GEORG-AUGUST-UNIVERSITÄT
GÖTTINGEN

Collaborative Research Centre 990

EFForTS

Ecological and Socioeconomic Functions of Tropical Lowland Rainforest Transformation Systems (Sumatra, Indonesia)

Georg-August-Universität Göttingen

Final Report

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2012 – 2023

Table of Contents

1. Summary

The overall goal of CRC990/EFForTS was to contribute to a profound understanding of the drivers and impacts of land-use changes in lowland rainforest areas and the complex ecological and socioeconomic synergies and trade-offs involved. The main research questions were: (1) What are the functions and services of tropical lowland rainforest and transformed land-use systems, such as rubber and oil palm plantations? (2) What are the environmental, economic and social impacts of deforestation and follow-up land-use changes? (3) How can the ecological and socioeconomic functions and services of transformed land-use systems be improved, and what are technological, institutional and policy preconditions for implementing landscape systems that reconcile ecological functions, agricultural productivity and human welfare?

EFForTS specifically addressed three overarching research themes that consecutively built on each other. **Phase 1** focused on ecological and socioeconomic functions of rainforest and rubber and oil palm plantations. **Phase 2** concentrated on landscape heterogeneity. **Phase 3** focused on perspectives for the establishment of sustainable landscapes.

Two landscapes within Jambi Province were chosen comprising two main remaining large lowland rainforests: National Park Bukit Duabelas and Harapan Rainforest. Three land-use systems were investigated: lowland rainforest and smallholder-owned monoculture plantations of rubber and oil palm. Further, EFForTS studied future management options of oil palm plantations in two experiments: (1) enrichment with native fruit and timber trees and (2) reduced nutrient and pesticide use as sustainable management options mitigating environmental nuisance and improving ecological functions of oil palm plantations. For scaling up our findings an integrated large scale sampling was conducted in Phase 3.

The transformation of the lowland forests of Jambi province towards a crop-dominated landscape had pronounced effects on ecological and socio-economic functions. While the environmental effects were predominantly negative, the cultivation of rubber and especially oil palm contributed to higher income, poverty reduction and improved living standards among smallholder farmers and rural workers although at times this contributed to increased conflict over land ownership. Management measures, such as enriching monoculture plantations with other tree species, as well as adoption of reduced fertilizer use and increased adoption of manual weed control instead of using chemical herbicides are able to mitigate negative effects and deserve closer attention. Overall, trade-offs between ecological and socio-economic effects need to be accounted for in sound policies for more sustainable land use.

Zusammenfassung

Das übergeordnete Ziel des CRC990/EFForTS war es, zu einem vertieften Verständnis der Triebkräfte und Auswirkungen von Landnutzungsänderungen in Tieflandregenwaldgebieten beizutragen. Die wichtigsten Forschungsfragen waren: (1) Welche Funktionen und Leistungen haben tropische Tieflandregenwälder und veränderte Landnutzungssysteme wie Gummi- und Ölpalmenplantagen? (2) Was sind die ökologischen, wirtschaftlichen und sozialen Auswirkungen der Entwaldung und der nachfolgenden Landnutzungsänderungen? (3) Wie können die ökologischen und sozioökonomischen Funktionen und Leistungen geänderter Landnutzungssysteme verbessert werden, und was sind die technologischen, institutionellen und politischen Voraussetzungen für die Umsetzung von Landschaftssystemen, die ökologische Funktionen, landwirtschaftliche Produktivität und menschliches Wohlergehen miteinander in Einklang bringen?

EFForTS befasste sich mit drei übergreifenden Forschungsthemen, die nacheinander aufeinander aufbauten. **Phase 1** konzentrierte sich auf die ökologischen und sozioökonomischen Funktionen des Regenwaldes und von Kautschuk- und Ölpalmplantagen. **Phase 2** konzentrierte sich auf die Heterogenität von Landschaften. **Phase 3** befasste sich mit den Perspektiven für die Schaffung nachhaltiger Landschaften.

Es wurden zwei Landschaften in der Provinz Jambi ausgewählt, die die beiden wichtigsten verbleibenden großen Regenwaldgebiete im Tiefland umfassen: Nationalpark Bukit Duabelas und Harapan Rainforest. Es wurden drei Landnutzungssysteme untersucht: Tieflandregenwald und kleinbäuerliche Monokulturen mit Kautschuk- und Ölpalmanbau. Außerdem untersuchte EFForTS in zwei Experimenten künftige Bewirtschaftungsoptionen für Ölpalmenplantagen: (1) Anreicherung mit einheimischen Obst- und Holzbäumen und (2) reduzierter Einsatz von Nährstoffen und

Pestiziden als nachhaltige Bewirtschaftungsoptionen, die Umweltbelastungen verringern und die ökologischen Funktionen von Ölpalmplantagen verbessern.
Die Umwandlung von Tieflandregenwäldern in landwirtschaftliche Nutzungssysteme hat drastische Auswirkungen auf die ökologischen und sozioökonomischen Funktionen. Während die Auswirkungen auf die Umwelt überwiegend negativ sind, trägt der Anbau von Kautschuk und vor allem von Ölpalmen zu höheren Einkommen, zur Verringerung der Armut und zur Verbesserung des Lebensstandards von Kleinbauern und Landarbeitern bei, auch wenn dies zuweilen zu verstärkten Konflikten um Landbesitz führt. Bewirtschaftungsmaßnahmen wie die Anreicherung von Monokulturen mit anderen Baumarten sowie die Einführung eines geringeren Düngemitteleinsatzes und die verstärkte Anwendung von manuellem Jäten anstelle des Einsatzes chemischer Herbizide können die negativen Auswirkungen abmildern und verdienen größere Aufmerksamkeit. Insgesamt müssen die Kompromisse zwischen ökologischen und sozioökonomischen Auswirkungen in einer soliden Politik für eine nachhaltigere Landnutzung berücksichtigt werden.

2. Published Results

2.1 Publications with scientific quality assurance

Barnes AD … (+19 coauthors) … Brose U (2017) Direct and cascading impacts of tropical land-use change on multi-trophic biodiversity. **Nature Ecology & Evolution** 1:1511–1519

Barnes AD, Jochum M, Mumme S, Haneda NF, Farajallah A, Widarto TH, Brose U (2014) Consequences of tropical land use for multitrophic biodiversity and ecosystem functioning. **Nature Communications** 5:5351 https://doi.org/10.1038/ncomms6351 Open access

Camarretta N, Ehbrecht M, Seidel D, Wenzel A, Zuhdi M, Merk MS, Schlund M, Erasmi S, Knohl A (2021) Using airborne laser scanning to characterize land-use systems in a tropical landscape based on vegetation structural metrics. **Remote Sensing** 13:4794 https://doi.org/10.3390/rs13234794 Open access

Clough Y … (+42 coauthors) … Scheu S (2016) Land-use choices follow profitability at the expense of ecological functions in Indonesian smallholder landscapes. **Nature Communications** 7:13137 https://doi.org/10.1038/ncomms13137 Open access

Cumming GS, Buerkert A, Hoffmann EM, Schlecht E, von Cramon-Taubadel S, Tscharntke T (2014) Implications of agricultural transitions and urbanization for ecosystem services. **Nature** 515:50–57 https://doi.org/10.1038/nature13945

Darras KFA, Furnas B, Fitriawan I, Mulyani Y, Tscharntke T (2018) Estimating bird detection distances in sound recordings for standardizing detection ranges and distance sampling. **Methods in Ecology and Evolution** 9:1928-1938 https://doi.org/10.1111/2041-210X.13031 Open access

Dellinger A, Essl F, Hojsgaard D, Kirchheimer B, Klatt S, Dawson W, Pergl J, Py P, van Kleunen M, Weber E, Winter M, Hörandl E, Dullinger S (2016) Niche dynamics of alien species do not differ among sexual and apomictic flowering plants. **New Phytologist** 209:1313–1323 https://doi.org/10.1111/nph.13694 Open access

Dislich C … (+21 coauthors) … Wiegand K (2016) A review of the ecosystem functions in oil palm plantations, using forests as a reference system. **Biological Reviews** 92:1539-1569 https://doi.org/10.1111/brv.12295 Open access

Drescher J … (+32 coauthors) … Scheu S (2016) Ecological and socioeconomic functions across tropical land-use systems after rainforest conversion. **Philosophical Transactions of the Royal Society B** 371:1694 https://doi.org/10.1098/rstb.2015.0275 Open access

Euler M, Krishna VV, Schwarze S, Siregar H, Qaim M (2017) Oil palm adoption, household welfare and nutrition among smallholder farmers in Indonesia. **World Development** 93:219-235 https://doi.org/10.1016/j.worlddev.2016.12.019

Gatto M, Wollni M, Qaim M (2015) Oil palm boom and land-use dynamics in Indonesia: The role of policies and socioeconomic factors. **Land Use Policy** 46: 292-303 https://doi.org/10.1016/j.landusepol.2015.03.001

Grass I … (+40 coauthors) … Wollni M (2020) Trade-offs between multifunctionality and profit in tropical smallholder landscapes. **Nature Communications** 11:1186 https://doi.org/10.1038/s41467-020-15013-5 Open access

Guillaume T, Kotowska MM, Hertel D, Knohl A, Krashevska V, Murtilaksono K, Scheu S, Kuzyakov Y (2018) Carbon costs and benefits of Indonesian rainforest conversion to plantations. **Nature Communications** 9:2388 https://doi.org/10.1038/s41467-018-04755-y Open access

Hapsari KA, Biagioni S, Jennerjahn TC, Saad A, Sabiham S, Corre MD, Veldkamp E, Behling H (2021) Late Holocene ENSO-related fire impact on vegetation, nutrient status and carbon accumulation of peatlands in Jambi, Sumatra, Indonesia. **Review of Palaeobotany and Palynology** 293:104482 https://doi.org/10.1016/j.revpalbo.2021.104482

Hapsari KA, Biagioni S, Jennerjahn TC, Reimer PM, Saad A, Achnopha Y, Sabiham S, Behling H (2017) Environmental dynamics and carbon accumulation rate of a tropical peatland in Central Sumatra, Indonesia. **Quaternary Science Reviews** 169:173-187 https://doi.org/10.1016/j.quascirev.2017.05.026

Iddris NA-A … (+19 coauthors) ... Corre MD (2023) Mechanical weeding enhances ecosystem multifunctionality and profit in industrial oil palm. **Nature Sustainability** 6:683–695 https://doi.org/10.1038/s41893-023-01076-x Open access

Jakob M, Steckel JC, Klasen S, Lay J, Grunewald N, Martínez-Zarzoso I, Renner S, Edenhofer O (2014) Feasible mitigation actions in developing countries. **Nature Climate Change** 4:961-968 https://doi.org/10.1038/nclimate2370

Jochum M, Barnes A, Ott D, Lang B, Klarner B, Farajallah A, Scheu S, Brose U (2017) Decreasing stoichiometric resource quality drives compensatory feeding across trophic levels in tropical litter invertebrate communities. **The American Naturalist** 190:131-143 https://doi.org/10.1086/691790 Open access

Klasen S, Meyer K, Dislich C, Euler M, Faust H, Gatto M, Hettig E, Melati DN, Jaya INS, Otten F, Pérez-Cruzado C, Steinebach S, Tarigan S, Wiegand K (2016) Economic and ecological trade-offs of agricultural specialization at different spatial scales. **Ecological Economics** 122:111–120 http://doi.org/10.1016/j.ecolecon.2016.01.001 Open access

Kotowska MM, Leuschner C, Triadiati T, Selis M, Hertel D (2015) Quantifying above- and belowground biomass carbon loss with forest conversion in tropical lowlands of Sumatra (Indonesia). **Global Change Biology** 21:3620-3634 https://doi.org/10.1111/gcb.12979

Kubitza C, Krishna V, Urban K, Alamsyah Z, Qaim M (2018) Land property rights, agricultural intensification, and Deforestation in Indonesia. **Ecological Economics** 147:312-321 https://doi.org/10.1016/j.ecolecon.2018.01.021

Kurniawan S, Corre MD, Matson AL, Schulte-Bisping H, Utami S, Veldkamp E (2018) Conversion of tropical forests to smallholder rubber and oil palm plantations impacts nutrient leaching losses and nutrient retention efficiency in highly weathered soils. **Biogeosciences** 15:5131-5154 https://doi.org/10.5194/bg-15-5131-2018 Open access

Li K, Grass I, Zemp DC, Lorenz H, Sachsenmaier L, Nurdiansyah F, Hölscher D, Kreft H, Tscharntke T (2023) Tree identity and canopy openness mediate oil palm biodiversity enrichment effects on insect herbivory and pollination. **Ecological Applications** 33:e2862 https://doi.org/10.1002/eap.2862 Open access

Mehraban N Debela BL, Kalsum U, Qaim M (2022) What about her? Oil palm cultivation and intra-household gender roles. **Food Policy** 110:102276 https://doi.org/10.1016/j.foodpol.2022.102276 Open access

Meijide A, de la Rua C, Guillaume T, Röll A, Hassler E, Stiegler C, Tjoa A, June T, Corre MD, Veldkamp E, Knohl A (2020) Measured greenhouse gas budgets challenge emission savings from palm-oil biodiesel. **Nature Communications** 11:1089 https://doi.org/10.1038/s41467-020-14852-6 Open access

Merten J … (+14 coauthors) … Hölscher D (2016) Water scarcity and oil palm expansion: social views and environmental processes. **Ecology and Society** 21:5 https://doi.org//10.5751/ES-08214-210205 Open access

Montoya-Sánchez V … (+18 coauthors) … Guerrero-Ramírez N (2023) Landscape heterogeneity and soil biota are central to multi-taxa diversity for oil palm landscape restoration. **Communications Earth & Environment** 4:209 https://doi.org/10.1038/s43247-023-00875-6 Open access

Moser S, Mußhoff O (2015) Ex-ante evaluation of policy measures: Effects of reward and punishment for fertiliser reduction in palm oil production. **Journal of Agricultural Economics** 67:84-104 https://doi.org/10.1111/1477-9552.12114

Otten F, Hein J, Bondy H, Faust H (2020) Deconstructing sustainable rubber production: contesting narratives in rural Sumatra. **Journal of Land Use Science** 2020:1-21 https://doi.org/10.1080/1747423X.2019.1709225

Petri H, Hendrawan D, Bähr T, Asnawi R, Musshoff O, Wollni M, Faust H (2023) Replanting challenges among Indonesian oil palm smallholders - a narrative review. **Environment, Development and Sustainability** https://doi.org/10.1007/s10668-023-03527-z Open access

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Potapov AM … (+18 coauthors) … Scheu S (2024) Rainforest transformation reallocates energy from green to brown food webs. **Nature** https://doi.org/10.1038/s41586-024-07083-y Open access

Potapov AM … (+85 coauthors) … Scheu S (2023) Globally invariant metabolism but density-diversity mismatch in springtails. **Nature Communications** 14:674 https://doi.org/10.1038/s41467-023-36216-6 Open access

