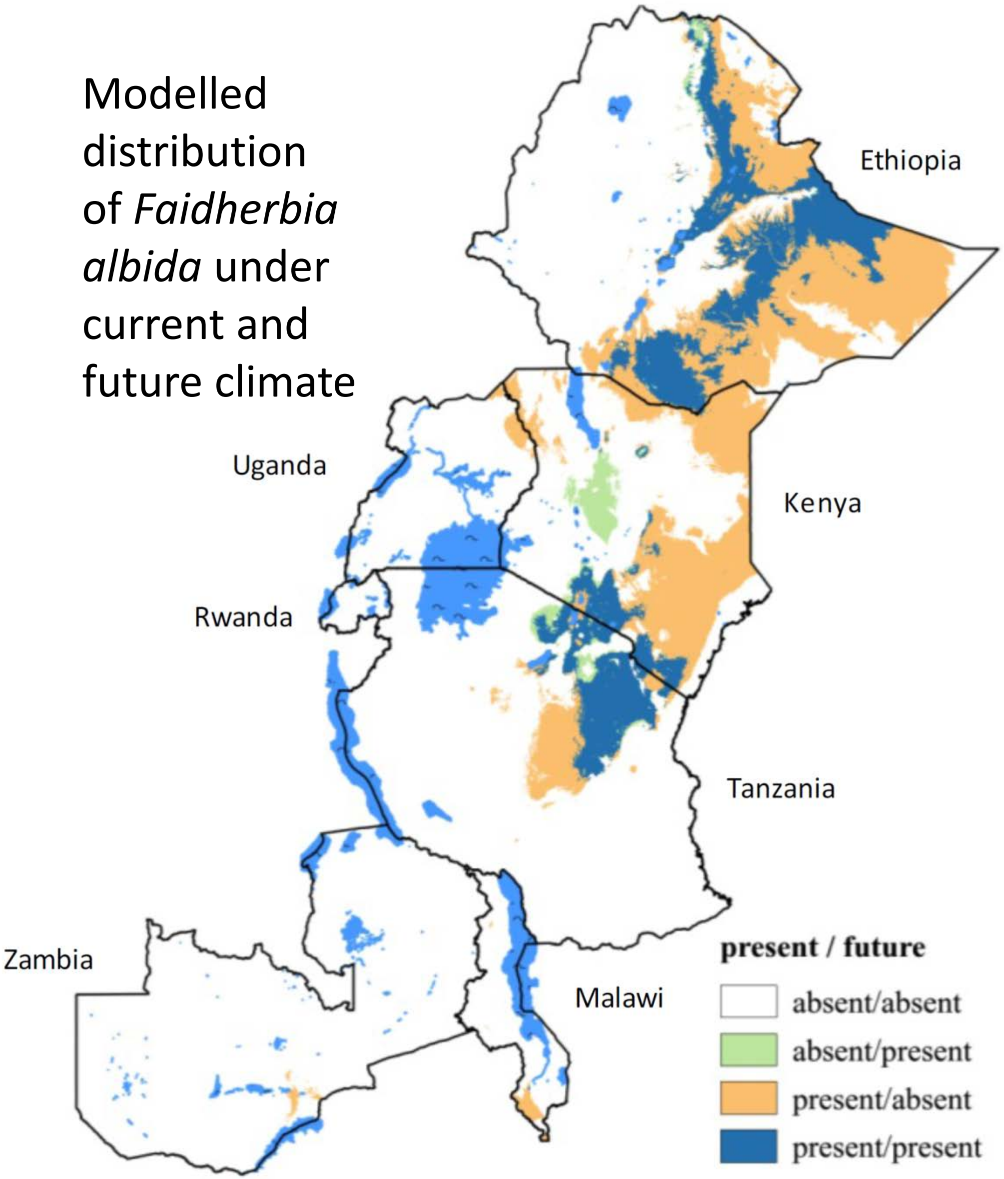
Yellow: Rangewide exploration/collection (> 20 mother trees x > 20 sites)

Red: Testing in 3 (BSOs) at 3 sites (High/wet, Low/wet, Low/dry)