Potapov AM … (+23 coauthors) … Scheu S (2022) Feeding habits and multifunctional classification of belowground consumers from protists to vertebrates. **Biological Reviews** 97:1057-1117 https://doi.org/10.1111/brv.12832 Open access

Potapov AM, Brose U, Scheu S, Tiunov AV (2019) Trophic position of consumers and size structure of food webs across aquatic and terrestrial ecosystems. **The American Naturalist** 194:823-839 https://doi.org/10.1086/705811

Potapov AM, Tiunov AV, Scheu S (2018) Uncovering trophic positions and food resources of soil animals using bulk natural stable isotope composition. **Biological Reviews** 94:37-59 https://doi.org/10.1111/brv.12434

Qaim M, Sibhatu KT, Siregar H, Grass I (2020) Environmental, economic, and social consequences of the oil palm boom. **Annual Review of Resource Economics** 12:321-344 https://doi.org/10.1146/annurev-resource-110119-024922 Open access

Röll A … (+20 coauthors) … Hölscher D (2019) Transpiration on the rebound in lowland Sumatra. **Agricultural and Forest Meteorology** 274:160-171 https://doi.org/10.1016/j.agrformet.2019.04.017

Romero M, Wollni M, Rudolf K, Asnawi R, Irawan B (2019) Promoting biodiversity enrichment in smallholder oil palm monocultures - Experimental evidence from Indonesia. **World Development** 124:104638 https://doi.org/10.1016/j.worlddev.2019.104638

Salecker J, Sciaini M, Meyer KM, Wiegand K (2019) The nlrx r package: A next-generation framework for reproducible NetLogo model analyses. **Methods on Ecology and Evolution** 10:1854-1863 https://doi.org/10.1111/2041-210X.13286 Open access

Schlund M, Wenzel A, Camarretta N, Stiegler C, Erasmi S (2023) Vegetation canopy height estimation in tropical landscapes with TanDEM-X supported by GEDI data. **Methods in Ecology and Evolution** 14:1639-1656 https://doi.org/10.1111/2041-210X.13933 Open access

Sibhatu KT, Krishna V, Qaim M (2015) Production diversity and dietary diversity in smallholder farm households. **Proceedings of the National Academy of Sciences** 112:10657-10662 https://doi.org/10.1073/pnas.1510982112 Open access

Simpkins CE, Hanß S, Spangenberg MC, Salecker J, Hesselbarth MHK, Wiegand K (2022) spectre: an R package to estimate spatially-explicit community composition using sparse data. **Ecography** 2022:e06272 https://doi.org/10.1111/ecog.06272 Open access

Tarigan S, Wiegand K, Sunarti, Slamet B (2018) Minimum forest cover required for sustainable water flow regulation of a watershed: a case study in Jambi Province, Indonesia. **Hydrology and Earth System Sciences** 22:581-594 https://doi.org/10.5194/hess-22-581-2018 Open access

van Straaten O, Corre MD, Wolf K, Tchienkoua M, Cuellar E, Matthews R, Veldkamp E (2015) Conversion of lowland tropical forests to tree cash crop plantations loses up to one-half of stored soil organic carbon. **Proceedings of the National Academy of Sciences** 112:9956-9960 https://doi.org/10.1073/pnas.1504628112 Open access

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Wenzel A … (+35 coauthors) … Grass I (2024) Balancing economic and ecological functions in smallholder and industrial oil palm plantations. **Proceedings of the National Academy of Sciences** Open access
Zemp DC … (+43 coauthors) … Kreft H (2023) Tree islands enhance biodiversity and functioning in oil palm landscapes. **Nature** 618:316–321 https://doi.org/10.1038/s41586-023-06086-5 Open access
Zhou Z, Lu J-Z, Preiser J, Widyastuti R, Scheu S, Potapov A (2023) Plant roots fuel tropical soil animal communities. **Ecology Letters** 26:742-753 https://doi.org/10.1111/ele.14191 Open access
Zhou Z, Krashevska V, Widyastuti R, Scheu S, Potapov A (2022) Tropical land use alters functional diversity of soil food webs and leads to monopolization of the detrital energy channel. **eLife** 11:e75428 https://doi.org/10.7554/eLife.75428 Open access

3. Overview of Projects

Table 1. Overview of projects: Project code, Title, Research area, PIs and affiliation, Duration

Project code	Title	Research area	Principal investigator(s), department, institution	Duration
A01	Long-term vegetation dynamics, plant phenology and plant-pollinator interactions in rainforest and rainforest transformations in central Sumatra	Botany, palynology, paleoecology, environmental history	Behling, Hermann, Faculty of Biology and Psychology, Albrecht-von-Haller Institute for Plant Sciences, Palynology and Climate Dynamics, Göttingen	2012 – 2023
A02	Tree and palm water use characteristics in rainforest transformation systems	Ecohydrology	Hölscher, Dirk, Faculty of Forest Sciences and Forest Ecology, Burckhardt Institute, Tropical Silviculture and Forest Ecology, Göttingen	2012 - 2023
A03	Understanding land-atmosphere exchange processes in land-use transformation systems	Forest meteorology, land-atmosphere exchange processes	Knohl, Alexander, Faculty of Forest Sciences and Forest Ecology, Büsgen Institute, Bioclimatology, Göttingen	2012 – 2023
A04	Carbon turnover and destabilization in heavily weathered soils under lowland rainforest transformation systems	Soil biogeochemistry, carbon cycle	Kuzyakov, Yakov, Faculty of Forest Sciences and Forest Ecology, Büsgen Institute, Soil Science of Temperate Ecosystems, Göttingen	2012 – 2019
A05	Optimizing nutrient management in oil palm plantations and upscaling greenhouse gas fluxes from plot to a rainforest-transformation landscape	Soil science, biogeochemistry, trace gases, soil N cycling	Veldkamp, Edzo, Corre, Marife D., Faculty of Forest Sciences and Forest Ecology, Büsgen Institute, Soil Science of Tropical and Subtropical Ecosystems, Göttingen	2012 - 2023
A07	Spatio-temporal scaling of the impacts of land-use and climate change in land transformation systems in Indonesia	Land surface modelling, C-cycle, N-cycle, water cycle	Knohl, Alexander, Bioclimatology, Veldkamp, Edzo, Soil Science of Tropical and Subtropical Ecosystems, Faculty of Forest Sciences and Forest Ecology, Büsgen Institute, Göttingen	2016 – 2023
B01	Structure, stability and functioning of macro-invertebrate communities in rainforest transformation systems in Sumatra	Ecology	Brose, Ulrich, Faculty of Biology and Psychology, J.F. Blumenbach Institute of Zoology and Anthropology, Animal Ecology, Göttingen	2012 - 2015
B02	Impact of rainforest transformation on phylogenetic and functional diversity of soil prokaryotic communities in Sumatra	Metagenomics and transcriptomics, microbial ecology	Daniel, Rolf, Faculty of Biology and Psychology, Institute of Microbiology and Genetics, Applied Microbiology & Göttingen Genomic Laboratory, Göttingen	2012 - 2019
B03	Plant genetic diversity in tropical lowland rainforest transformation systems	Biodiversity, plant genetics	Finkeldey, Reiner, Faculty of Forest Sciences and Forest Ecology, Büsgen Institute, Forest Genetics and Forest Tree Breeding, Göttingen	2012 - 2015
B04	Plant productivity and belowground resource partitioning in gradients of tropical land-use intensity and tree species diversity	Plant ecology, ecosystems research, tree ecophysiology	Leuschner, Christoph, Kotowska, Martyna M., Faculty of Biology and Psychology, Albrecht-von-Haller Institute of Plant Sciences, Ecology and Ecosystem Research, Göttingen	2012 - 2023

B05	Land-use changes and vegetation structure in Jambi	Forest monitoring	Kleinn, Christoph, Faculty of Forest Sciences and Forest Ecology, Burckhardt Institute, Forest Inventory and Remote Sensing, Göttingen	2012 - 2019
B06	Taxonomic, functional, phylogenetic, and biogeographical diversity of vascular plants in rainforest transformation systems on Sumatra (Indonesia)	Ecology, tropical ecology, biodiversity	Kreft, Holger, Faculty of Forest Sciences and Forest Ecology, Burckhardt Institute, Biodiversity, Macroecology and Biogeography, Göttingen	2012 - 2023
B07	Functional diversity of mycorrhizal fungi along a tropical land-use gradient	Mycorrhizal functions, tree physiology, resource utilisation	Polle, Andrea, Faculty of Forest Sciences and Forest Ecology, Büsgen Institute, Forest Botany and Tree Physiology, Göttingen	2012 - 2019
B08	Structure and functioning of the decomposer systems in lowland rainforest transformation systems	Soil ecology	Scheu, Stefan, Faculty of Biology and Psychology, J.F. Blumenbach Institute of Zoology and Anthropology, Animal Ecology, Göttingen	2012 – 2023
B09	Aboveground biodiversity patterns and processes across rainforest transformation landscapes	Agroecology, community ecology, ecological entomology	Tscharntke, Teja, Westphal, Catrin, Faculty of Agricultural Sciences, Department of Crop Sciences, Functional Agrobiodiversity, Göttingen Grass, Ingo, Faculty of Agricultural Sciences, Institute of Agricultural Sciences in the Tropics, Ecology of Tropical Agricultural Systems, Hohenheim, Stuttgart	2012 - 2023
B10	Landscape-level assessment of ecological and socio-economic functions of rainforest transformation systems in Sumatra (Indonesia)	Ecology, socioeconomics	Wiegand, Kerstin, Faculty of Forest Sciences and Forest Ecology, Büsgen Institute, Ecosystem Modelling, Göttingen Lay, Jann, Faculty of Business and Economics, Department of Economics, Göttingen & GIGA Institute, Hamburg	2012 - 2023
B11	Biodiversity enrichment in oil palm plantations: plant succession and integration	Ecology, agricultural economics	Hölscher, Dirk, Faculty of Forest Sciences and Forest Ecology, Burckhardt Institute, Tropical Silviculture and Forest Ecology, Göttingen Kreft, Holger, Faculty of Forest Sciences and Forest Ecology, Burckhardt Institute, Biodiversity, Macroecology and Biogeography, Göttingen Wollni, Meike, Faculty of Agricultural Sciences, Department of Agricultural Economics and Rural Development, Environmental and Resource Economics, Göttingen	2012 - 2023
B12	Establishment strategies of weedy flowering plants in tropical rainforest transformation systems	Plant biology, Biodiversity	Hörandl, Elvira, Faculty of Biology and Psychology, Albrecht-von-Haller Institute of Plant Sciences, Biodiversity and Evolution of Plants, Göttingen	2012 - 2015
B13	Impact of management intensity and tree enrichment on soil invertebrates in oil palm plantations of Sumatra	Animal ecology	Maraun, Mark, Faculty of Biology and Psychology, J.F. Blumenbach Institute of Zoology and Anthropology, Animal Ecology, Göttingen	2015 - 2019
B14	The use of DNA barcoding to assess landscape effects on phylogenetic and functional diversity	Community phylogenies, DNA barcoding, functional and phylogenetic diversity	Gailing, Oliver, Faculty of Forest Sciences and Forest Ecology, Büsgen Institute, Forest Genetics and Forest Tree Breeding, Göttingen	2016 - 2023
C01	Smallholder productivity, market access, and international linkages in rubber and palm oil production in Jambi Province	Agricultural economics	Brümmer, Bernhard Faculty of Agricultural Sciences, Department of Agricultural Economics and Rural Development, Agricultural Market Analysis, Göttingen	2012 - 2023
C02	Social transformation processes and sustainable resource use in rural Jambi	Human geography: Social geography and	Faust, Heiko, Faculty of Geosciences and Geography, Institute of Geography, Human Geography, Göttingen	2012 - 2023

		sustainable resource use		
C03	Culture-specific human Interaction with tropical lowland rainforests in transformation in Sumatra	Cultural and social anthropology	Hauser-Schäublin, Brigitta, Faculty of Social Sciences, Institute for Cultural and Social Anthropology, Göttingen	2012-2015
C04	Mitigating trade-offs between economic and ecological functions and service through certification	Development economics	Klasen, Stephan, Department of Economics, Development Economics, Göttingen Lay, Jann, Faculty of Business and Economics, Department of Economics, Göttingen & GIGA Institute Hamburg	2012 - 2019
C06	Understanding the certification and replanting behaviour of Indonesian smallholder farmers	Agricultural economics	Mußhoff, Oliver, Faculty of Agricultural Sciences, Department of Agricultural Economics and Rural Development, Göttingen	2012 - 2023
C07	Determinants of land-use change and welfare impacts among rural farm and non-farm households	Agricultural economics	Qaim, Matin, Faculty of Agricultural Sciences, Department of Agricultural Economics and Rural Development, International Food Economics and Rural Development, Göttingen	2012 - 2023
C08	Designing effective policy instruments to induce sustainable land use	Agricultural economics, experimental economics	Wollni, Meike, Faculty of Agricultural Sciences, Department of Agricultural Economics and Rural Development, Environmental and Resource Economics, Göttingen	2012 - 2023
C10	Localized environmental and land use policies, palm oil conversion and deforestation	Environmental and landuse policies	Kis-Katos, Krisztina, Faculty of Business and Economics, Department of Economics, International Economic Policy, Göttingen	2020 - 2023
C11	Integrated analyses of policies for sustainable rural economies	Socioeconomic and ecol functions, trade-offs	Lay, Jann, Faculty of Business and Economics, Department of Economics, Göttingen & GIGA Institute Hamburg, Corre, Marife D., Faculty of Forest Sciences and Forest Ecology, Soil Science of Tropical and Subtropical Ecosystems, Göttingen Grass, Ingo, Faculty of Agricultural Sciences, Institute of Agricultural Sciences in the Tropics, Ecology of Tropical Agricultural Systems, Hohenheim, Stuttgart Wiegand, Kerstin, Faculty of Forest Sciences and Forest Ecology, Büsgen Institute, Ecosystem Modelling, Göttingen Wollni, Meike, Faculty of Agricultural Sciences, Department of Agricultural Economics and Rural Development, Environmental and Resource Economics, Göttingen	2020 - 2023
C12	Collaborative farm-modelling for reconciling socioeconomic and ecological functions	Socioeconomic and ecological functions, integrative land-use optimization modelling	Paul, Carola, Faculty of Forest Sciences and Forest Ecology, Burckhardt Institute, Forest Economics and Sustainable Land-use Planning, Göttingen	2020 - 2023
INF	Research data management and integrative statistical analysis	Applied informatics, information science, statistics	Horstmann, Wolfram, State and University Library (SUB), Göttingen Kneib, Thomas, Faculty of Business and Economics, Department of Economics, Statistics, Göttingen Yahyapour, Ramin, Göttingen Society for Scientific Data Processing GmbH (GWDG), Göttingen	2012 - 2023
PR	Teacher education for society: Making EFForTS knowledge available for Indonesia	Education for sustainabl development, science education, teacher education	Bögeholz, Susanne, Faculty of Biology and Psychology, Albrecht-von-Haller Institute for Plant Sciences, Biology Education, Göttingen	2020 - 2023

Z02	Central Scientific Support Project		Scheu, Stefan, Faculty of Biology and Psychology, J.F.Blumenbach Institute of Zoology and Anthropology, Animal Ecology, Göttingen Knohl, Alexander, Faculty of Forest Sciences and Forest Ecology, Büsgen Institute, Bioclimatology, Göttingen Erasmi, Stefan, Faculty of Geosciences and Geography, Institute of Geography, Cartography, GIS and Remote Sensing, Göttingen	2012 - 2023
Z01	Central Administrative Project		Scheu, Stefan, Faculty of Biology and Psychology, J.F. Blumenbach Institute of Zoology and Anthropology, Animal Ecology, Göttingen	2012 - 2023

4. Research Achievements of EFForTS

Due to their exceptional diversity, tropical lowland forests are among the most complex and least understood ecosystems. At the same time, tropical lowland forests are disappearing at high rates. In many parts of the world, including Indonesia, lowland rainforests were logged for timber extraction and later cleared for agricultural use, especially for the establishment of plantation crops. The period between 1990 and 2000 was characterised by particularly high rates of deforestation and land-use change. Today most of the province consists of monoculture plantations. In terms of area covered, rubber and oil palm are the two most important crops in Jambi, with the oil palm area expanding particularly fast. Despite this massive transformation of tropical lowland ecosystems, the implications for biodiversity and sustainable development are not yet well understood. Better knowledge on the forces responsible for the transformation of forest ecosystems into agricultural land use, on the drivers of follow-up land-use changes, and on the impacts of various agricultural land-use systems and production patterns on biodiversity, ecosystem functioning and human welfare is necessary for developing strategies towards more sustainable land use. The overall goal of this research was to contribute to a profound understanding of the drivers and impacts of land-use changes in lowland rainforest areas and the complex ecological and socioeconomic synergies and trade-offs involved. The main medium- and long-term research questions were:

- What are the functions and services of tropical lowland rainforest and transformed land-use systems, such as rubber and oil palm plantations? Which characteristics of the land-use systems are responsible for which functions/services?
- What are the environmental, economic and social impacts of deforestation and follow-up land-use changes?
- How can the ecological and socioeconomic functions and services of tropical lowland rainforest land-use systems be improved? What are technological, institutional and policy preconditions for implementing landscape systems that reconcile ecological functions, agricultural productivity and human welfare?

EFForTS specifically addressed three overarching research themes that consecutively built on each other. Phase 1 focused on **Differences in ecological and socioeconomic functions** of land-use changes due to rainforest conversion into rubber and oil palm plantations in Indonesia. Phase 2 concentrated on **Heterogeneity** as a new umbrella theme. Phase 3 extended the investigation of heterogeneity in space and time by focusing on the theme ***From heterogeneity towards sustainable landscapes.***

Research setting

EFForTS was established in Jambi Province, Sumatra, one of the tropical lowland rainforest area in SE Asia and one of the hotspots of Indonesia's recent oil palm boom that has experienced massive land-use changes during the last 30 years. Two landscapes within Jambi Province were chosen comprising the two main remaining large swaths of lowland rainforest: National Park Bukit Duabelas and Harapan Rainforest. Our research activities focused on three land-use systems (*EFForTS Core*

Plot Design): (i) lowland rainforest as reference sites (old-growth forest that has been subject to selective logging in the past), and smallholder-owned monoculture plantations of (ii) rubber and (iii) oil palm. Jungle rubber (an extensively managed agroforestry system) was included as a fourth land-use system in Phase 1 but discontinued in Phase 2 because of its low economic revenue and increased transformation into more intensive land-use systems, in particular oil palm plantations. In each of the two landscapes (comprising blocks in a randomized complete block design), four replicates of each of the three land-use systems (including the lowland rainforest as reference) were investigated. These 24 plots constituted our *Core Plot Design*. In Phase 2, we extended the study sites and included riparian areas as major component or hotspot of *heterogeneity* of the landscape. For this new analysis, 12 additional core plots were included, i.e. 4 plots each located in forest, rubber and oil palm systems (Harapan landscape only). We also incorporated non-farm rural households and rural-urban linkages to reflect socioeconomic heterogeneity. In Phase 3, we integrated a comprehensive landscape-scale assessment (100 new sites distributed widely in space and including important land-use systems such as fallow land and shrubland; *Landscape assessment*) to extrapolate heterogeneity to the landscape level and to estimate the full range of biodiversity and ecological functions in space and time.

To provide policy recommendation towards the development of more sustainable management of tropical lowland rainforest regions *EFForTS* studied future management options of oil palm plantations in two experiments: (1) enrichment with native fruit and timber trees as a sustainable management option for improving ecological functions of oil palm plantations (*Biodiversity enrichment experiment; EFForTS-BEE,* established in Phase 1), and (2) reduced nutrient and pesticide use as a sustainable management option mitigating environmental nuisance and improving ecological functions of oil palm plantations (*Oil palm management experiment; EFForTS-OPMX,* established in Phase 2). Both experiments address a major goal of *EFForTS* of how to establish sustainable oil palm management systems, optimizing both conservation needs and socioeconomic benefits, and restore important ecological functions in an impoverished oil palm landscape (addressed in the *Landscape Assessment*).

The global Corona-virus crisis has challenged *EFForTS* in many and unexpected ways, especially as we could not carry out the research program in 2020 and 2021 as anticipated (and as outlined in the proposal). Besides the planned field activities of the respective subprojects, above all this concerned the integrative *Landscape Assessment* (the campaign was planned for 2020), one of the central research platforms of *EFForTS* in Phase 3.

Given the situation, we decided to conduct the *Landscape Assessment* campaign “remotely” in 2021 – meaning that on-site fieldwork was conducted primarily by our local assistants under the supervision of the head coordination in Indonesia, counterparts and Göttingen PIs and Postdocs. Postdocs in Göttingen developed illustrated teaching material and learning videos for training purposes of the field assistants. Data management was handled via the app 'KoboCollect' to collect field data via android devices; the data were synchronized with a virtual server specially set up and hosted in Göttingen by the GWDG. All 132 plots located in two landscapes and four areas were sampled in 2021/2022 by our field assistants thanks to many years of trusting cooperation and dedicated efforts.

Highlights Project Group A - Environmental Processes

Project Group A studied the effects of land transformation on environmental processes in soil, water and atmosphere at multiple temporal and spatial scales and under different management regimes. The conversion of rainforests to other land-use types caused substantial carbon losses from the ecosystem. Oil palm cultivation resulted in high carbon storage losses, but due to the high oil palm yield it was actually an efficient land use, i.e. oil palm had the highest yield per unit of carbon storage loss (Guillaume et al. 2018). Based on analyses of sediment/peat archives for the past few millennia, forest conversion will also diminish the belowground long-term capacity to sequester and store

carbon (Hapsari et al. 2017, 2021), that will take decades or even centuries to regain (Hapsari et al. 2018, 2022).

The hydrological cycle was also affected by forest transformation. Transpiration decreased from forest to rubber and smallholder oil palm plantations but was high from intensively managed oil palm plantations (Röll et al. 2019). Total evapotranspiration from intensively managed oil palm plantations was also substantial (Meijide et al. 2017). Soil structure degradation and associated erosion after forest conversion (Guillaume et al. 2015) strongly reduced soil water infiltration and increased surface run-off (Tarigan et al. 2018). High evapotranspiration and low soil water infiltration together even led to periodic water scarcity in oil palm dominated landscapes (Merten et al. 2016), but also flooding became more frequent and severe (Merten et al. 2020).

Conversion of forest to oil palm plantation changed the soil N cycling from tightly-coupled to leaky, signified by reduced rates of internal N cycling and high N_2O emission and N leaching (Allen et al. 2015, Chen et al. 2024, Formaglio et al. 2020, 2021; Hassler et al. 2017, Kurniawan et al. 2018). Compared to smallholder plantations (Hassler et al. 2017, Kurniawan et al. 2018), large-scale oil palm plantations had 3-6 times higher N fertilization rates and resulting in up to 10 times larger N_2O emission and NO_3^- leaching losses (Chen et al. 2024, Formaglio et al. 2020).

Converting forest to plantation also affected the local climate. The air inside oil palm and rubber monocultures was warmer and drier than inside forests, and forest conversion amplified the diurnal range of all microclimatic variables studied (Meijide et al. 2018). Remote sensing data further indicated a local warming effect after forest conversion (Sabajo et al. 2017). The analysis of the land surface temperature trend of the past 16 years indicated that the average daytime surface temperature in Jambi province increased by 1.1°C exceeding the effects of climate warming (Sabajo et al. 2017).

The potential of palm-oil biofuels to reduce greenhouse gas emissions compared with fossil fuels is increasingly questioned. We conducted the first life-cycle assessment based on measured CO_2, CH_4 and N_2O fluxes in young and mature oil palm plantations. The young plantation is a carbon source and mature plantation a sink. The life-cycle assessment showed higher greenhouse gas emissions for palm-oil biodiesel than traditional ways assuming carbon neutrality (Meijide et al. 2020).

Scaling from our research area to larger regions required spatially explicit modelling. We developed new components for oil palm and for rubber plantation in the Community Land Model (CLM). The model was validated against observations done in *EFForTS* and applied to the scale of Indonesia (Ali et al. 2022, Fan et al. 2015, 2019).

Further, we searched for ways of mitigating negative environmental effects of oil palm cultivation (Iddris et al. 2023, Wenzel et al. 2024). Reduced fertilizer application and mechanical weeding were highly effective in reducing nitrogen leaching losses and N_2O emissions. The integration of trees into oil palm cultivation systems very positively influenced attributes of the carbon cycle, surface and air temperatures, the ecosystem water cycling and nutrient fluxes (Donfack et al. 2021; Zemp et al. 2023).

Highlights Project Group B - Biota and Ecosystem Services

The main aim of Project Group B was to gain a comprehensive understanding of how land-use change affects multiple dimensions of biodiversity and associated ecological functions at various spatial and temporal scales. A main strength of Project Group B was the coordinated data collection within common study designs on identical plots (*Core Plot Design*, *OPMX*, *BEE* and *Landscape Assessment*) providing a unique opportunity for assessing different taxonomic groups (more than 20 taxonomic groups ranging from bacteria to birds) and different trophic groups above and below ground. This allowed us to disentangle complex ecological, multitrophic relationships, matter and energy fluxes of the focal transformation systems including biodiversity restoration and optimized management perspectives in oil palm.

The massive land-use transformation in Jambi Province has profound impacts on structural composition, biodiversity and provision of functions by the ecosystems (Dislich et al. 2017, Grass et al. 2020). For instance, data collected across the *Core Plots* showed that different indicators of naturalness and species richness were highest in the forest, and successively decreased in jungle rubber, rubber and oil palm plantations (Clough et al. 2016). Comprehensive analyses of the biodiversity of different taxonomic and functional groups, including plants, bacteria, fungi, protists, soil and canopy invertebrates as well as vertebrates, documented an overall strong decrease in local diversity in oil palm and rubber plantations compared to rainforest (Potapov et al. 2020, Rembold et al. 2017). However, local birds and bats showed no response to land-use change and soil bacteria and archaea (Schneider et al. 2015) as well as certain protist groups (Schulz et al. 2019) had higher diversity in rubber and oil palm plantations than in rainforest. Land-use intensification also affected the taxonomic, functional and phylogenetic composition of biological communities. Oil palm and rubber plantations differed markedly from rainforest, while jungle rubber agroforests shared more similarities with forests (Brinkmann et al. 2019, Prabowo et al. 2016, Rembold et al. 2017) and were colonized by species of high conservation value (Paoletti et al. 2018). While there was no reduction in local diversity in soil fungal and soil bacterial communities substantial shifts in composition occurred (Berkelmann et al. 2018, 2020). Another important trend was the increased abundance and dominance of invasive alien species in the monoculture plantations (Nazarreta et al. 2020, Potapov et al. 2021, Rembold et al. 2017). The detailed biodiversity inventories led to numerous new species descriptions.

Key ecological functions including tree biomass, litter decomposition, root health, microbial activity and biomass were significantly reduced in monoculture plantations (Clough et al. 2016, Krashevska et al. 2018, Sahner et al. 2015, Zhou et al. 2023). While the harvested biomass increased from forest to jungle rubber to monoculture plantations, total biomass showed the opposite pattern (Clough et al. 2016, Kotowska et al. 2015). Carbon stock loss with rainforest conversion to rubber and oil palm originated mainly from aboveground pools representing a loss of 41% and 61% in carbon, respectively (Guillaume et al. 2018) and halving nutrient return through litterfall (Kotowska et al. 2015). These detailed field-based assessments also feed into real-world application improving accuracy of carbon and water flux estimation in vegetation models (Ali et al. 2022, Fan et al. 2015). Our multidisciplinary research also revealed how direct and cascading land-use effects alter biomass and species richness of taxa across trophic levels (Barnes et al. 2017, Grass et al. 2020, Pollierer et al. 2023) and demonstrated an up to 51% reduction in the flux of energy to higher trophic levels of litter food webs in monoculture plantations than in rainforests, indicating strongly reduced predator control of prey species (Barnes et al. 2014, Potapov et al. 2020, 2024). Also, a decrease in stoichiometric resource quality with increasing land-use intensity was observed (Jochum et al. 2017). Simultaneously, the flux of energy into detritivore animal species was strongly increased in monoculture plantations, mainly due to invasive earthworms benefitting from higher pH in plantations (Potapov et al. 2019). In rainforest, more than 90% of the total animal energy flux was channelled by arthropods in soil and canopy (Potapov et al. 2024, Fig. 1), whereas in plantations more than 50% of the energy was allocated to earthworms. Land-use change led to a consistent decline in multitrophic energy flux aboveground, whereas belowground food webs responded with reduced energy flux to higher trophic levels, down to −90%, and with shifts from slow (fungal) to fast (bacterial) energy channels and from faeces production towards consumption of soil organic matter. Furthermore, trenching and litter removal experiments revealed a strong role of root-derived carbon in structuring soil animal communities and food webs (Zhou et al. 2023, 2024). Multidiversity and multifunctionality indicators also formed the basis of high-profile interdisciplinary studies of ecological-socio-economical trade-offs (Fig. 2, Grass et al. 2020, Wenzel et al. 2024).

Highlights of Project Group C – Human Dimensions

Our studies have documented that significant land-use change dynamics in Indonesia, including in our research area in Jambi, were driven by various socioeconomic and policy factors. Relying on

panel data estimates across all Indonesian regions, Cisneros et al. (2022) show how both economic and political incentives at the local level contributed to land-use change and deforestation in Indonesia over the last decades. Their results show that forest clearing was especially intense before local mayoral elections but also when global oil palm prices were increasing, with both factors reinforcing each other. Besides large-scale plantations, smallholder farmers are important actors of land-use change in our research area. Gatto et al. (2015) and Euler et al. (2016) show for the case of Jambi that smallholder oil palm expansion occurred at the expense of rubber, bushland and forestland. The importance of contract schemes has diminished more recently (Gatto et al. 2017, Qaim et al. 2020).