Lillesø et al. in prep

Domestication and productivity in changing climates and to diversify production

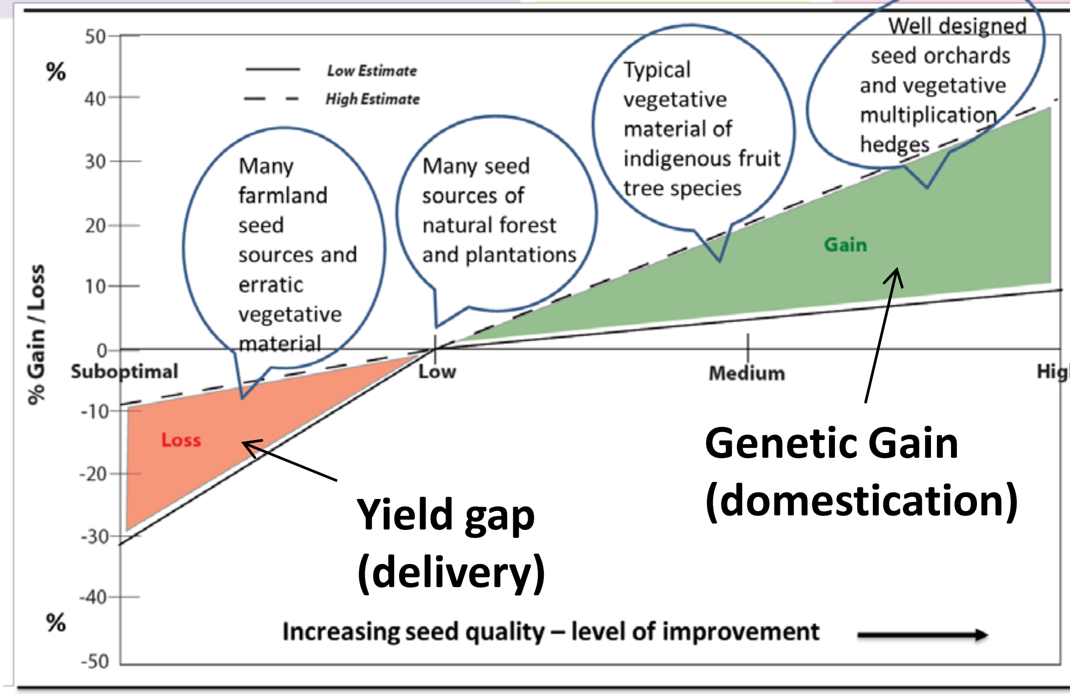
Modelled distribution of *Faidherbia albida* under current and future climate

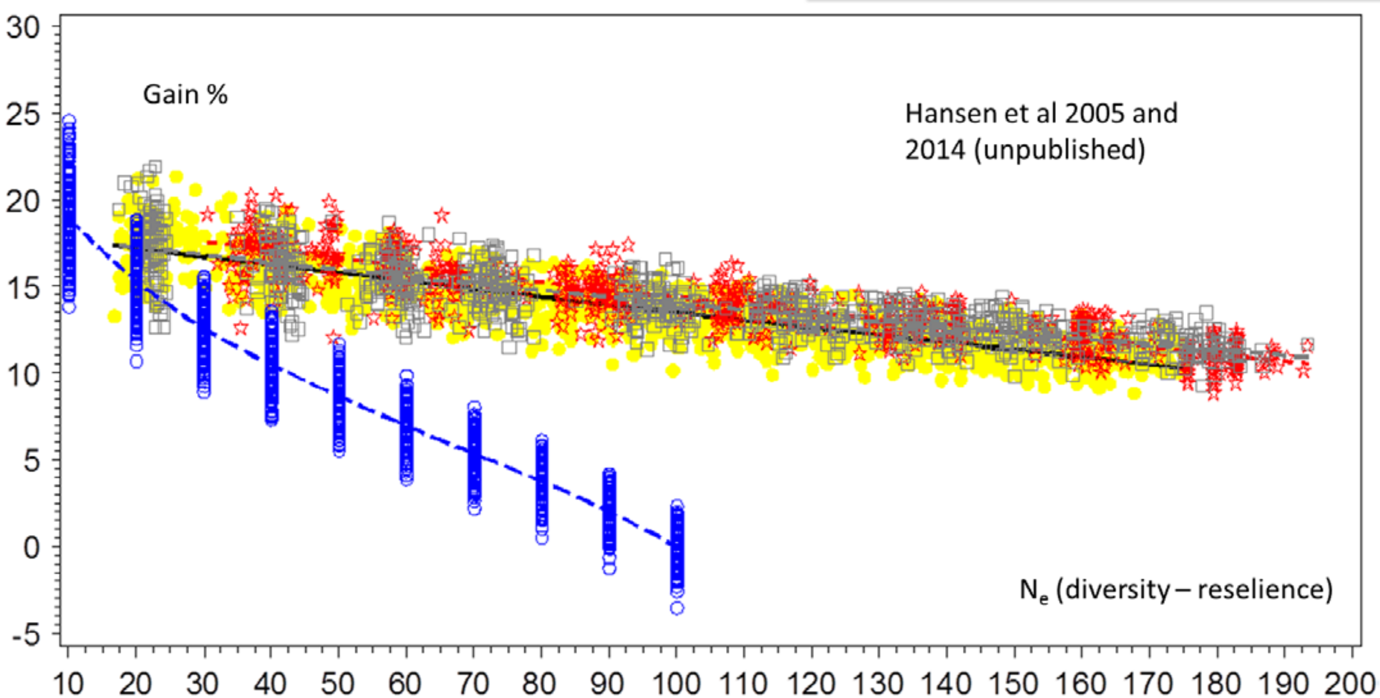


- Distribution and recommendation domains may change as a result of climate change (van Breugel et al 2011, cf. Dawson et al. 2014)
- Modelled for 1000+ species – more underway (Kindt et al, 2014)
- A challenge of domestication is to increase productivity and adaptability at the same time while exploring the resource **before it disappears**
- We know how to do it (Graudal et al 2014a)

Traditional and novel approaches to breeding for productivity and resilience

- Realized gains can be huge (Foster et al. 1995, Graudal et al. 2014b)
- Fast-track knowledge and materials: BSOs, Quasi field trials, genomic tools and low-input breeding (Hansen & McKinney 2010, Kjær et al. 2006)





- Traditional perception of breeding
- Low input – high diversity
- Mobilisation of genetic resources, conservation, breeding, adaptability and deployment combined provides a solution