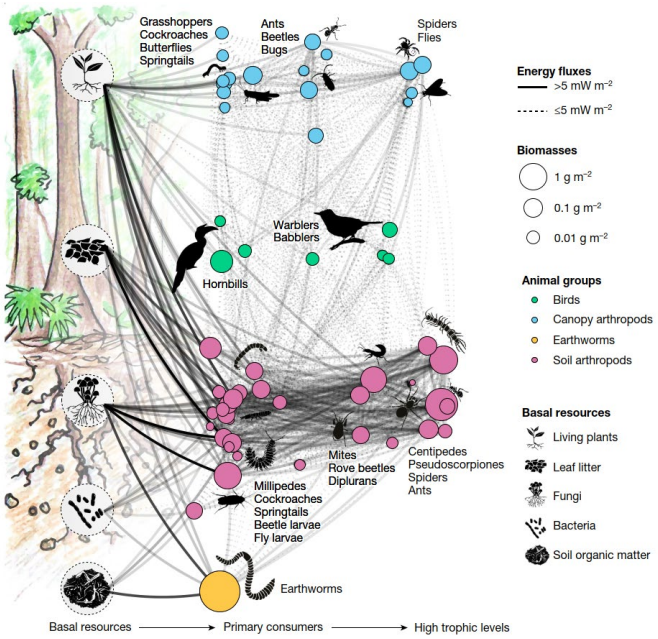

Fig. 1. Distribution of energy across birds, earthworms and arthropods in rainforest food webs across aboveground and belowground compartments (Potapov et al. 2024).

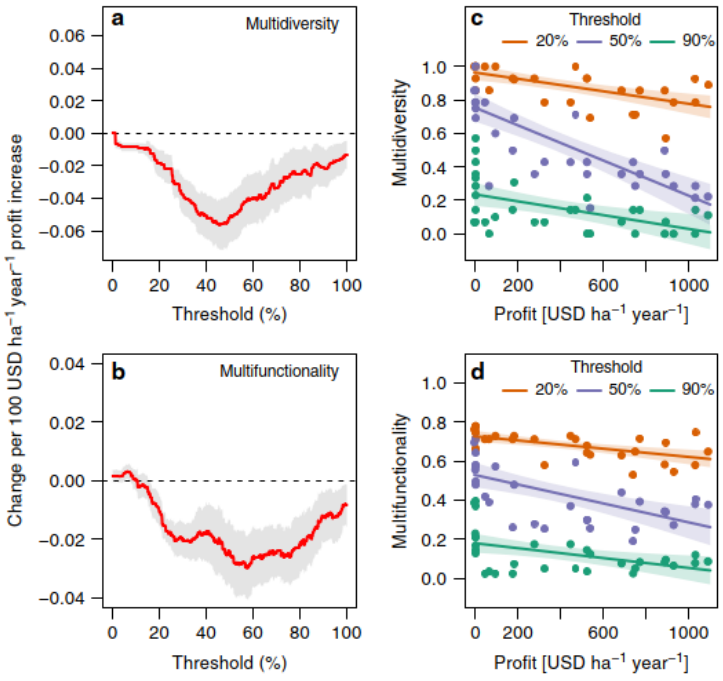

Fig. 2. Multidiversity-profit and multifunctionality-profit relationships are generally negative, regardless of thresholds used to define multidiversity or multifunctionality (Grass et al. 2023).

Our results emphasize the great economic importance of oil palm for the local population having positive impacts on smallholder living standards and nutrition (Chrisendo et al. 2020, 2022, Euler et al. 2017, Krishna et al. 2017). But even for households not involved in agriculture, the expansion of

oil palm cultivation has contributed to the reduction of rural poverty on a broad scale (Bou Dib et al. 2018). However, limited access to capital and other constraints are obstacles for many rural households (Chrisendo et al. 2021). The oil palm boom is contributing to structural change, as agricultural holdings are becoming larger over time (Kubitza et al. 2024).

Some of the social implications were more deeply investigated in our qualitative case studies, which showed that the expansion of oil palm plantations and the simultaneous expansion of protected areas have fostered tensions over land (Hein et al. 2015, Hein 2018, Kunz et al. 2017). Recent territorial conflicts mirror the contradictory interests of different governmental organizations, transnational actors and local people (Hein et al. 2018, Hein 2018). Also, the establishment of socially inclusive 'model' plantations of external actors can restrict the local population's access to land and limit their development opportunities instead of generating additional income (Kunz et al. 2019, Otten et al. 2020).

These social challenges need to be addressed for more inclusive development. Husmann et al. (2022) developed a multi-criteria optimization approach that was used to explore the composition of a hypothetical "multifunctional landscape" mitigating trade-offs between different ecological and socio-economic functions. Our modelling shows that the prevailing trade-offs cannot be resolved by a single best land use option. Rather, a balanced mix of different intensive and extensive forms of land use is most promising to provide multiple socio-economic and ecological functions.

The land-use experiments that we have carried (*EFForTS-BEE*, *EFForTS-OPMX*) show ways in which oil palm plantations can be managed in a more ecologically sustainable way. However, smallholders will only implement such measures if they are provided with the necessary information and support (Moser and Musshoff 2015, Romero et al. 2019, Rudolf et al. 2020). While our studies did not show significant welfare effects for existing oil palm certification schemes, well-designed payments for ecosystem services or certification schemes with price premiums could be an additional way to provide economic incentives and promote a transformation to more sustainable forms of oil palm cultivation (Sarwosri et al. 2019). Our experiments have shown that simple requirements (in terms of minimum areas) are preferable to more complex designs, since excessive coordination requirements reduce the success of the incentive mechanisms (Rudolf et al. 2022). They have further shown that distributional mechanisms can be incorporated in the payment design to achieve more equal outcomes, while maintaining the same level of conservation outcomes (Vorlaufer et al. 2017). Based on the research results of *EFForTS*, teaching and learning units on sustainable oil palm management were developed for higher education as part of our PR project.

Highlights of *EFForTS-BEE*

The EFForTS Biodiversity Enrichment Experiment (*EFForTS-BEE*) addresses restoration strategies that allow enhanced biodiversity and ecosystem functions in cash crop-dominated tropical landscapes. A total of 52 'islands' of native trees, of varying size and of between zero to six tree species, were planted across a 140 ha oil-palm plantation that was otherwise essentially a monoculture (Fig. 3).

We used methods ranging from acoustic monitoring of birds to laser scanning of vegetation structure to evaluate 10 indicators of above- and below-ground biodiversity, and 19 indicators of ecosystem functioning. This broad assessment showed that biodiversity and ecosystem multifunctionality were higher in tree islands, but also that larger tree islands led to larger gains, primarily because those islands became dominated by trees other than oil palms (Fig. 4, Zemp et al. 2023). Although oil palm yield was on average 24% lower than in the surrounding monocultures, the thinning of palm trees that was conducted to plant the native trees actually led to gains in yield around the islands, which compensated for the reductions within the islands. The experiment is ongoing. Over one decade, we have continuously monitored multidimensional restoration outcomes and the results are very promising.

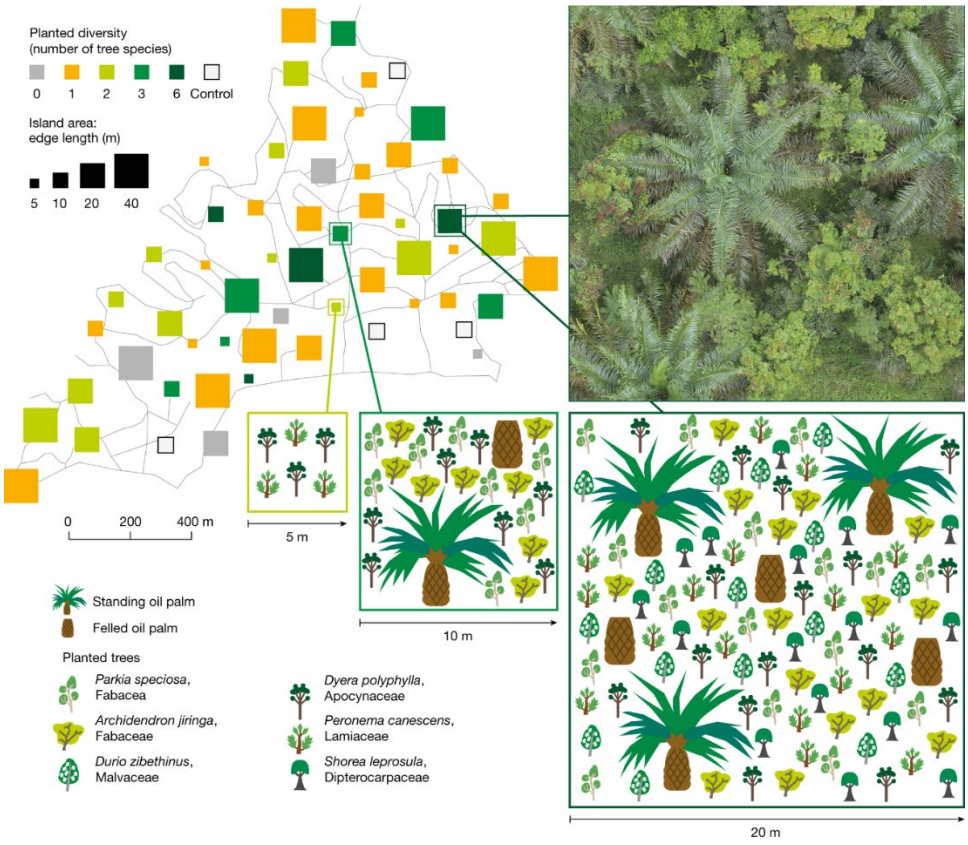

Fig. 3. Experimental design that tests the ecological restoration outcomes of tree island establishment in oil palm-dominated landscapes (Zemp et al. 2023).

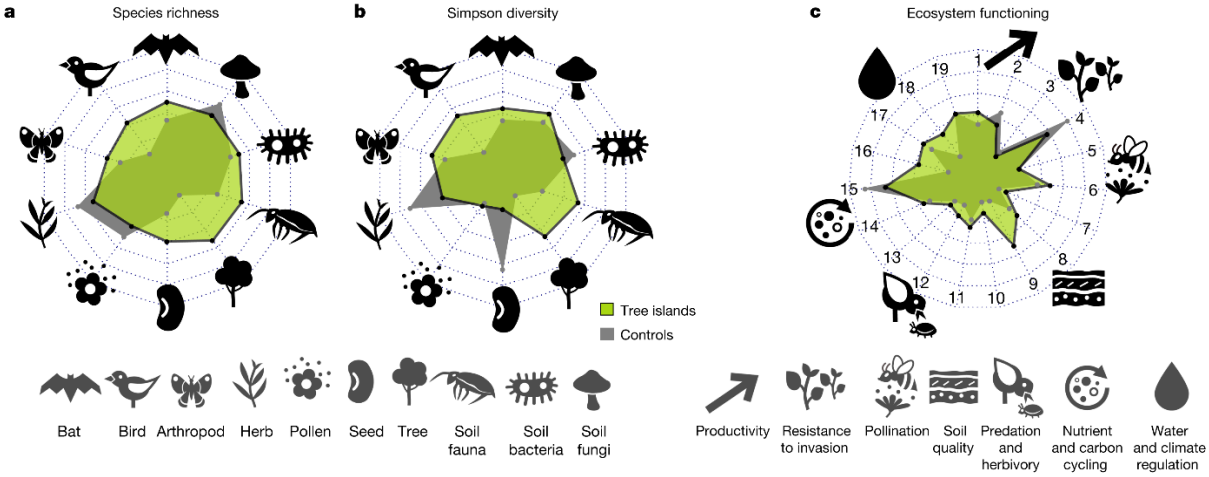

Fig. 4. Multidimensional ecological restoration outcomes in an oil palm-dominated landscape. We measured 10 and 19 indicators of biodiversity and ecosystem functioning, respectively, in tree islands and compared their responses to those in plots representing conventionally managed oil palm monocultures. For ecosystem functioning, we measured: productivity as (1) oil palm yield and (2) above-ground biomass; resistance to invasion of (3) native seeds and (4) resistance to invasive plants; pollination as (5) pollinators and (6) pollination rate; soil quality as (7) soil P, (8) soil decompaction and (9) 1/soil C:N; predation and herbivory as (10) predators (vertebrates), (11) predators (arthropods), (12) predators (soil fauna) and (13) herbivores (soil fauna); carbon and nutrient cycling as (14) decomposers, (15) litter decomposition and (16) litter input; water and climate regulation as (17) evapotranspiration, (18) water infiltration and (19) microclimate buffering. Oil palm yield (calculated per island) is considered as an ecosystem functioning because of its contribution to primary productivity, as well as agricultural productivity. **a**–**c**, Indicators of biodiversity calculated as species richness (**a**) and Simpson diversity (**b**), which emphasizes the contribution of abundant species and ecosystem functioning (**c**) across 52 tree islands (green polygons) compared to four control plots of conventionally managed oil palm monocultures (grey polygons) (Zemp et al. 2023).

Highlights of *EFForTS-OPMX*

Industrial, large-scale oil palm plantations represent a substantial part of oil palms in Indonesia and are highly productive, but this is largely driven by intensive management, i.e. large fertilizer and herbicide applications, resulting in loss of biodiversity and ecosystem functions. We established an Oil Palm Management Experiment (*EFForTS-OPMX*) to evaluate alternative management strategies in oil palm production that can maintain high productivity and economic profitability while minimizing associated losses of ecosystem functions and biodiversity. *EFForTS-OPMX* is a 2^2 full factorial experiment with two fertilization rates (conventional and reduced fertilization, equal to nutrients exported via fruit harvest) and two weeding methods (herbicide and mechanical), each with four replicate plots, from 2016 to 2023 in a >15-year-old, large-scale oil palm plantation. Eleven subprojects collected data on indicators of ecosystem functions, biodiversity and economic profitability.

One year after establishing the experiment, bacterial diversity and community composition did not differ among the four management treatments (Berkelmann et al. 2020). Gross and net soil N cycling rates were comparable between reduced and conventional management (Chen et al. 2024, Formaglio et al. 2021). However, the frond-stacked area had higher soil N cycling rates and soil fertility than inter-row and palm circle (Formaglio et al. 2021). Mulching with senesced fronds enhanced soil microbial biomass, which promoted nutrient cycling. Thus, returning leaf litter to the plantation can contribute to restoring extant nutrient input and cycling, consequently reducing reliance on chemical fertilizers. The reduced management intensity increased belowground animal group richness by 16% compared to conventional management (Darras et al. 2019). Mechanical weeding significantly enhanced plant cover and insect richness compared to herbicide use. Overall, the probability of achieving economic-ecological win-wins was higher in reduced management intensity compared to conventional management (Wenzel et al. 2024).