The right tree for the right place and for the right purpose

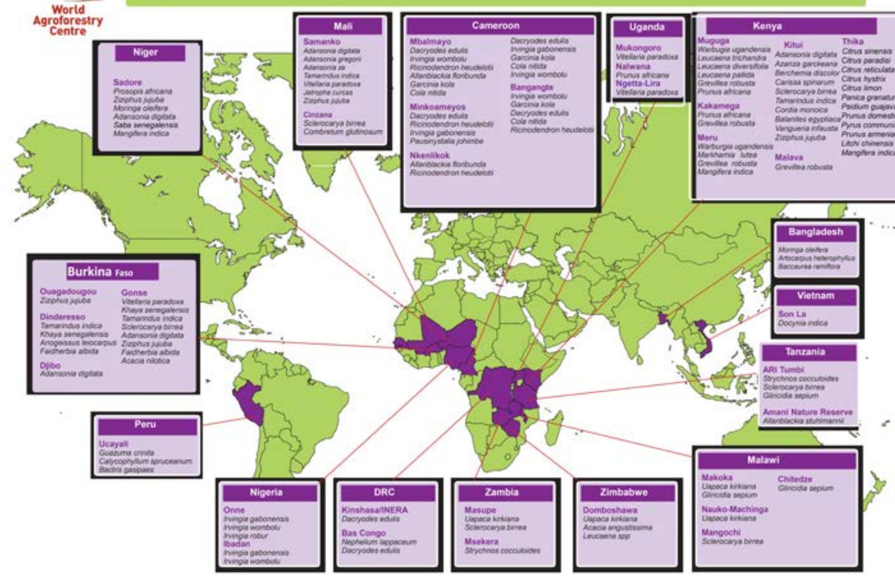
A. Trees for Products

food & nutrition | firewood | medicine | income | sawn wood | fodder

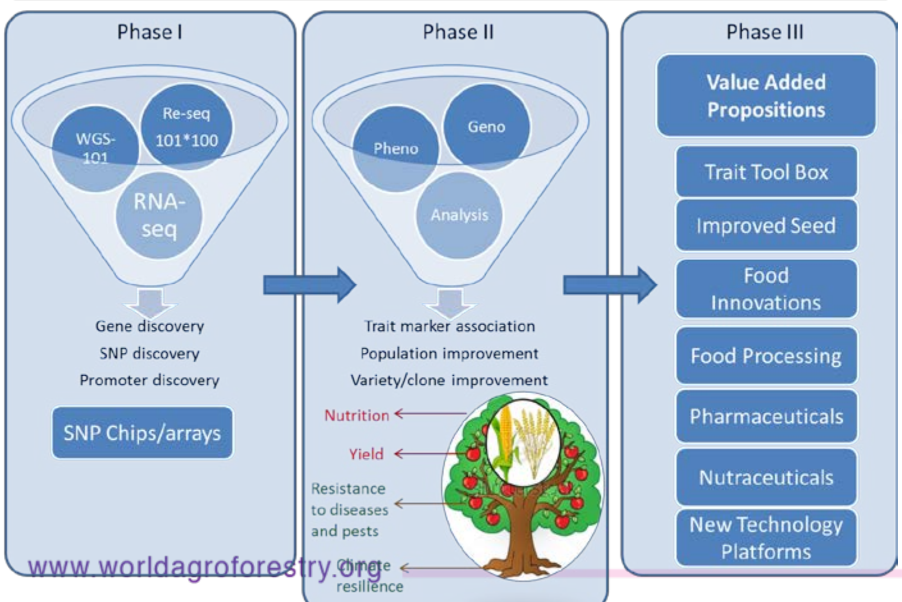
B. Trees for Services

soil fertility | carbon | erosion | watershed | shade | biodiversity

Agroforestry Tree Field Genebanks

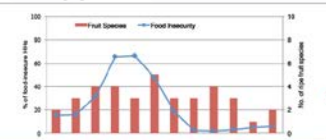


African Orphan Crops Consortium: Genome Sequencing Rationale



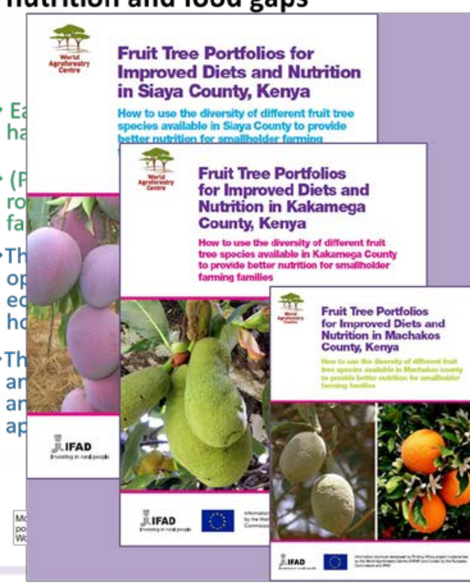
Hendre et al.

Diversified diet portfolios for Africa: year round consumption of nutritious foods (tree foods and vegetables), an agroforestry approach to addressing nutrition and food gaps