After four years reduced management led to a 68% increase in nitrogen response efficiency, 200% increase in partial factor productivity of phosphorus and 22% increase in partial factor productivity of potassium compared to conventional management (Chen et al. 2024). Soil greenhouse gas fluxes and global warming potential did not differ among the management treatments, implying legacy effects of over a decade of conventional management prior to the start of the experiment. The palm circle, where fertilizers are applied, covered 18% of the plantation area but accounted for 79% of soil N_2O emissions and soil N_2O emission contributed 55% to the global warming potential (Chen et al. 2024). Higher soil N_2O emissions in the studied plantation compared to nearby smallholder plantations could be attributed to a higher N fertilization rate (Hassler et al. 2017, Meijide et al. 2020).

A synthesis of all the data collected in *EFForTS-OPMX* revealed that reduced management intensity exhibited higher ecosystem multifunctionality and biodiversity than conventional management (Fig. 5, Iddris et al. 2023). This was driven by increases in understory plant diversity resulting from replacing herbicide use with mechanical weeding. The four-year cumulative yield did not differ among treatments, but reduced fertilization and mechanical weeding increased profit by 12% and relative gross margin by 11% due to reductions in material costs. The similar yields among treatments suggest a more efficient use of applied fertilizers in the reduced management system (Chen et al. 2024, Formaglio et al. 2020). Additionally, reduced management resulted in a 60% decrease in dissolved aluminum leaching and a 73% reduction in dissolved potassium leaching (Formaglio et al. 2020). Overall, the results of the *EFForTS-OPMX* provide strong evidence that mechanical weeding, together with reduced, compensatory fertilization rates in mature, industrial oil palm plantations is a tenable management option for enhancing ecosystem multifunctionality and biodiversity and increasing profit, providing win–win situations.

Highlights Landscape Assessment

Rainforest transformation in Indonesia is multiscalar, with local, landscape, provincial and regional scales being important (Klasen et al. 2016, Qaim et al. 2020). In addition, many local ecological and

socioeconomic processes are moderated by the surrounding landscape context (Li et al. 2022, Tscharntke et al. 2012). This calls for a spatial framework that considers landscape moderation and scaling up of local functions for understanding complex ecological and socioeconomic patterns across spatial scales in rainforest transformation landscapes. To fill this knowledge gap, we established the novel large-scale *EFForTS* Landscape Assessment (*EFForTS-LA*) in Phase 3 of *EFForTS*, which added 100 new study plots to the existing 24 study plots of the core design of *EFForTS*. The resulting 124 study plots allowed us to target spatial heterogeneity in land-use management, biodiversity and ecological and socioeconomic functions within and between multiple dominant land-use types, at the landscape level and the even larger regional level of the study province.

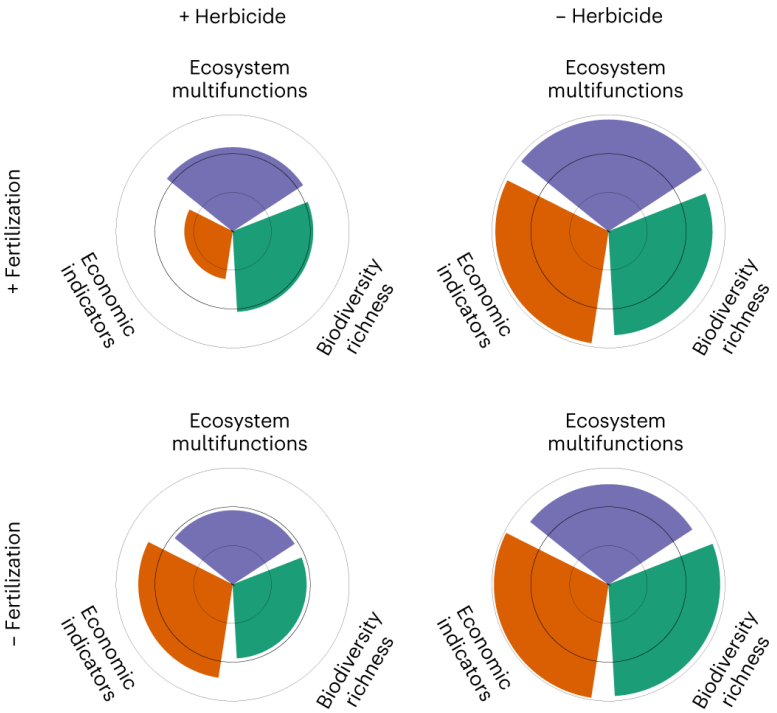

Fig. 5. Conventional vs reduced management and their associated ecosystem and economic functions in an industrial oil palm plantation in Jambi, Indonesia. For each petal, the centre (fifth quantile) and the outer edge (95th quantile) are based on the z-standardized values of eight ecosystem functions (purple), seven multitrophic richness for biodiversity (green) and six indicators for yield and profit (orange). 22 factorial treatments: + indicates conventional fertilization and herbicide treatment; − denotes reduced fertilization and mechanical weeding (Iddris et al. 2023).

The 124 study plots of the *EFForTS-LA* were distributed across a 6800 km^2 study region (Fig. 6). The *EFForTS-LA* plots covered independent gradients of local land-use intensity and landscape heterogeneity focusing on four dominant land-use types in Jambi province: tropical lowland rainforest (34%), shrubland (10%), rubber plantations (20%), and oil palm plantations (12%). The entire known heterogeneity (topography, management intensity, plantation age) of these four land-use types was comprehensively covered with 25 plots each. All plantation plots were linked to households covered in socioeconomic household panels, allowing to relate socioeconomic heterogeneity to biodiversity and ecosystem functions. To systematically cover variation of the surrounding landscape, the 25 study plots per land-use type were situated along a landscape heterogeneity gradient characterizing the landscape surroundings of each study plot across spatial scales (250-3000 m radius). This heterogeneity gradient was primarily focused on landscape composition (e.g., forest cover) (Arroyo-Rodríguez et al. 2020).

In total, twelve subprojects of *EFForTS* recorded data within the *EFForTS-LA*. The collected ecological data comprised eleven taxonomic groups, nine ecosystem functions/processes and ten environmental variable groupings, providing a detailed assessment of above- and belowground biodiversity and ecosystem processes. The socioeconomic household survey conducted covered 300 households of eleven villages across the entire study region. A detailed assessment of landscape-wide vegetation structure was based on two airborne LiDAR campaigns in 2020 and 2023. From the LiDAR data ecologically informative vegetation parameters were derived (Camarretta et al. 2021), such as above ground biomass changes (Schlund et al. 2021), vegetation canopy height (Schlund et al. 2023). Comprehensive syntheses work could not be completed due to

the delays caused by the Covid-19 pandemic-related work restrictions and will be continued within the framework of a follow-up bundle of projects.

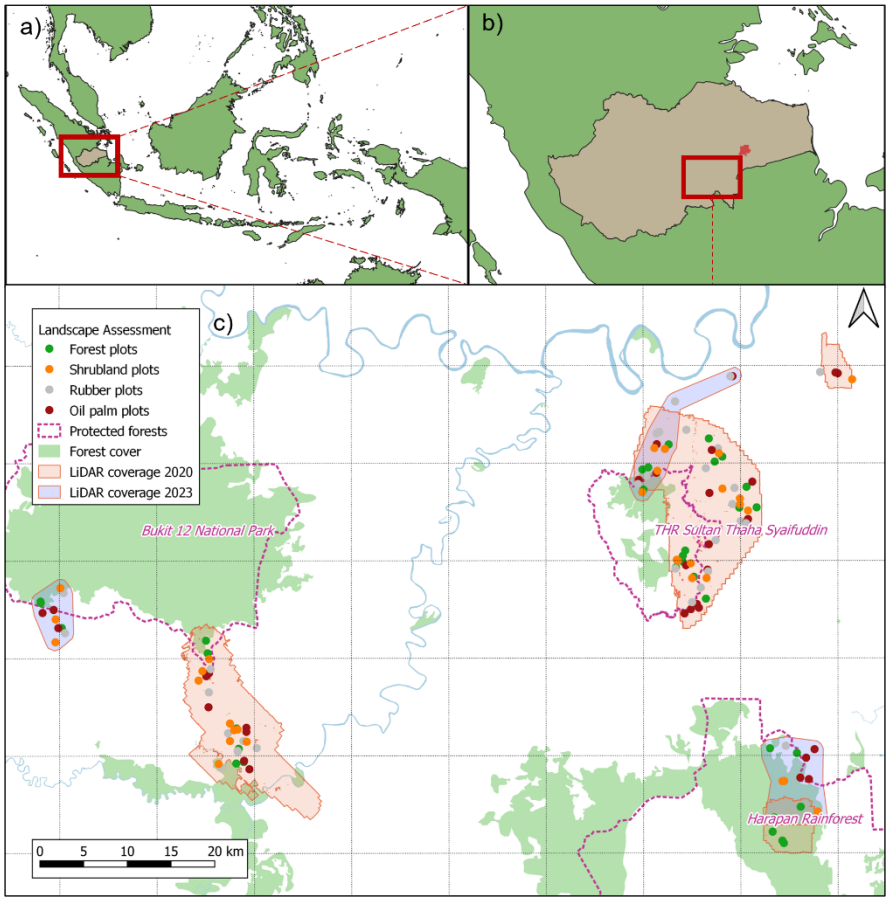

Fig. 6. (a) Map of the Indonesian archipelago with Jambi province on Sumatra highlighted in grey. (b) Jambi province with the city of Jambi illustrated in red. c) Map of the study region in Jambi Province on Sumatra, Indonesia. Points indicate EFForTS-LA study plots across land-use types (green = forest, orange = shrubland, grey = rubber, red = oil palm). Remaining lowland rainforest cover is shown in green. The area covered with airborne LiDAR is filled with orange (2020 scans) and blue (2023 scans) with orange outlines. The outlines of protected forest reserves are displayed with dotted red lines.

Focus 1: Assessment of ecological and socioeconomic functions, synergies and trade-offs across different land-use systems

The mechanisms and relationships between rainforest transformation and responses among ecological and socioeconomic functions are still poorly understood. With its focus on valuation of local synergies and trade-offs among these functions, the research efforts combined in *Focus 1* centre on three hypotheses:

(1) Transformation of rainforest to monoculture production systems is associated with a strong decline in biodiversity and ecological functions, however, these monoculture production systems are socioeconomically more valuable than rainforests, resulting in ecological-socioeconomic trade-offs.

(2) Differences in management or ecological setting of rubber and oil palm plantations have both additive and interactive effects on ecological and socioeconomic functions, resulting in non-linear relationships and both synergies and trade-offs among and between functions.

(3) Enrichment of oil palm plantations by planting of indigenous multi-purpose trees and environmentally-friendly oil palm management mitigate the ecological-socioeconomic trade-offs that are associated with the conversion of tropical lowland forest to oil palm monoculture.

In Phase 1, we addressed hypothesis 1 with an interdisciplinary synthesis of ecological and socioeconomic functions across different land-use systems (Clough et al. 2016). This synthesis, and many more disciplinary case studies, clearly demonstrated that rainforest transformation to monocultures causes pronounced trade-offs between socioeconomic and ecological functions by reducing biodiversity and ecosystem functioning at the expense of increasing socioeconomic benefits. Examples of losses in biodiversity in ecosystem functioning include decreases of at least 45% in species diversity, density and biomass of invertebrate communities (Barnes et al. 2014, Drescher et al. 2016) and a loss of soil carbon content in the Ah-horizon of about 70% when

comparing rainforest to oil palm plantations (Guillaume et al. 2015). However, monoculture production systems have higher socioeconomic benefits, as indicated by gains in average household welfare and village wealth through oil palm expansion (Euler et al. 2016, 2017, Gatto et al. 2015, Kubitza et al. 2018).

In Phase 2, we addressed hypothesis 2 and focussed on non-linear relationships between economic and ecological functions across land-use transitions (Grass et al. 2020). We found widespread non-linear biodiversity-profit trade-offs, for aboveground and belowground species and ecosystem multidiversity and multifunctionality with increasing economic profits from land use (Grass et al. 2020). These findings suggest that losses in biodiversity and ecosystem functioning can only be reduced if economic incentive structures are changed through well-designed policies that promote more sustainable palm oil production.

In Phase 3, we addressed hypothesis 3 and the need for identifying best practices for improving the ecological value of oil palm plantations. A major finding of the *EFForTS-OPMX* was that reducing management intensity promotes biodiversity and ecosystem functions within oil palm plantations, while maintaining crop yields and allowing for greater economic profits because of reduced inputs (Darras et al. 2019, Iddris et al. 2023). The *EFForTS-BEE* demonstrated that enrichment of oil palm plantations with native tree species can partially restore biodiversity and ecosystem functions, without reducing palm oil yields (Zemp et al. 2023). In a final synthesis study coordinated by Focus 1, we explored strategies to enhance biodiversity and restore ecological value while also considering the economic demands associated with oil palm cultivation (Wenzel et al. 2024). Thereby, we included from all oil palm systems that had been studied in the 12 years of *EFForTS*, including data on biodiversity, ecosystem functions and oil palm yields, covering smallholder plantations, industrialized company estates, and innovative experimental estates with improved agronomic management (*EFForTS-OPMX*) and native tree enrichment (*EFForTS-BEE*). We found that oil palm yields in industrialized estates were, on average, twice as high as in smallholder plantations (Fig. 7). Ecological indicators such as biodiversity displayed substantial variability across systems, regardless of yield variations, highlighting great potential for economic-ecological win-wins (Wenzel et al. 2024).

Reducing management intensity (e.g, mechanical weeding) did not lower yields but improved ecological outcomes, making it an effective measure for balancing economic and ecological demands. Additionally, maintaining forest cover in the landscape generally enhanced biodiversity and ecosystem functioning within plantations (Wenzel et al. 2024). Enriching oil palm plantations with native trees is a further most promising strategy to increase ecological value without reducing productivity (Wenzel et al. 2024). Overall, we recommend closing yield gaps in smallholder cultivation through careful intensification, whereas conventional plantations could reduce management intensity without sacrificing yield. Our study highlights various pathways to reconcile economic and ecological interests in palm oil production and identifies new management practices for a more sustainable future of oil palm cultivation.

Focus 2: Spatial and temporal variability: Quantifying the effects of spatial, temporal and social heterogeneity on ecological and socioeconomic functions

Evapotranspiration within tropical rainforests fluctuated both in space and time and these fluctuations were related to specific site conditions (Bulusu et al. 2023). By contrast, e.g. soil silicon pools changed little even after conversion of rainforest into oil palm plantations for 20 years (Greenshields et al. 2023) found that. Investigations of seasonal and spatial dynamics of biodiversity showed that plantations displayed markedly stronger seasonal changes in microbial community indicators, soil and canopy invertebrates as well as energy fluxes than rainforest (Krashevska et al. 2022, Pollierer et al. 2023). Overall, the results suggest that land use temporarily shifts and increases the magnitude of seasonal variations in above- and below-ground ecosystem compartments, with microbial communities responding most strongly.

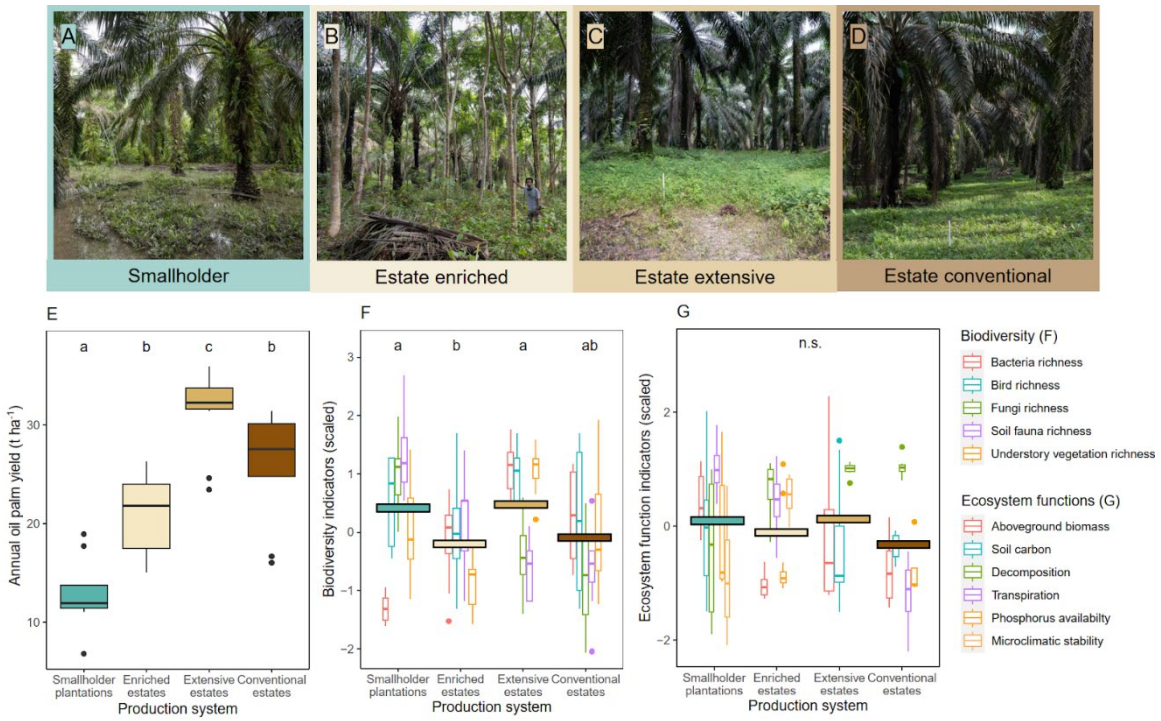

Fig. 7. Oil palm production systems considered in the synthesis study: Smallholder plantations (A), estates enriched with trees (B), estates with extensive management (C) and conventionally managed estates (D). Boxplots of mean annual oil palm yields per hectare for each system (E) and boxplots of standardized biodiversity indicators (F) and ecosystem function indicators per cultivation system (G). Boxplots represent the median (bars), the 25–75% intervals (box edges) and the 1.5 interquartile range (whiskers) of the raw data (n = 355). Boxplot colors (in F and G) indicate ecological indicator identity. Colored horizontal bars represent the mean indicator scores per system. Letters indicate statistically significant differences between systems (Tukey test, $p < 0.05$).

In the framework of *EFForTS-BEE*, we showed that dissimilarity in both vegetation structure and soil conditions significantly influences beta diversity and turnover across multiple taxa, which was more pronounced in above- than belowground taxa (Montoya-Sánchez et al. 2023). Further, studies on pollen loads of stingless bees using DNA metabarcoding and light microscopy highlighted the importance of seasonal and spatial fluctuations (Moura et al. 2022). Integrating data from various projects, the EFForTS-ABM model evaluated the influence of diverse landscape designs and pricing scenarios on socio-economic and ecological functions, along with the resulting trade-offs. The results will be pivotal in pinpointing landscape designs that mitigate declines in ecological functions while still allowing for economic benefits.

Focus 3: Scaling-up of ecological and socioeconomic functions from local to landscape and broader scales

In Phases 1 and 2, we demonstrated that agricultural specialization decreased from the household to the province level (Klasen et al. 2016) and that the labour savings achieved through palm oil expansion resulted in increasing land use (at the cost of deforestation, Cisneros et al. 2021) at all scales of analysis (Kubitza et al. 2024). In Phase 3, our activities centred around exploring ecological and socioeconomic functions and trade-offs across multiple spatial scales, ranging from plot surroundings up to several kilometres to the scale of Jambi province and beyond as facilitated by the novel *EFForTS-LA* (Fig. 8)

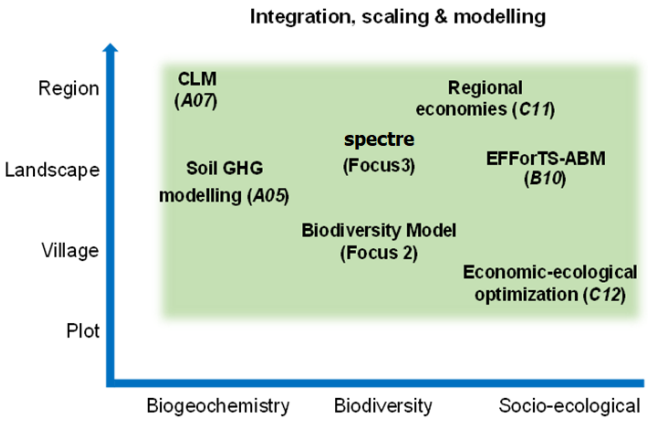

Fig. 8. Integration, scaling up and modelling via the Landscape Assessment platform. Only subprojects with a major focus on modelling and/or scaling are indicated.

For example, Camaretta et al. (2021) generated a three-dimensional representation of vegetation structure based on airborne laser scanning metrics and showed differences across land-use and land-cover types across a gradient of land-use management intensities. The airborne LiDAR and hyperspectral campaigns were also used to assess biomass change with high accuracy compared to field measurements to further support the understanding of ecosystem dynamics like fires (Schlund et al. 2021). Moreover, semi-empirical models for large-scale and consistent mapping of vegetation canopy height have been developed to assess biomass and carbon stocks in tropical landscapes (Schlundt et al. 2023). Ruml et al. (2022) analysed the role of oil palm for rural development by comparing Ghana's and Indonesia's oil palm sectors using a mixed methods approach at the macro and micro level. Software solutions, such as spectre (Simkins et al. 2022), landscapemetrics (Hesselbarth et al. 2019) and or EFForTS-Lgraf (Salecker et al. 2019) proved extremely useful for ongoing interdisciplinary synthesis work.

Focus 4: Towards more sustainable land use in lowland tropical regions

The findings from *EFForTS* illustrate that more sustainable land use in Jambi could be achieved by improvements in on-farm management practices as outlined by Gerard et al. (2017) and Iddris et al. (2023) and adjustments to existing policy frameworks. Throughout Phase 2 and 3, comprehensive analyses of specific policies were conducted, such as REDD+ (Hein et al. 2015, Hein et al., 2018, Kunz et al. 2019), the influence of international trade agreements (Kopp et al. 2020), the regulatory framework governing land-use rights (Kubitza et al. 2018, Kunz et al. 2016) and the effects of Roundtable on Sustainable Palm Oil (RSPO) certification (Kunz et al. 2019, Martens et al. 2019, Rosyani et al. 2022). Integrative research illustrated how the combined effects of changing bio-geophysical soil properties in monoculture plantations, encroachment of wetlands, non-compliance with environmental legislation and construction of water infrastructure led to decreasing water regulation services in Jambi province (Merten et al. 2016, 2020). A resulting policy briefing paper recommended that the European Union should set mandatory sustainability standards for all palm oil products (Merten et al. 2016). In Phase 3, the emphasis shifted toward future land-use scenarios. Petri et al. (2023) reviewed the challenges associated with future replanting and highlighted that information, proper training, access to high-quality seedlings and eligibility for public replanting funds determine successful smallholder replanting Halmschlag (2022) developed a concept for testing different schemes for ecosystem service payments in EFForTS-ABM. EFForTS-LGraf explored trade-offs between biodiversity and economic multifunctionality and developed a Social Accounting Matrix (SAM) of a rural economy which captures the interlinkages between sectors and stakeholders. As an example of a shared learning process, we engaged in the "Sustainable Village Project" with additional support from Documenta 15. First results were shown in the Göttingen Forum Wissen special exhibition "Saujana Membumi" in summer 2022.

Handling of research data

The research data generated by the CRC 990 has been initially stored and made available via a repository based on the "Biodiversity Exploratories Information System" (BEXIS). The system included the research data and an elaborated set of related meta-data for the first two funding

periods. During the third project phase, this data has been migrated to a sustainable institutional solution, which is operated by the Göttingen Campus through the eResearch Alliance service unit independent of any third-party funding. Data created after the migration has been directly stored there, too. The CRC 990's data is now available at https://data.goettingen-research-online.de/dataverse/crc990 in a concise and well-documented manner according to the FAIR data management principles. "GRO.data", the respective repository, is findable e.g. through the "Registry of Research Data Repositories (https://www.re3data.org/) and data is openly accessible in many cases. The metadata related to the CRC's data sets has been derived from the initial BEXIS system and provides comprehensive and comparable information for each and every set. The data is re-usable based on the CRC's data policy, which allows open access in many cases, but also enforces embargos or specific licenses where applicable. The data comprises 43 so-called Dataverses, i.e. sub-repositories for particular scientific projects, but also for workshops or other categories of data. Overall, 1,137 data sets with 4,895 files show the rich and broad results of the CRC 990 that are provided to interested researchers globally also after the end of the funding of the CRC. The data will be available at least 10 years into the future, but as of today, no plans exist to delete any of the data after that period.

EFForTS was the largest collaborative scientific project between Germany and Indonesia, integrating biodiversity, ecosystem functions, socio-economics, and society. It has resulted in more than 400 peer-reviewed publications revealing trade-offs between losses of ecosystem functions and improved living standards among farmers, showing climate impacts of oil palm plantations, and identifying transformation pathways based on improved land management. Overall, the results highlight that science-based knowledge on trade-offs between ecological and socio-economic functions is needed for developing policies for sustainable land use not only in the tropics but also in other regions of the world.

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4.1 Scientific Event and Science Communication

EFForTS used classic PR activities, social media interactions, educational trainings and public science communication events to disseminate the scientific findings and to engage / interact with the public and stakeholders at both our locations in Göttingen and Indonesia. Important external scientific events hosted by or with *EFForTS* are summarized in Table 2.

Table 2. External scientific events hosted by or with *EFForTS*.

Date and location	External scientific events hosted by or with EFForTS
Mar 6, 2014, Jambi, Indonesia	Workshop "*Oil-palm livestock integration towards sustainable and future oil palm plantation management systems"* ➢ Topic: Use of by-products from oil palm production through livestock integration in plantations. ➢ Guests: Officials from the Indonesian Ministry of Agriculture and oil palm companies in Indonesia and Malaysia, scientists from Indonesia, Malaysia and the UK.
Apr 12-17, 2015, Vienna, Austria	European Geosciences Union General Assembly 2015 ➢ Topic: *EFForTS* convened the session BG2.1 *Biogeochemistry, ecohydrology, and land-use in the tropics*. ➢ Guests: International scientists (>100).
Jul 12-16, 2015, Honolulu, Hawaii	52nd Annual Meeting of the ATBC "*Resilience of Island Systems in the Context of Climate Change: Challenges for Biological and Cultural Diversity and Conservation*" ➢ Topic: *EFForTS* organized a special section on *Consequences of Rainforest Transformation in the Southeast Asian Archipelago* ➢ Guests: International scientists (>500).
Feb 23-26, 2016,	29th Annual Conference of the Society for Tropical Ecology, co-organized by the Centre of Biodiversity and Sustainable Land Use (CBL), Göttingen and *EFForTS*

Göttingen Germany	➢ Topic: Tropical diversity, ecology and land use. ➢ Guests: International scientists (>500).
Apr 17-22, 2016, Vienna, Austria	European Geosciences Union General Assembly 2016 ➢ Topic: *EFForTS* convened the session BG2.11 Biogeochemistry, ecohydrology, and land-use in the tropics. ➢ Guests: International scientists (>100).
Apr 23-28, 2017, Vienna, Austria	European Geosciences Union General Assembly 2017 ➢ Topic: *EFForTS* convened the session BG4.3/SSS5.20 Biogeochemistry, ecohydrology, and land-use in the tropics and subtropics. ➢ Guests: International scientists (>100).
Sep 11-17, 2017, Bogor, Indonesia	Workshop "*Tropical plant identification"* ➢ Topic: Overview of the most commonly encountered tropical vascular plant families in Indonesia, introduction to plant morphology and identification tools. ➢ Guests: Royal Botanical Gardens Kew (UK), scientists from Indonesian research centres and universities (>50).
Apr 08-13, 2018, Vienna, Austria	European Geosciences Union General Assembly 2018 ➢ Topic: *EFForTS* convened the session BG4.3 Biogeochemistry, ecohydrology, and land-use in the tropics and subtropics. ➢ Guests: International scientists (>100).
Oct 7-11, 2018 Bali, Indonesia	International Symposium "*Socio-ecological transformations of tropical lowland rainforests"* ➢ Topic: Bridging disciplines and bringing together researchers from all fields of science integrating ecological and socioeconomic perspectives as well as stakeholders in the field of land use changes in tropical lowlands. ➢ Guests: International scientists from Australia, Czech Republic, Germany, UK, and Indonesia, and representatives from national authorities in Indonesia (>100).
Apr 07-12, 2019, Vienna, Austria	European Geosciences Union General Assembly 2019 ➢ Topic: *EFForTS* co-convened the session BG2.11 Biogeochemical cycles and ecohydrology in changing tropical systems. ➢ Guests: International scientists (>100).
May, 4-8, 2020 Vienna, Austria	European Geosciences Union General Assembly 2020 (online only) ➢ Topic: *EFForTS* co-convened the session BG3.30 Tropical landscapes and peatlands: Biogeochemistry, ecohydrology and land use impacts. ➢ Guests: International scientists (>100).
Apr 19-30, 2021 Vienna, Austria	European Geosciences Union General Assembly 2021 ➢ Topic: *EFForTS* co-convened the session BG2 Tropical ecosystems – biomes of global significance in transition. ➢ Guests: International scientists (>100).
Nov 21-25, 2022, Metz, France	SFE^2 GfÖ EEF conference "*Ecology and Evolution: New perspectives and societal challenges*" (>1.000 participants). ➢ Topic: *EFForTS* convened the session "*Rainforest transformation into agricultural lands: current and future challenges*". Recent advances in ecological research on consequences and sustainable alternatives on rainforest transformation were showcased and research challenges and future perspectives highlighted. ➢ Guests: International scientists (> 100).
Oct 31-Nov 5, 2022 Bogor, Indonesia	Workshop "*Tropical plant identification"* ➢ Topic: Overview of the most commonly encountered tropical vascular plant families in Indonesia, introduction to plant morphology and identification tools. ➢ Guests: Royal Botanical Gardens Kew (UK), universities, research institutions, protected area administrations, and NGOs all over Indonesia and from the Philippines (>50).
Sep 12-16, 2023, Leipzig, Germany	52th GfÖ Annual Meeting "*The Future of Biodiversity – overcoming barriers of taxa, realms and scales*" (1.200 participants). ➢ Topic: *EFForTS* convened the session "*Land-use change in the tropics: ecosystem-level impacts and restoration approaches*". This session focused on providing an ecosystem perspective on the impact of land-use changes and assessing diverse approaches aiming to enhance biodiversity and ecosystem functioning in human-modified tropical ecosystems across various projects in Africa, South America and Asia. ➢ Guests: International scientists (>100).
Oct 4-7, 2023, Jambi, Indonesia	Workshop for Professional Learning Community and PR stakeholders: "*Making EFForTS education available for Indonesia and the world*". ➢ Guests: Officials, educators, lecturers, research assistants, and two journalists (>25).
Oct 11-13, 2023 Yogyakarta, Indonesia	International Symposium "*Transformation of tropical rainforest: social and ecological consequences and perspectives"* ➢ Topic: Science-driven approaches that target the enhancement of ecological and socioeconomic functions within tropical lowland forests and agricultural transformation systems, all within the broader context of landscape-scale solutions. ➢ Guests: International scientists from Australia, USA, UK, and Indonesia, representatives from national authorities in Indonesia (>100).