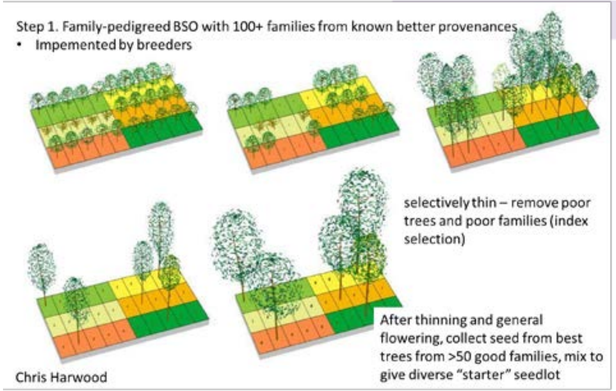


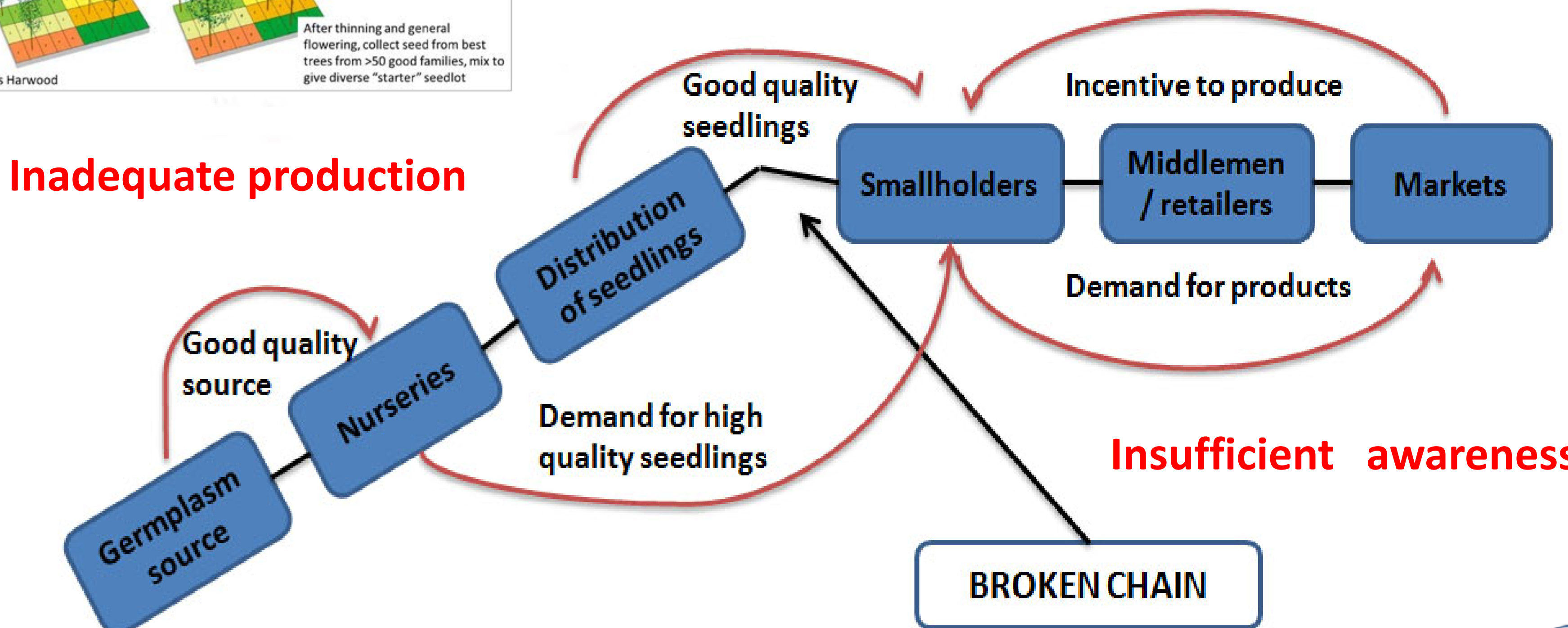
English name	Species name	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Vit A	Vit C
Jackfruit	*Artocarpus heterophyllus*														(+)
Passion	*Passiflora edulis*													+	
Water berry	*Syzygium spp.*													+++	
Pawpaw	*Carica papaya*													+++	+
Guava	*Psidium guajava*													+	+++
Avocado	*Persea americana*														
Loquat	*Eriobotrya japonica*													+++	
Mango	*Mangifera indica*													+++	+
Soursop	*Annona muricata*														(+)
Lemon	*Citrus limon*														+
Orange	*Citrus sinensis*														+
	Available vitamin C and A- rich fruit species	2	3	4	4	3	5	3	3	4	3	1	2		

The fruit tree portfolio for Kakamega County, comprises of a selection of 10 fruit tree species (plus avocado) ecologically suited to the area which can be promoted to meet year round harvest needs and contribute towards supplying pro-vitamin A and vitamin C in people's diet. Ratings of beta carotene (vitamin A) and vitamin C contents are given as +++ = very high; + = intermediate; and (+) = moderate. Harvest periods of vitamin A and C-rich fruits are indicated by the shaded boxes. Avocado does not contain as high content of vitamin A and C as other fruits in the portfolio; it is included for its (4)month harvest availability and contains other important nutrients, particularly fat content (a 146g portion can provide 21% of Recommended Daily Amount, and dietary fibre).[Data from the ICRAF Fruiting Africa Project 2015]



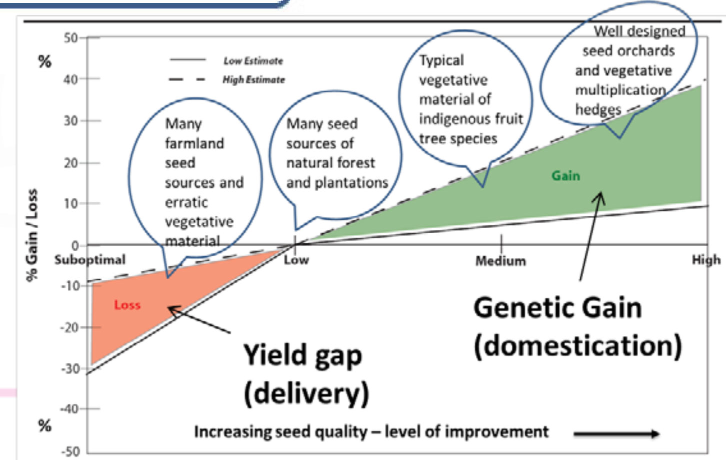
Major bottlenecks in input supply and demand with a broken chain of availability information and value