EFForTS benefitted from the existing university's internal public relations work. Of particular importance for *EFForTS* local activities were the biennial Göttingen Night of Science (over 25,000 visitors) in close cooperation with the partner research institutes at the Göttingen Campus.

The project received broad support for the organization of a special exhibition of science and art in the Forum Wissen in Göttingen in 2022. *EFForTS* and the Forum Wissen, Göttingen's academic museum, have launched a joint cooperation with *documenta* fifteen in Kassel (Germany), the most recognized exhibition of contemporary art worldwide, and Rumah Budaya Sikukeluang, a collective of artists from Riau province on Sumatra Island, Indonesia (see Table 2B for details).

Besides, in close cooperation with the Public Relations Department of the University of Göttingen, the projects overall results were presented in the central public lecture series of the University of Göttingen in the winter semester of 2023/2024, entitled *"Umwandlung tropischer Regenwälder – Soziale und ökologische Folgen und Perspektiven"*. *EFForTS* science communication measures and their resonance with target communities are outlined in Table 2.

(Open-access)Publications in high-ranking journals and presentations of results in international conferences raised the significance of *EFForTS* within the field of research: Number of citations (Web of Science, Cross Ref. ReseachGate) and recommendations in ResearchGate. Open-access databases contribute to the scientific community beyond the scope of *EFForTS*.

The networking events and educational trainings with local communities and national authorities in Indonesia raised the visibility and awareness of *EFForTS*. We could build trust with the villagers and plot owners of our core sites as well as popularize / disseminate the project's activities in the villages. As a result, at local level we were able to maintain our trial areas for over 12 years and get people interested and engaged in the work. At national level, for instance, the Ministries of Foreign Affairs and Research, Technology and Higher Education and German institutions on site (DAAD, German Embassy) hosted national symposia and workshops related to *EFForTS* (see Table 3 for details). The demand for our manuals and handbooks was high and included not only local farmers but also universities, research centres and stakeholders from politics and the oil palm sector. It is not without reason that the State Ministry of Research, Technology, and Higher Education of Indonesia regards *EFForTS* as best practice example in increasing benefit sharing resulting from international research collaboration. The high visitor numbers and the numerous queries at the public events showed the interest in the topic and the type of presentation / measure. It helped building public awareness and promoting curiosity and understanding.

Table 3. List of most important science communication measures with national authorities, stakeholders and the interested public

Date and location	Strategic / networking events with local and national authorities in Indonesia
Sep 11, 2017, Jakarta, Indonesia	National symposium: *"CRC 990: Towards Indonesian sustainable palm oil"* – hosted by The Agency for Policy Review and Development (BPPK) of The Ministry of Foreign Affairs ➢ Topic: Key findings of *EFForTS* towards sustainable management practices of oil palm plantations. ➢ Guests: Representatives and ambassadors of Indonesian palm oil producing and using countries such as Germany, Italy, Colombia and Spain, as well as governmental and non-governmental organisations concerned with palm oil issues.
Feb 24, Mar 26, Apr 28, May 15, 2017, Harapan Landscape, Indonesia	Network events and training workshops ➢ Topic: Human capacity development in the partner villages – Water infiltration, compost production, bird branding, Indonesian Sustainable Palm Oil / ISPO. ➢ Guests: Local authorities, Governmental agencies, village heads and villagers / plot owners from core villages of *EFForTS*.
May 8, 2018, German Embassy Jakarta, Indonesia	Workshop *"Sharing best practices – doing research together"*, hosted by the German Academic Exchange Service (DAAD). ➢ Topic: Challenges and opportunities of international collaborative research projects. Development of recommendations for higher education leadership and policy-makers, building on the experiences of *EFForTS*. ➢ Guests: Indonesian Ministry of Agriculture, DAAD, German Embassy, Museum für Naturkunde, Berlin, Germany, Indonesian Higher Education Institutions.
Jul 16, 2018,	Workshop with local Governmental institutions in Jambi province:

Jambi, Indonesia	➢ Topic: Status-quo of the collaborative project activities (research work, field activities, capacity building measures, joint publications, involvement of students). ➢ Guests: BAPPEDA (Development Planning Agency at sub-national level), KESBANGPOL (Office for National Unity and Politics), Dinas Perkebunan (Estate Plantation Office), Dinas Pertanian (Agricultural Office), Dinas Kehutanan (Forestry Office), BALITBANGDA (Province Research Body), Badan Lingkungan Hidup Daerah (BLHD) (Environmental Agency), Badan Pengkajian Teknologi Pertanian (BPTP) (Agricultural Technology Body), BMKG (Meteorology, Climatology, and Geophysics Agency), Imigrasi (Immigration Office), Balai Pemanfaatan Hutan Produksi (BPHP) (Forest Utilization Production Agency), BPDAS (Watershed Management Agency), BKSDA (Natural Resources Conservation Agency), Badan Karantina Pertanian (Quarantine Office), Sekber Kehutanan (Joint Secretariat of Forestry).
Apr 30, 2019, Jakarta, Indonesia	National workshop *"Evaluation of capacity building as impact of research permit"*, hosted by the Directorate General Research and Development of the Ministry of Research, Technology and Higher Education (KEMENRISTEKDIKTI): ➢ *Topic: Best practice and lesson learned of CRC 990 U to U research collaboration in maximizing benefit sharing*. ➢ Guests: National authorities and Higher Education institutions from Indonesia.
Nov 29, Dec 02, Dec 06, Dec 10, 2019, Bukit Duabelas Landscape, Indonesia	Network meetings and training workshops ➢ Topic: Human capacity development in the partner villages – Hydroponic cultivation of vegetables and postharvest processing. ➢ Guests: Local authorities, Governmental agencies, village heads and villagers / plot owners from core villages of EFForTS in the Bukit Duabelas landscape.
Date and location	**Science communication events: Schools / Universities / General Public**
Jan 17 2015, Jan 21 2017, Jan 26 2019, Jul 9 2022, Göttingen, Germany	2nd to 5th Night of Science at the University of Göttingen ➢ Topic: *EFForTS* displayed its research activities through a multifaceted spectrum of research presentations, hands-on activities and cultural exhibitions. ➢ Guests: General public, school and university students (> 20.000).
Aug 2018, Jambi, Indonesia	Outreach and training events for an elementary and a primary school in Bungku as part of the collaboration between SciEd (lecturers without borders) and the local initiative "*Klas Inspirasi Jambi*". ➢ Topic: Multiple lectures about ecology, biology and health in Indonesia, excursion to the EFForTS-Biodiversity Enrichment Experiment (tree leaves diversity, leave sampling and identification), and animal diversity under the stereomicroscope. ➢ Guests: school kids and teachers (>100).
Apr 2021 – Feb 2022	Joint virtual classroom courses (3 Credits) on Education for Sustainable Development offered in two semesters (Certificate programme "Interdisciplinary Teaching" at the University of Göttingen (Lehramt PluS in cooperation with the Schlözer Programm Lehrerbildung, and the Ganesha University of Education in Singaraja, Bali, Indonesia). ➢ Topic: Students from both universities met via ZOOM each day for 2.5 weeks to work together on pressing global as well as local issues of (non-)sustainable courses of action such as climate change, loss of biodiversity, water pollution, problems of mobility and the impact of the COVID-pandemic on these issues. Students exchanged ideas on how to implement these issues of sustainable development in their own future classrooms. http://schloezerlb.newsletter.uni-goettingen.de/2021/08/04/eggert/ ➢ Guests: Students UGoe (27) and Indonesia (35).
Apr 2021 – Feb 2023	*EFForTS* Education unit on *'Research-Based Oil Palm Agroforestry: How Can Tree Enrichment Contribute to Sustainable Oil Palm Cultivation*?' for Indonesian Forestry education, ➢ Topic: Five units à 5 weeks, each week with 90 min face-to-face time + 120 min supervision of students working on self-learning modules integrated into: Community/Social Forestry course at IPB University; Agroforestry course at IPB University; Agroforestry course at Jambi University; Communication and community science course at IPB University. ➢ Guests: 588 students
Apr 2021 – Feb 2023	*EFForTS* Education unit on '*Research-based Oil Palm Management Strategies: How Can Weeding and Fertilizing Contribute to Sustainable Oil Palm Management*?' for Indonesian Teacher Education. ➢ Topic: Seven units à 5 weeks, each week with 90 min face-to-face time + 120 min supervision of students working on self-learning modules integrated into: Plant Physiology course at Jambi University; Biology Education course at Ganesha University of Education; Chemistry of Life course at State University of Malang; Ecology course State University of Malang; Horticulture course at Ganesha University of Education; Organic Chemistry course at Jambi University. ➢ Guests: 355 students
Feb-Jun 2022, Göttingen, Germany	Project *„Soziales Lernen"* in collaboration with Forum Wissen and the Theodor-Heuss-Gymnasium Göttingen ➢ Topic: *Was haben Palmölplantagen in Indonesien eigentlich mit mir zu tun?* Sustainability topics and human-environmental-arts interactions were discussed in 12 teaching units. ➢ Guests: Grade eight students.

Mar 11-13, 2022, Pematang Kabau, Indonesia	*Semah Bumi* (balancing-serving-seeding) art-science festival, co-organized by the artist collective *Rumah Budaya Sikukeluang* from Riau and *EFForTS*. ➢ Topic: Human-environmental interaction, featuring concerts, art exhibitions, theatre performances and events for children (scientific puzzles and animal observations under the stereomicroscope). ➢ Guests: Villagers, local authorities, school and university students.
Jun 18–Sep 25, 2022, Göttingen, Germany	Special exhibition of science and art in the Forum Wissen in Göttingen, a collaboration with documenta 15 ➢ Topic: *Saujana Membumi – Exploring sustainability*: based on a holistic understanding of sustainability, visitors experienced the social and ecological dimensions of research in Indonesia from different perspectives. Together with the art collective *Rumah Budaya Sikukeluang* from Indonesia, *EFForTS* provided insights into the numerous specialized, interdisciplinary research practices used to collect and analyse data on site. ➢ Guests: General public, school and university students.
Oct 26, 2023 – Feb 8, 2024 Göttingen, Germany	Public lecture series "*Umwandlung tropischer Regenwälder: Soziale und ökologische Folgen*". ➢ Topic: Based on the research results of *EFForTS* and in selected international guest lectures, the lecture series shed light on the transformation process from different perspectives and using various case studies. ➢ Guests: General public, scientists and students from the university.
Date and location	**Media / Film / Open-access biodiversity data / Open Educational Resources**
Since 2012	Binational websites at University of Göttingen, Germany (http://www.uni-goettingen.de/crc990) and IPB University, Indonesia (http://efforts.ipb.ac.id/) – serving as source of information and as download-archive for the access to databases, publications and information materials.
Since 2014	Film documentation (German, English and Bahasa Indonesia) of the work of *EFForTS* in Indonesia, published on the *EFForTS* website and on youtube.com.
Since 2018	Social media: Facebook (https://www.facebook.com/efforts.crc990), Twitter (https://twitter.com/efforts_crc990), Instagram (https://www.instagram.com/efforts.crc990/)
Since 2016	➢ *EFForTS* Sumatra Plant Database: List of families and species, single species view, and search by keyword (http://134.76.19.22/sumatra/home) ➢ EcoSound: Internet audio platform for soundscape biodiversity identification (https://ecosound-web.de/ecosound_web/). ➢ Ecotaxonomy database: Data on morphology, ecology and biogeography of organisms, and link it with literature and media materials (http://ecotaxonomy.org/).
2017	Dragonflies and damselflies of the *EFForTS* study area in Jambi and Bogor (Indonesia) (Rembold K, Schröter A). https://doi.org/10.3249/webdoc-3980
2017	Common wayside plants of Jambi Province (Sumatra, Indonesia) (Rembold K, Tjitrosoedirdjo SS, Kreft H). https://doi.org/10.3249/webdoc-3979
Since 2020	Interactive field tour of the *EFForTS* project in Jambi (https://www.crc990.uni-goettingen.de/Interactive_Field_Tour/crc990-webversion/Interactive_Field_Tour.html)
2021	Guide to the ants of Jambi (Sumatra, Indonesia): Identification key to ant genera and images of the *EFForTS* collection (Nazarreta R, Buchori D, Hashimoto Y, Hidayat P, Scheu S, Drescher J). https://penerbit.brin.go.id/press/catalog/book/273
2021	The butterflies of Jambi (Sumatra, Indonesia): An *EFForTS* field guide (Panjaitan R, Hidayat P, Peggie, Buchori D, Scheu S, Drescher J). https://doi.org/10.14203/press.370
2022	Guidebook of beetles and weevils of Jambi, Sumatra, Indonesia (Hidayat P, Siddikah F, Kasmiatun, Noerdjito WA, Amrulloh R, Hiola MS, Najmi L, Nazarreta R, Scheu S, Buchori D, Drescher J). https://doi.org/10.55981/brin.321
2022	Keanekaragaman Serangga Hutan Hujan Tropis Dataran Rendah di Provinsi Jambi, Sumatra: Dampak Perubahan Tata Guna Lahan (Buchori D, Hidayat P, Nazarreta R, Ardiyanti RM, Siddikah F, Amrulloh R, Azhar A, Kasmiatun, Scheu S, Drescher J). https://penerbit.brin.go.id/press/catalog/book/280
2024	The Open Book on *EFForTS* Education (Matthiesen FK, Bögeholz S) ➢ Evidence-based) *EFForTS* education units with their modules for flexible usage were compiled and published as Open Educational Resources (OER) in the so-called "Open Book on *EFForTS* Education: https://www.efforts.education.uni-goettingen.de.

4.2 National and international collaboration

EFForTS extensively collaborated with partners in Germany, Indonesia and abroad.

Universities

- Bogor Agricultural University (IPB University; Java, Indonesia): Administrative head office on-site, central contact for higher education institutions and national authorities, researchers participated as counterparts and board members.
- University of Jambi (UNJA; Sumatra, Indonesia): Central contact for local authorities and stakeholders, local logistics centre; researchers participated as counterparts and board members;

collaboration with Biology Education, Chemistry Education and Agroforestry departments for the development of (evidence-based) EFForTS education units.

- Tadulako University (UNTAD; Sulawesi, Indonesia): Satellite study area for some research projects (A03 Knohl, C04 Klasen/Lay), researchers participated as counterparts and board members.
- Brawijaya University (UB; Java, Indonesia): Researchers participated as counterparts.
- Ganesha University of Education (UNDIKSHA; Bali, Indonesia: Collaboration with Biology, Physics, and Chemistry Education for the development of (evidence-based) EFForTS education units
- State University of Malang (UM; Java, Indonesia): Collaboration with the Science Education department for the development of (evidence-based) EFForTS education units.

Governmental Organisations

- Indonesian Institute of Science (LIPI, since 2021 part of the newly formed National Research and Innovation Agency BRIN; Java, Indonesia): EFForTS collaborated with the Cibinong Research Centre for Biology of LIPI. It hosts the Herbarium Bogoriense and the Zoological Museum. Experts of LIPI were supportive for sample identification and administrative issues e.g., the export of samples.

National Parks and Forest Restoration Concessions

- The National Park Bukit Duabelas (TNBD; Jambi, Sumatra)
- PT. REKI – Harapan Rainforest (Hutan Harapan; Jambi Sumatra): Both host lowland tropical rainforest core sites of EFForTS. Researchers of EFForTS and REKI and TNBD conducted joint training and capacity building measures with villages of related research sites. EFForTS supported staff in the frame of ABS benefit sharing (research projects and master studies, see Chapter 5. Impact on Research Priorities and International Visibility).

Crop Estate Companies

- PT. Humusindo Makmur Sejati, a privately held oil palm plantation company, Jambi, Indonesia: Hosts the EFForTS-BEE since its establishment in December 2013 (see B11 Hölscher/Kreft/Wollni, Chapter 4 Research Achievements of the CRC and Chapter 7 Individual Project Reports). With support of EFForTS-ABS, Humusindo collaborated with UNJA's Bachelor programme in Forestry (study sites).
- PT. Perkebunan Nusantara VI (PTPN VI), a government-owned company, Jambi, Indonesia: Hosts the eddy covariance flux tower since 2014 (see A03 Knohl, Chapter 7 Individual Project Reports) and the oil palm management experiment (EFForTS-OPMX), established in 2017 (see A05 Corre/Veldkamp, Chapter 4 Research Achievements of the CRC and Chapter 7 Individual Project Reports).
- PT Berkat Sawit Utama (PT BSU), a privately held company, Jambi, Sumatra: Hosts four of the plots of the Landscape Assessment Experiment of EFForTS (EFForTS-LA) (see Chapter 4 Research Achievements of the CRC).

Local farmers

EFForTS collaborated with about 130 smallholder farmers, which hosted the project's core plots (Phases 1 to 3) as well as plots of the Landscape Assessment (Phase 3).

Intergovernmental Organisations

- Southeast Asian Regional Centre for Tropical Biology (SEAMEO-BIOTROP, Java, Indonesia): Researchers of EFForTS and SEAMEO-BIOTROP conducted joint training measures and developed a joint open access online database of plant specimens of Jambi province, Sumatra, Indonesia, the first of its kind in Indonesia (https://crc.biotrop.org/).
- The Intergovernmental Panel on Climate Change (IPCC, UN): Researchers of EFForTS collaborated with IPPC on the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4: Agriculture, Forestry and Other Land Use (https://www.ipcc-nggip.iges.or.jp/public/2019rf/vol4.html).

Research Projects and Research Networks

- The Biodiversity and Ecosystem Function in Tropical Agriculture (BEFTA) Project, a research collaboration between the University of Cambridge and Sinar Mas, one of the largest

conglomerates in Indonesia: Researchers of EFForTS and BEFTA collaborated on experimental designs and setups as well as support in species identification and publication of joint papers.
- The Centre for Natural History (CeNak) at the University of Hamburg, one of the major centres for biodiversity and evolution research in Germany: Researchers of CeNak supported and trained EFForTS in identification of species and store type specimen in the collection of CeNak. Further, researchers of CeNak and EFForTS published joint papers.
- AsiaFlux, a research and training network with focus on carbon dioxide, water vapour and energy cycles in Asia: Researchers of EFForTS collaborated with Asia Flux; the project's climate tower at PTPN VI is an official AsiaFlux site with the name Jambi Oil Palm Plantation (JOP, http://asiaflux.net/index.php?page_id=1688).
- TreeDivNet, the largest network of biodiversity experiments worldwide: EFForTS-BEE is a participating experiment (see B11 Hölscher/Kreft/Wollni, Chapter 4 Research Achievements of the CRC and Chapter 7 Individual Project Reports).
- TRY Plant Trait Database, an open access global database of curated plant traits: EFForTS has been contributing plant trait data.
- sPlot – The Global Vegetation Database, the largest repository for plant community data in the world, hosted by iDiv (Jena, Germany): EFForTS has been contributing plot data.
- Public relation (PR) network "Changing Academy": Serves as a space for interaction and transfer of PR projects of CRC's, in which effective public communication strategies of different actors and institutions are presented and evaluated from different perspectives with regard to underlying practices of comparison.
- DFG scientific network "*Towards Evidence-Based Science Outreach: Integrating Science Education and Communication Research for the Development of a Framework Model*": Identification of key concepts regarding the goals, challenges and impact of science outreach.

5. Impact on Research Priorities and International Visibility

The University of Göttingen (UGOE) has a long-standing tradition in integrative / multidisciplinary environmental research. With four 'green' faculties, the University hosts an extraordinarily broad spectrum of departments in this field, ranging from forestry, agricultural, natural, life and social sciences to the humanities. Interdisciplinary research in all knowledge domains is carried out among a network of research institutions, centres and networks.

The interdisciplinary research centre *EFForTS* brought together institutions of five faculties, the State and University Library and the IT Centre of the University (Gesellschaft für Wissenschaftliche Datenverarbeitung; GWDG). EFForTS' twelve years of research work significantly contributed to sharpening the university's profile in the scope of future inter-faculty research projects and new inter-disciplinary and innovative networking. It has also contributed substantially to strengthen its leading role in interdisciplinary land-use research.

Long-term structural impacts

EFForTS is the flagship project of the University's research priority area on 'Sustainable Use of Natural Resources'

EFForTS was an integral part of the institutional strategy of the University of Göttingen, which has established sustainable land use as one of the research focus areas (University of Göttingen: Positions and Perspectives 2014-2024). A recent evaluation of the university's research strengths revealed three transdisciplinary strategic objectives: (1) Understanding Energy, Information and Life, (2) Creating Knowledge in a Changing World, and (3) Building a Sustainable Future. Six core topics underpin these strategic objectives of which *EFForTS* contributed to the core topics Sustainable Land Use and Biodiversity as well as Global and Local Dynamics, Sustainable Development and Responsibility (Research strategy 2023-2037, https://www.uni-goettingen.de/en/683057.html). Many of *EFForTS'* PIs were hired with the goal to strengthen the research focus on Sustainable Use of Natural Resources (see Chapter 6.1 Staffing).

EFForTS raised the international visibility and significance of the University of Göttingen within the field of research

The University of Göttingen is ranked 12th in third-party funding among the universities in Germany (not counting the funds for future concepts in the Excellence Strategy, it is ranked 9th). An indicator of the success of the research focus *Sustainable Use of Natural Resources* is that UGOE is ranked as the number one university in Germany in agriculture/forestry and as number 22 worldwide (Shanghai Ranking 2022). The University of Göttingen is by far the university with the most DFG funding in the research area "Agriculture, Forestry, Veterinary Medicine and Biology" (DFG "Funding Atlas" 2021). In the 2023 Global Ranking of Academic Subjects the University Göttingen is ranked 14th in Agricultural Sciences and 24 in Ecology (https://www.shanghai ranking.com/rankings/gras/ 2023/RS0303), two of *EFForTS'* research foci. In the field of Ecology and Evolution the University of Göttingen is ranked 1st of German universities (Research.com). EFForTS has contributed considerably to strengthening and improving all these indicators.

EFForTS was the largest collaborative scientific project between Germany and Indonesia, integrating biodiversity, ecosystem functions, socio-economics and society. It has resulted in more than 405 peer-reviewed publications, partly in highest-ranking quality journals, contributing to strengthening the international visibility in research and the scientific reputation of the university. In sum, *EFForTS* published 445 journal articles (91% peer reviewed), thereof 115 interdisciplinary publications with two or more scientific projects involved. 110 publications are led by Indonesian counterparts as first author. Besides, results were presented in relevant conferences to the scientific community, to policy makers, Indonesian teachers, and the general public (see Chapter 4.1 Scientific Event and Science Communication).

Furthermore, *EFForTS* helped to increase international visibility with regard to the Sustainable Development Goals (SDGs), adopted by the United Nations in 2015. *EFForTS* was selected as one of 20 Best-Practice Cases/Partnerships worldwide to highlight how access to genetic resources and the fair and equitable sharing of benefits arising from their utilization (ABS) contributes to conservation and sustainable use, as well as to the United Nations SDGs. The report was presented at the 10 years celebration of the Nagoya Protocol and is published on the Convention on Biological Diversity (CBD) website (https://absch.cbd.int/en/articles/ 5fbd1f585b11d0000171fc01). The ABS National Focal Points of the respective countries have also been informed about the best practice cases and presented with handouts. In this context, it should be mentioned that The State Ministry of Research and Technology and Higher Education (KEMENRISTEK-DIKTI/BRIN) of Indonesia regards *EFForTS* as a best practice example of how to increase benefit sharing resulting from international research collaboration.

EFForTS contributed to other joint research initiatives in the areas of sustainable land use

A unique feature of *EFForTS* was the integrative study of environmental processes, biota and socioeconomic perspectives. It was a very successful platform for collaboration in land-use science and was instrumental in bringing together the PIs for a proposed Cluster of Excellence on Integrative Land Use Science for Sustainable Development (LUSci) within Germany's current Excellence Strategy. The LUSci consortium was invited to submit a full proposal in February 2018. Despite not being funded, this sharpened and strengthened further collaborations on sustainable land use of natural resources at the University of Göttingen, namely: (1) The proposed Collaborative Research Centre / Transregio – "Forests and climate extremes – Legacy-dependent feedbacks across spatio-temporal scales (FATE)", currently being revised, (2) The proposed Cluster of Excellence (draft application for the future Excellence Strategy) – "Towards Climate-Smart and Resilient Landscapes (SmartLand)", although not invited for a full proposal it serves as the basis for a future CRC application, and (3) the funded Bundle of Projects (PAK proposal) „Conversion of rainforest into rubber and oil palm plantations in Sumatra, Indonesia: Landscape-scale changes in biodiversity and ecosystem functioning, and restoration pathways". The research initiatives heavily build on the collaboration (net)works of *EFForTS*.

Projects in Phase 3

A	**Environmental Processes**	
A01	Long-term vegetation dynamics, plant phenology and plant-pollinator interactions in rainforest and rainforest transformations in central Sumatra	Behling, Hermann
A02	Tree and palm water use characteristics in rainforest transformation systems	Hölscher, Dirk
A03	Understanding land-atmosphere exchange processes in land-use transformation systems	Knohl, Alexander
A05	Optimizing nutrient management in oil palm plantations and upscaling greenhouse gas fluxes from plot to a rainforest-transformation landscape	Veldkamp, Edzo Corre, Marife D.
A07	Spatio-temporal scaling of the impacts of land-use and climate change in land transformation systems in Indonesia	Knohl, Alexander Veldkamp, Edzo
B	**Biota and Ecosystem Services**	
B04	Plant productivity and belowground resource partitioning in gradients of tropical land-use intensity and tree species diversity	Leuschner, Christoph Kotowska, Martyna
B06	Taxonomic, functional, phylogenetic, and biogeographical diversity of vascular plants in rainforest transformation systems on Sumatra (Indonesia)	Kreft, Holger
B07	Functional diversity of mycorrhizal fungi along a tropical land-use gradient	Polle, Andrea Pena, Rodica
B08	Structure and functioning of the decomposer systems in lowland rainforest transformation systems	Scheu, Stefan
B09	Aboveground biodiversity patterns and processes across rainforest transformation landscapes	Westphal, Catrin Grass, Ingo
B10	Landscape-level assessment of ecological and socio-economic functions of rainforest transformation systems in Sumatra (Indonesia)	Wiegand, Kerstin Lay, Jann
B11	Biodiversity enrichment in oil palm plantations: plant succession and integration	Hölscher, Dirk Kreft, Holger Wollni, Meike
B14	The use of DNA barcoding to assess landscape effects on phylogenetic and functional diversity	Gailing, Oliver
C	**Human Dimensions**	
C01	Smallholder productivity, market access, and international linkages in rubber and palm oil production in Jambi Province	Brümmer, Bernhard
C02	Social transformation processes and sustainable resource use in rural Jambi	Faust, Heiko
C06	Understanding the certification and replanting behaviour of Indonesian smallholder farmers	Mußhoff, Oliver
C07	Determinants of land-use change and welfare impacts among rural farm and non-farm households	Qaim, Matin
C08	Designing effective policy instruments to induce sustainable land use	Wollni, Meike
C10	Localized environmental and land use policies, palm oil conversion and deforestation	Kis-Katos, Krisztina
C11	Integrated analyses of policies for sustainable rural economies	Lay, Jann Corre, Marife D. Grass, Ingo Wiegand, Kerstin Wollni, Meike
C12	Collaborative farm-modelling for reconciling socio-economic and ecological functions	Paul, Carola
INF	**Information Infrastructure Project**	
INF	Research Data Management and Integrative Statistical Analysis	Horstmann, Wolfram Kneib, Thomas Yahyapour, Ramin
PR	**Public Relations Project**	
PR	Teacher education for society: Making EFForTS knowledge available for Indonesia	Bögeholz, Susanne
Z	**Central Management**	
Z02	Central Scientific Service Project	Scheu, Stefan Knohl, Alexander Erasmi, Stefan
Z01	Central Administrative Project	Scheu, Stefan