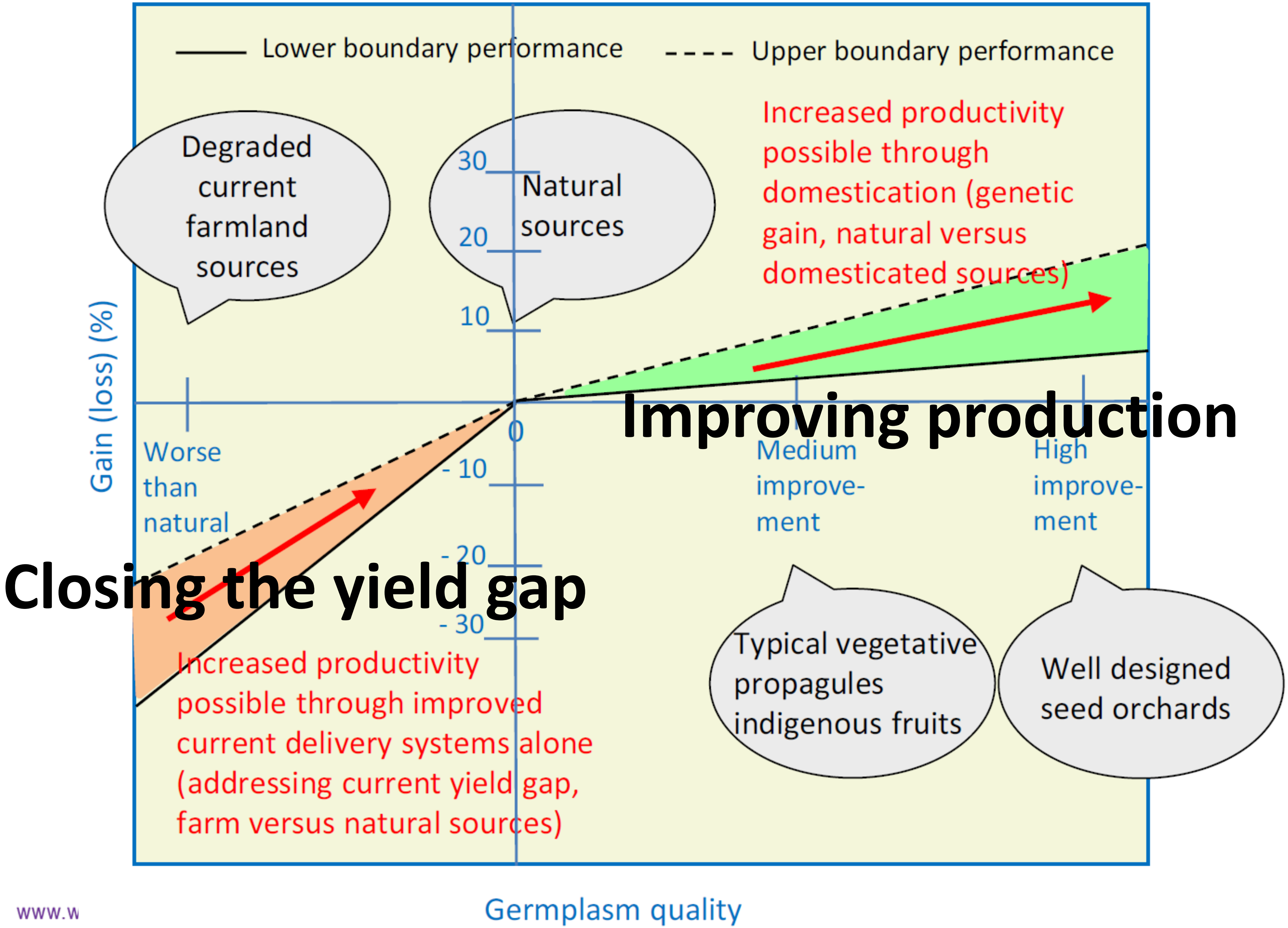
- Smallholders must know that "high quality" seedlings perform better than alternatives – need results from comparative trials.

- Supply chain for "high quality" seedlings must be financed



Specific challenges with respect to reproductive material

- Innovations in field testing to address multiplicity of species and functions
- Link between domestication/breeding and delivery to enable scaling up
- Efficiency of delivery systems (knowledge, standards, ‘trust and traceability)

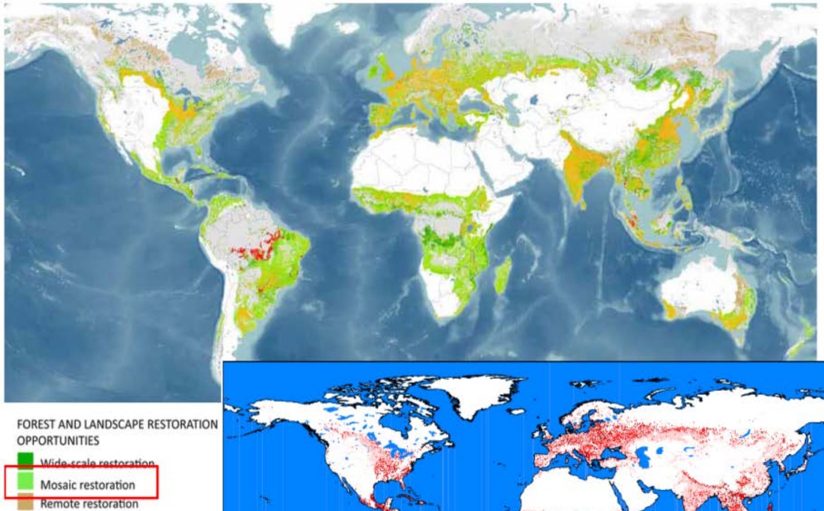

Lower boundary performance
Upper boundary performance
Degraded current farmland sources
Natural sources
Increased productivity possible through domestication (genetic gain, natural versus domesticated sources)
30
20
10
0
- 10
- 20
- 30
Gain (loss) (%)
Improving production
Worse than natural
Medium improve-ment
High improve-ment
Closing the yield gap
Increased productivity possible through improved current delivery systems alone (addressing current yield gap, farm versus natural sources)
Typical vegetative propagules indigenous fruits
Well designed seed orchards
Germplasm quality

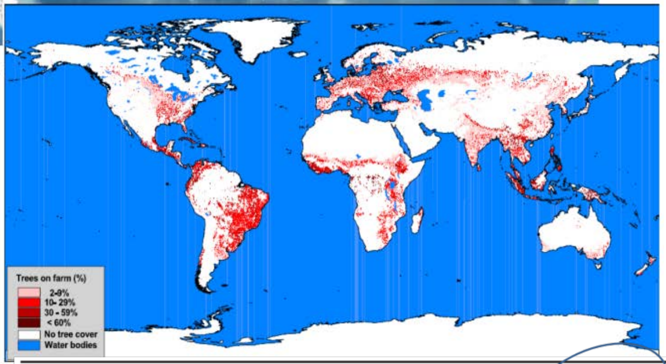
Impact: Enhancing productivity and resilience of FLR in Ethiopia

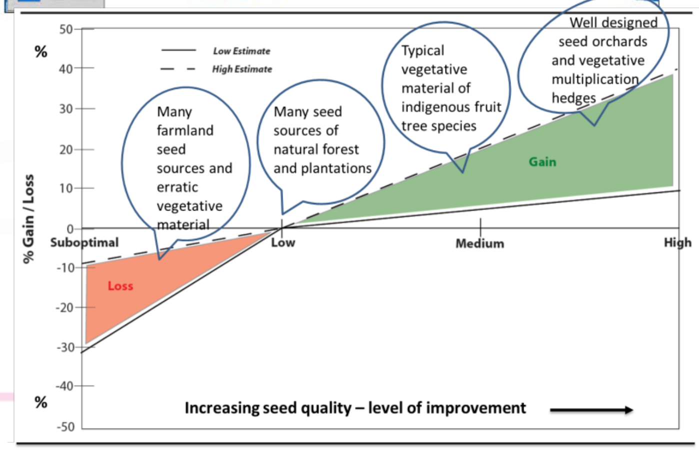
- 20 million ha of FLR in 20 years
- Cost of planting material alone > 3.3 billion US$ (around 70 billion birr)
- Investment in more productive and resilient material 5% →
- Benefit 60% higher productivity of more diverse (resilient) material and more diverse production
- Based on a catalytic investment in this programme of less than 0.2%

Conclusions: FLR and the integration of trees in agricultural landscapes

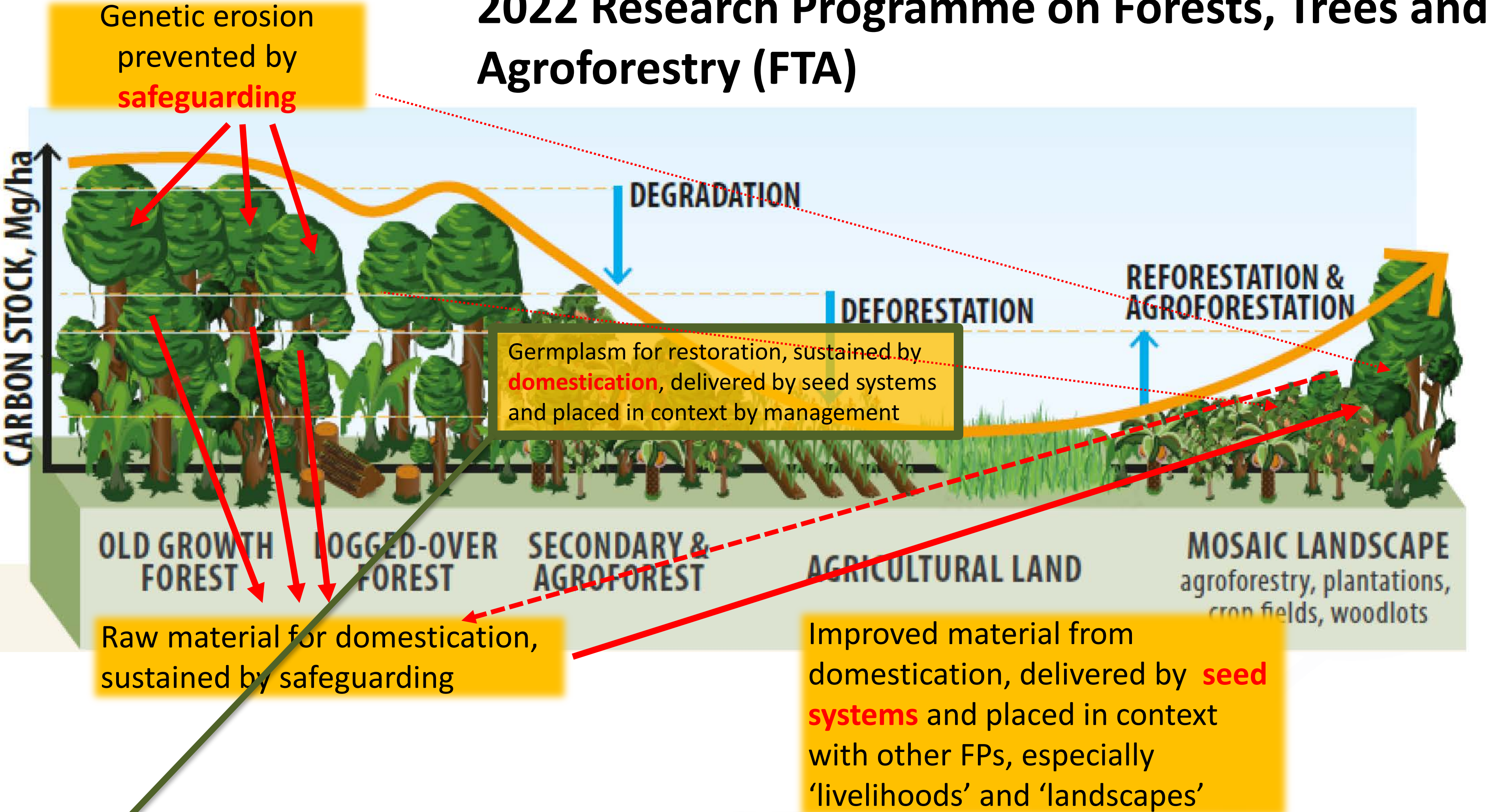
- Agroforestry and trees in mosaic agricultural landscapes can be among the major tools to achieve large scale restoration
  - The environmental and economic benefits are huge but needs to be better quantified and documented
- Proper context matching at species and genetic level can be considered a necessary condition (but of course not a sufficient one in itself) to achieve the ambitions of the Bonn Challenge and other international commitments, like e.g. SDGs 2, 13 and 15
  - Mobilization of the 'biodiversity' resource (species and genetic) to achieve this is critical and a matter of urgency to avoid serious losses of this resource







FLR is therefore high priority in the CGIAR 2017-2022 Research Programme on Forests, Trees and Agroforestry (FTA)



- In the new FTA flagship on tree genetic resources 2017-2022, **restoration** is a major priority area

RESEARCH PROGRAM ON
Forests, Trees and Agroforestry

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Thanks for listening